

# One century of experiments on electron-atom and molecule scattering: a critical review of integral cross-sections

## I. – Atoms and diatomic molecules

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## 1. – Introduction

1.1. *Foreword.* – First experiments on electron interaction with gases started soon after the discovery of this elementary particle. One hundred years ago, Lenard (1894, 1895, 1903) noticed from his drift experiments performed in air,  $H_2$ , He, Ar and  $CO_2$  that the apparatus transmission function was increasing monotonically for all gases, above a certain electron energy. This can be interpreted today as the evidence of a monotonic decrease of atomic and molecular total cross-sections above, say, 100 eV. He was also the first who hypothesized that the total cross-section for molecules can be estimated by summing contributions from separate atoms. This latter idea was further explored by Brüche (1929) for a number of targets ( $CH_4$ ,  $NH_3$ ,  $H_2O$ , Ne, HCl, Ar, Kr and Xe).

Franck and Hertz's (1914) observation of the occurrence of negative-slope sections in the voltage-current characteristics of a cell containing mercury vapour was a strong direct proof of the quantization of atomic energy levels. At the same time this has been the first observation of inelastic thresholds in electron-atom scattering.

At the beginning of the twenties, Ramsauer (1921) performed the first experiments aiming at the measurement of total electron-atom molecule cross-sections at low energies. His first apparatus was covering the energy range from 0.7 eV to 36 eV and allowed to observe an unpredicted, non-monotonic behaviour of the total cross-section in argon, with values diminishing at low energies. In the same years Townsend and Bailey (1922, 1923) and Sponer (1923) detected a rise of the cross-section at energies just below those explored by Ramsauer. Their experiment was instrumentally much easier, but of more difficult interpretation. This was the beginning of a class of experiments (electron «swarm» measurements) which need the solution of the Boltzmann equation to deduct momentum transfer cross-sections. The existence of the minima in Ar, Kr, and Xe has been confirmed later in beam experiments (Rusch, 1925; Ramsauer and Kollath, 1929). The explanation of such minima has been a success of wave mechanics (Holtsmark, 1929). Seventy years later, the precise measurement of total cross-sections in the region of Ramsauer-Townsend minima is still an open question.

Already in the twenties and thirties, the need of performing measurements on selected scattering channels has been realized. Elastic differential cross-sections have been measured by Ramsauer and Kollath (1931, 1932) and ionization cross-sections by Jones (1927) and Smith (1930).

The field of experimental electron scattering shows a gap of low activity from the late thirties to the early sixties. This is coincident with the development of nuclear physics. The start of space flights and of space research was a reminder that our knowledge of electron interactions in gases was incomplete, if not episodic. The sixties were marked by the work of George Schulz, who first discovered and studied resonant phenomena in the electron-atom (and molecule) cross-sections. Those years have seen a new interest in the field and since then both the experimental and the theoretical activity is steadily growing.

In spite of this growth, the measured data available at the time mark of the last experimental review (Trajmar *et al.*, 1983) were far from giving a complete picture of the atomic and molecular scattering phenomena. This situation has been particularly unsatisfactory from the standpoint of the development of theoretical models. As a matter of fact, theoretical models and techniques have made substantial progress in

the last thirty years (see for example the reviews of Lane, 1981, Gianturco and Jain, 1986, Gien, 1988). A certain degree of inconsistency and the lack of reliable experimental data over a sufficiently large energy range has made the comparison between theory and experiment difficult. As a consequence, theoreticians are producing highly sophisticated models which—until now—cannot be fully validated by comparison with reliable observations. The situation described in these lines is probably close to a turning point. The amount of experimental data about electron-atom (molecule) total and partial cross-sections, their reliability, the precision of these measurements and the energy extension have been increasing at a fast rate in recent years (cf. Trajmar and McConkey, 1994). A number of new laboratories have joined the competition. It is therefore the right time to attempt an exhaustive collection of the experimental data for different processes and numerous targets.

Different recent reviews partially covered the subject. These works regard:

- chosen targets, like  $N_2$ ,  $O_2$ , O (Itikawa *et al.*, 1986, 1989; Tawara *et al.*, 1990);

- particular processes, like ionization (Bell *et al.*, 1983 and Lennon *et al.*, 1988), electron-impact-induced optical emission (van der Burgt, 1989; Heddle and Gallagher, 1989), electron attachment (Chutjian *et al.*, 1995), resonances (Buckman and Clark, 1994);

- particular techniques, like scattering from surface-adsorbed molecules (Sanche, 1990), Rydberg's atoms quenching (Dunning, 1995);

- particular descriptive goals, like the comparison between electron and positron scattering (Dupasquier and Zecca, 1985; Kauppila and Stein, 1990; Knudsen and Reading, 1992).

We note the actuality of the most important earlier reviews (Brode, 1933; Ramsauer and Kollath, 1933; Bederson and Kieffer, 1971; Brandsen and McDowell, 1978 for total cross-sections; Kieffer and Dunn, 1966 for ionization; Schulz 1973a, b for resonances). Total and partial cross-sections for certain «exotic» targets (metals, in particular) can be found in these older reviews only. Internal reports and data bases (from laboratories in Belfast, Orsay, Boulder, Oak Ridge) include tabulated data. Critical reviews for using these bases have been recently given by Gallagher (1994) and McDaniel and Mansky (1994). We also refer the reader to numerous textbooks in the matter (Märk and Dunn, 1985 for ionization; Shimamura and Takayanagi, 1984, Christophorou, 1984 and McDaniel, 1989 for different processes).

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**1'2. Goals of the paper.** – The aim of this paper is to review updated experimental data on electron scattering by atoms and molecules. Both total and partial cross-sections will be presented in the widest possible energy interval. Sporadically, also differential cross-sections (DCS) for elastic and inelastic processes will be presented if they are essential for understanding the physics of the collision process. The present review does not aim at a full completeness: nevertheless we have attempted to include both the new and old data when useful to complete the description of a given target.

No special emphasis will be given to special gases. A «naturally selected» emphasis will arise from the fact that some gases (like molecular hydrogen, noble gases and  $N_2$ ) have been chosen for studying by many experimenters. As a consequence a wider set of data is available and this will show up in our treatment.

Theoretical data will not be reviewed: however theoretical data will be presented occasionally. Theoretical data have been used on the basis of two criteria: *a*) when experimental data for a given gas were not available, and the addition of a few theoretical results was sufficient to give a view of the scattering phenomena; *b*) when there was no way to adjudicate between contradictory experimental results from different laboratories. We have to stress here that the choice of these theoretical data has been subjective and does not imply a judgement on other theoretical works performed on the same target.

The present paper does not contain a review of the experimental techniques used for cross-section measurements. Occasionally in the text, some experimental details will be discussed. This will be useful: *a*) to explain discrepancies among different laboratories; *b*) to justify results which deviate from the majority of results for the same measured quantity. The same argument applies for data analysis procedures: in particular, normalization procedures will be discussed in a few instances.

**1'3. Organization of the paper.** – Each subsection inside the following sections is dedicated to a single gas. Alkali dimers, alkali halides and a few metals have been grouped in three subsections: the scarcity of available data allows to show them in a single figure for all gases in each group.

Each subsection will not discuss, usually, all measured data available in the literature. A selection has been made: this has been more stringent for those gases which received more attention from experimentalists. The reason for this selection lies in the (already declared) aim of this review. The goal of the work has been to produce a critically selected set of data which should be representative of our best present knowledge of electron scattering phenomena on atoms and molecules. Therefore the measurements data have been selected to form a set as much coherent as possible. We are aware of the fact that this search for internal coherence of the presented data sets is subject to lead to a polarization of the judgements and therefore to wrong choices. An *a posteriori* overview of the final choices for each gas has convinced the authors that this (undetected) bias can affect only a fraction of the examined targets. The authors believe that different choices of the data sources selected for each section, could lead to differences in total cross-sections of the order of a few per cent over limited energy ranges. This statement is less true in the energy regions below 1 eV, where data from different authors are very scattered. The possible errors introduced by our choices can be larger for partial cross-sections. In fact, for these quantities, both the number of available measurements and their quality is generally lower.

Each of the subsections contains a variable number of sub-subsections: total, elastic, vibrational and electronic excitation, optical emission, ionization cross-sections will be presented where data are available. The last sub-subsection in each chapter is entitled: «Sum Check». Here we attempt to make a consistency check on the available data by summing up the partial cross-sections and comparing this sum with the total cross-section at selected energies. For many targets this sum check is rather rough: in spite of this, it can give useful information on the general quality of the available experimental data. Sometimes, it can give limits about one of the integral cross-sections being affected by a larger error.

Throughout the paper the following acronyms will be used: CS for Cross-Section, TCS for Total Cross-Section and DCS for Differential Cross-Section. These acronyms will be used undifferentiated for singular and plural.

The energy range covered by the present review spans from 0 eV up to 5000 eV. Whenever an energy interval has to be indicated, the following convention will be observed:

- very low energies:  $E < 1$  eV;
- low energies:  $1 \text{ eV} < E < 30$  eV;
- intermediate energies:  $30 \text{ eV} < E < 300$  eV;
- high energies:  $E > 300$  eV.

Those limits have to be considered with some fuzziness.

*Numerical tables.* A few tables only will be found in the paper. We have decided to avoid printing large numerical tables containing the measurements data collected from the literature. Moreover, such numerical data are of interest for a limited number of readers. All numerical data in table form and the files needed to reproduce the figures are available at *Il Nuovo Cimento* Editorial Office as a floppy disk (\*).

*Reading the figures.* This paper will rely heavily upon the use of figures representing integral cross-sections as a function of energy. In order to keep the number of printed pages within reasonable limits, we were forced to compress the result of many experiments in a single figure. Therefore we had to find a few rules to render these figures readable and unambiguous. Here follows a description of a typical figure: we will refer to fig. 21, subsect. 4'2, which shows the  $N_2$  integral cross-sections. This description will serve as a guide to the reading of all the figures in the text.

In all figures regarding the integral cross-sections, the energy axis will span from 0.001 eV to 5000 eV. This will make the comparison of different figures (different targets) easier. A few figures only (alkali metals and alkali halides) will use a different energy scale. Willing to show an energy range of several decades, our choice for a logarithmic axis was a must. This implies the absence of a zero-energy abscissa: in all figures where we wanted to show a zero-energy cross-section ( $\sigma_0$ ), this has been plotted as a point placed attached to the vertical axis. Again for easiness of the comparison, the cross-section axis has a span of two decades for all figures: the reader

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(\*) Disk or file is available upon request at Redazione del Nuovo Cimento, Via Castiglione 101, I-40136 Bologna, Italy; e-mail: cimento@sif.it. The price is 50 US \$, airmail additional.

will check easily that the total cross-sections of most gases vary by a factor smaller than 100 in the above-quoted energy range.

Each integral cross-section figure will report a number of total and partial cross-section measurements (sometimes partially overlapping). Eleven TCS measurements, seven elastic CS and a few other CS are reported in fig.21. Having a limited number of symbols which can be clearly distinguished in the printing, it has been unavoidable to use the same symbol more than once to indicate different measurements. In order to avoid ambiguity the following rules have been adopted in the making of the figures.

- A given symbol has not been used twice to indicate measurements of the same integral cross-sections. The same symbol can be found to indicate *different* integral cross-sections. As an example, in fig.21 full triangles indicate both the total CS measurements of Karwasz, the elastic CS of Shyn and the dissociation CS of Cosby. Due to the difference in the absolute values of these cross-sections, there is no possible ambiguity in locating them in fig.21.

- A further discrimination can be achieved by observing the order in which the symbols are listed within the figure frame in each homogeneous group. This listing is always in an order of increasing energy going from the top to the bottom. For instance, in fig.21 the total cross-sections are in order of increasing energy range from Kennerly to García.

- As a last means to identify correctly the data from different laboratories, sometimes points of a given symbol are connected by straight line segments (Srivastava in fig.21). These segments also act as a guide for the eye, every time the measured points are very sparse.

Please note that lines are also used in the figures:

- to represent theoretical results;
- to represent experimental data, whenever the density of points in the original paper was high;
- to represent momentum transfer cross-sections.

*References.* The standard presentation of references would lead to a single large list. We have considered such a list to be of difficult handling for the reader. On this basis, each subsection (dealing with a single target) will end with a reference list regarding this target only. This will lead to some redundancy of these lists (about 30%) due to the fact that often a published paper presents results regarding two or more different gases. This organization will yield a better usability of the references from the side of the reader(\*).

1'4. *Definitions and formulae.* - Recent years witnessed a variety of theoretical approaches to electron scattering problems, an enlarging range of their applicability and an increasing precision (see, for example, reviews of Lane, 1980; Gianturco and Jain, 1986; Gien, 1988). Nevertheless, simple theoretical or semiempirical formulae are still in use in the experimentalist community to normalize, compare or scale

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(\*) A bibliography update, added in proofs, can be found at the end of the paper, page 146.

laboratory data. For this reason, we find it useful to remind a few simple formulae which will be mentioned in this review, mainly during the discussion of experimental results. Only a simplified description will be given, referring the reader to specific theoretical reviews and books.

*Definitions.* *Differential cross-section* (DCS)  $d\sigma/d\omega$  is defined as the ratio between the portion  $dN'$  of the initial flux  $N_0$  of incident particles, scattered into a solid angle  $d\omega$ :

$$(1) \quad \frac{d\sigma}{d\omega} = \frac{dN'}{N_0}.$$

*The total cross-sections* (TCS) is defined as the total flux scattered into the  $4\pi$  solid angle:

$$(2) \quad \sigma_t = 2\pi \int_0^\pi \frac{d\sigma}{d\omega} \sin \theta d\theta.$$

A different angular weighting factor defines the *momentum transfer cross-section*:

$$(3) \quad \sigma_m = 2\pi \int_0^\pi \frac{d\sigma}{d\omega} (1 - \cos \theta) \sin \theta d\theta,$$

which enters into the Boltzmann transport equation.

*Partial cross-sections* for a given scattering process are defined as the flux of particles undergoing that particular process, divided by the initial flux  $N_0$ .

*Partial differential cross-sections* for the process  $P$  are defined as the fraction  $dN_p$  of the initial flux  $N_0$  which has been scattered into a solid angle  $d\omega$  after a collision implying process  $P$ .

*Partial integral cross-sections* for process  $P$  are often obtained by integration over all scattering angles of the partial DCS. They are defined as the total flux of particles scattered in a  $4\pi$  solid angle, after a collision implying process  $P$ . The sum of all partial cross-sections at any given energy yields the total cross-section at this energy. The sharing of total cross-sections as a function of energy among the possible partial cross-sections is referred to as partitioning of the TCS. Partial integral cross-sections in a few cases, like ionization or dissociative attachment, can be obtained directly from the total yield of products. In the case of ionization experiments, a distinction has to be made between the integral *gross* ionization CS, measured as the total charge of ions collected, and the *counting* ionization CS in which each ion is counted only once. For some processes, like excitation to electronic states, the same CS can be measured in different, equivalent ways: via angular-resolved electron energy loss studies, via intensity of optical emission for the transition into the ground state or (for metastable and/or autodissociating electronic states) via detection of metastable states and/or dissociated fragments. However, in the presence of multiple-step de-excitation («cascading»), the electron-impact excitation and optical emission CS can differ substantially.

*Partial waves.* Quantum mechanics defines DCS through the amplitude  $f(\theta)$

$$(4) \quad \frac{d\sigma}{d\omega} = |f(\theta)|^2$$

of the scattered spherical component of the wave function  $\Psi$ ,

$$(5) \quad \Psi = \exp[ikz] + \frac{f(\theta)}{r} \exp[ikr],$$

which describes the colliding particle at a large distance  $r$  from the scattering centre; the  $z$ -axis corresponds to the direction of the incoming plane wave and  $\mathbf{k}$  is the wave vector. Development of the spherical part of  $\Psi$  into partial waves, according to their angular momentum  $l$ -leads (Faxén and Holtsmark, 1927) to the following expression for the scattering amplitude:

$$(6) \quad f(\theta) = \frac{1}{2ik} \sum_{l=0}^{\infty} (2l+1) [\exp[2i\delta_l] - 1] P_l(\cos \theta),$$

and through eqs. (4) and (2) for the total cross-section

$$(7) \quad \sigma_t = \frac{4\pi}{k^2} \sum_{l=0}^{\infty} (2l+1) \sin^2 \delta_l,$$

where  $\delta_l$  is the additional shift, as observed at a large distance, introduced by the scattering centre to the phase of the  $l$ -wave, while  $P_l(x)$  are Legendre polynomials.

In general, the phase shifts  $\delta_l$  should be obtained from a solution of the Schrödinger equation or of its equivalent (Calogero, 1963). Analysis of formulae (6), (7) simplifies if a single partial wave dominates the scattering. In this case, DCS at a fixed energy vary with the angle as  $P_l^2(\cos \theta)$ , *i.e.* are symmetric with respect to  $\theta = 90^\circ$  and exhibit  $l$  zeros. Examples of such a simple behaviour of DCS at intermediate energies for  $\text{PH}_3$  and  $\text{H}_2\text{S}$  have been already illustrated by Massey and Burhop (1969) and will be frequently invoked in the present review.

At very low energies only the lowest, usually only the  $s$ -partial wave shift contributes to the scattering amplitude. Therefore, in the zero-energy limit, one can expect an isotropic differential cross-sections (no  $\theta$ -dependence). As a consequence, we also expect an equality between the integral (formula (2)) and momentum transfer (formula (3)) cross-sections. On this ground, in the present review we will use the momentum transfer cross-section to extend the presentation of TCS towards low energies.

The total cross-section (eq. (7)) can fall to almost-zero values, if the dominating  $\delta_l$  ( $s$ -wave shift, in the case of heavier noble gases) passes through a multiple of  $\pi$ . This effect was first observed by Ramsauer and by Townsend in different experiments. The depth of the Ramsauer-Townsend minimum is determined by contributions from other than  $s$ , higher-order partial waves.

*Zero-energy cross-sections.* Experimental cross-section at zero scattering energy can be obtained by a method suggested by Fano. In this method test atoms/molecules are produced in a highly excited state. The investigated gas is mixed with the test gas and produces a shift in the optical absorption of the test gas itself. Vapours of cesium,

$C_6H_6$  or  $CH_3I$  have been used as test media (see Rupnik *et al.*, 1990 and references therein). Alternatively, the zero-energy CS has to be evaluated via extrapolation of low-energy momentum transfer (from swarm or microwave methods) or total and/or elastic CS from beam experiments. The effective-range theory provides a useful tool for these extrapolations and relates the low-energy momentum transfer and total cross-sections.

The effective-range theory (Blatt and Jackson, 1949) defines the near-to-zero energy CS in terms of the scattering length  $A_0$ , with  $\sigma(E=0) = 4\pi A_0^2$ , and the «effective range» (cf. Joachain, 1975). The polarization potential leads to a singularity in the original effective-range formula. A modified theory (O'Malley *et al.*, 1961, 1962), overcoming this singularity, develops the near-to-zero energy TCS for electron-atom scattering into the series of  $k$  (O'Malley, 1963):

$$(8) \quad \sigma_t(E) = 4\pi \left[ A_0^2 + \frac{2\pi}{3a_0} \alpha A_0 k + \frac{8\pi}{3a_0} \alpha A_0^2 k^2 \ln(ka_0) + Bk^2 + \dots \right],$$

where  $\alpha$  is the electric polarizability of the atom and  $a_0$  is the Bohr radius. The modified effective-range theory relates, in particular, the energy  $E_T$  of the observed minimum in the momentum transfer CS and the energy  $E_R$  of the observed minimum in the total CS (O'Malley, 1963) for all cases where a Ramsauer-Townsend minimum is present:

$$(9) \quad E_T = \left( \frac{5}{6} \right)^2 E_R.$$

From the reasonable assumption that other than  $l=0$  partial-wave shifts rise monotonically with  $E$  from zero value at  $E=0$ , one concludes that the same minimum as measured in the momentum transfer CS should be deeper than that seen in the TCS. The modified effective-range theory reveals to be successful in relating the low-energy momentum transfer and total cross-sections; however, the accuracy of its implementation depends both on the energy range of experimental data used as well as on the number of terms in the expansion (8) (compare with the study of Buckman and Mitroy (1989)).

*Born approximation.* Perturbative calculation techniques can be applied if the scattering potential can be considered as a small distortion to a free (unscattered) wave. The Born approximation, being a simple implementation of the perturbative method, leads to several useful applications.

In the case of elastic scattering at high energies numerous partial waves contribute to the TCS. The scattering amplitude can be described in terms of the Fourier transform of the scattering potential in the  $k$ -space. The differential elastic cross-section at zero-scattering angle remains, according to the Born approximation, constant with energy. The integral elastic cross-section has been expanded into a series of  $(1/E)^n$  powers (Inokuti and McDowell, 1974):

$$(10) \quad \sigma_{el}(E) = A_1 \frac{R}{E} + A_2 \frac{R^2}{E^2} + \dots,$$

where  $R$  is the Rydberg energy and  $A_i$  are adjustable parameters.

This series cannot describe correctly the elastic cross-section in the intermediate-energy range where it passes from a constant or a maximum value to the high-energy,  $1/E$  slope. Several alternative series, adding new terms to the equation, have been proposed (cf. Browning *et al.*, 1994 and references therein). It has been shown (Zecca *et al.*, 1992; Karwasz *et al.*, 1993) that a formula

$$(11) \quad \sigma_t(E) = \frac{\sigma_0 B}{B + \sigma_0 E},$$

with  $\sigma_0$  being an «asymptotic» zero-energy CS and parameter  $B$  determining the high-energy values, reproduces the experimentally observed TCS for a number of molecules ( $N_2$ , CO,  $CH_4$ ,  $H_2O$ ). Zecca *et al.* (1992) have argued that the same energy dependence governs the integral elastic cross-sections for scattering on a Yukawa potential:

$$(12) \quad V(r) = V_0 \frac{\exp[-r/a]}{r},$$

with  $V_0$  and  $a$  being the strength and range of the potential, respectively.

We also remind that, using Thomas-Fermi model to derive the atomic field, one gets a  $Z^{4/3}/E$  proportionality of integral elastic CS at high energies,  $Z$  being the atomic number (see Mott and Massey, 1965). Scaling analogies for molecules have been proposed by March (1957).

For inelastic scattering, Bethe developed a formula somewhat similar to the one for the interaction of a point charge with the electromagnetic continuum (see for example Jackson, 1975):

$$(13) \quad \sigma_{in}(E) = 4\pi a_0^2 \frac{R}{E} \left[ M_{tot}^2 \ln \left( 4C_{tot} \frac{E}{R} \right) + \gamma_{tot} \frac{R}{E} \right],$$

where coefficients  $M_{tot}$ ,  $C_{tot}$  and  $\gamma_{tot}$  can be obtained from the moments of the electronic-charge distribution in the atom. The logarithmic term in (12) allows to reproduce both the near-to-threshold rise as well as the high-energy  $1/E$  fall of the inelastic (ionization, electronic excitation) cross-sections. The theoretical  $(1/E)$ -dependence of the inelastic CS is used in the present review to extrapolate available data toward high energies.

An application of the Born approximation at low collision energies regards the calculation of vibrational and rotational excitation CS under the assumption of a weak interaction. Integral CS for rotational  $\Delta J = \pm 1$  transitions (Massey, 1931; Takayanagi, 1966; Crawford, 1967) in the Born approximation amounts to

$$(14) \quad \sigma_{rot}(J \Rightarrow J \pm 1) = \frac{8\pi}{3k^2} D^2 \frac{J_{>}}{2J+1} \ln \frac{k+k'}{|k-k'|},$$

where  $k$  and  $k'$  are initial and final wave numbers, respectively; and  $D$  stands for the permanent dipole moment of the molecule (atomic units  $m = \hbar = e = 1$  are used in formulae (14) and (15)). The Born approximation indicates a fast rise of DCS for rotational excitation in the limit of small scattering angles. Formula (14) has been modified, for example, by Dickinson (1977) who adopted a classical perturbation theory at intermediate angles and a constant DCS value at high scattering angles (see

subsect. 6'2 for alkali halides). Theoretical aspects of scattering on polar targets have been reviewed, for example, by Norcross and Collins (1982).

A formula analogous to (14) has been derived for vibrational excitation of molecules (Takayanagi, 1966; Itikawa, 1974):

$$(15) \quad \sigma_{\text{vib}}(\nu \Rightarrow \nu') = \frac{8\pi}{3k^2} g' |\langle \nu' | D | \nu \rangle|^2 \ln \frac{k + k'}{|k - k'|}.$$

In this case the temporary dipole transition moment  $\langle \nu' | D | \nu \rangle$ , with  $\nu$  and  $\nu'$  indexing initial and final vibrational states, respectively, is the «driving force» of the excitation ( $g'$  stands for the degeneracy of the upper state). The matrix elements  $\langle \nu' | D | \nu \rangle$  can be obtained from intensities of Raman and infrared optical spectra of molecules (see Sverdlov *et al.*, 1974). A review of other methods of calculating vibrational excitations has been given, for example, by Thompson (1983).

According to the Born-Bethe approximation, DCS ( $d\sigma_{\text{exc}}/d\omega$ ) for the electronic excitation is related, in the limit of zero transferred momentum  $\mathbf{K}$  ( $\mathbf{K} = \mathbf{k} - \mathbf{k}'$ ) to the values derived from optical absorption (Lassetre *et al.*, 1969). The generalized oscillator strength  $F$  defined (in atomic units) as

$$(16) \quad F = \frac{\Delta E}{2} \frac{k}{k'} K^2 \frac{d\sigma_{\text{exc}}}{d\omega}$$

tends for  $\mathbf{K} \rightarrow 0$  to the optical oscillator strength  $F_0$ , which is encountered in the theory of the refraction and absorption of radiation ( $\Delta E$  is the excitation energy). This relation is widely used to normalize electronic excitation cross-sections (see the alkali metals subsections in the present review, for example).

*The additivity rule* is an old concept dating to the first experiments by Lenard (1894, 1895) in the field of electron scattering. It deals with the expectation that TCS for molecules can be obtained by summing TCS for separate atoms (Brüche, 1927). The validity of the additivity rule for calculating total cross-sections for molecules (Raj, 1991, 1993; Joshipura and Patel, 1994; Sun *et al.*, 1994) is doubtful, as will be discussed for atomic oxygen or chlorofluoromethanes, for example. However, this concept has been effectively used in the independent-atom model used to calculate high-energy elastic CS (see, for example, the  $\text{O}_2$  subsection in this review). Taking the hydrogen molecule for simplicity and under the assumption of the validity of the Born-Yukawa approximation, the elastic DCS can be described (van Wingerden *et al.*, 1977) as

$$(17) \quad \frac{d\sigma_{\text{el}}}{d\omega} = \frac{8(8a_0^{-2} + K^2)^2}{(4a_0^{-2} + K^2)^4} \left[ 1 + \frac{\sin Kd}{Kd} \right] a_0^2,$$

where the first term in square parentheses corresponds to scattering on the two atoms and the second factor accounts for interference effects ( $d$  stands for the internuclear distance). In subsect. 4'3 we present intermediate energy DCS for  $\text{O}_2$ ,  $\text{N}_2$  and CO molecules with such interference patterns.

*Dispersion relation.* Different experimental quantities such as the scattering length, the high-energy zero-angle elastic DCS and total cross-section over an energy range from zero to infinity are unified by the dispersion relation. This relation,



originally proposed for electron scattering by Gerjuoy and Krall (1960), relates the real part of the forward-scattering amplitude  $\text{Re}[f(\theta = 0, E)]$  at a given energy with the amplitude  $f_B$  ( $\theta = 0, E = \infty$ ) at a high, Born-approximation energy and with the integral of TCS over the energy:

$$(18) \quad \text{Re}[f(0, E)] = f_B(0, E) - g_B(0, E) + \frac{k}{4\pi^2} \int_E^\infty \frac{\sigma_t(E')}{E' - E} dE'.$$

The additional term  $g_B$  stands for the forward-scattering amplitude attributable to exchange forces. The dispersion relation in the form (17) has not been confirmed for electron-hydrogen-atom and electron-helium scattering (de Heer *et al.*, 1977) but seems to be verified for positron scattering on He, Ne and probably Ar (Kauppila *et al.*, 1981). Several alternative ways to modify the relation have been developed (cf. Kuchiev, 1985; Temkin *et al.*, 1986). An experimental verification requires special methods to measure the near-to-zero angle DCS (Wagenaar *et al.*, 1986) as well as the knowledge of TCS in a large energy interval.

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## 2. – Noble gases

Noble gases, although not being historically the first gases studied in electron collisions, contributed in a decisive way to understand the quantum-mechanical nature of scattering. Numerous experiments have been performed in consequence. In spite of this, still some discrepancies exist both at very low as well as at high energies. This prompts to continued laboratory efforts.

**2.1. Helium (He).** – Knowledge of cross-sections for electron scattering on helium can be considered good. Due to successful applications of theory to the  $e^- + \text{He}$  system (see, for example, Nesbet, 1979), helium cross-sections serve as standards in elastic CS (Register *et al.*, 1980) and electronic excitations (Trajmar *et al.*, 1992b) normalizations. The discovery (Schulz, 1963) of a resonant state close below the first inelastic threshold opened studies of resonant phenomena in atomic and molecular scattering. A comprehensive summary of earlier partial and total cross-sections measurements for all noble gases was published by Bederson and Kieffer (1971) and for He specifically by de Heer and Jansen (1977). Figure 1 shows an outline of He integral cross-sections.

*Total cross-section.* Pioneering work on the He cross-sections by beam methods has been performed in the twenties by Ramsauer at 0.7–1.0 eV and 0.8–50 eV (1921a and 1921b, respectively), Brode (1924, 1925) at 2–360 eV, and by Brüche (1927) at 1–50 eV. These old measurements are generally of very high quality. Measurements of Brode (1925) on a Ramsauer-like set-up showed a fall (by 50% going from 4 eV to 1 eV) of the helium TCS towards the zero energy. The data of Normand (1930) from the same set-up exhibit an oscillatory structure around 1 eV. It is believed now that these findings were produced by an instrumental effect.

We will confine our study to more recent measurements. Our choice includes time-of-flight (Ferch *et al.*, 1980; Buckman and Lohmann, 1986; Kennerly and Bonham, 1978) and electrostatic-spectrometer (Szmytkowski *et al.*, 1995) experiments

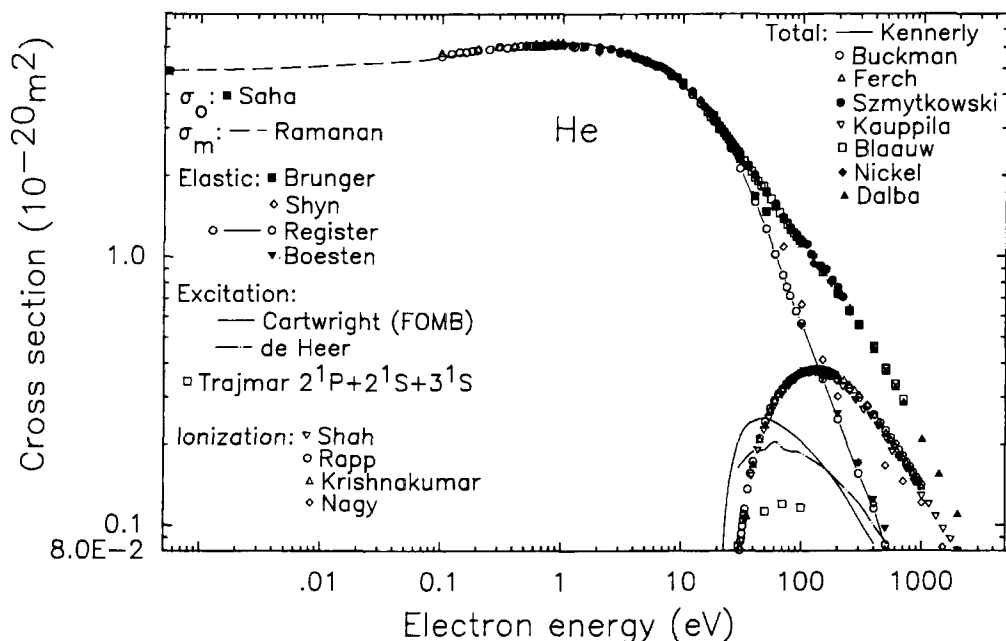


Fig. 1. – *Integral cross-sections* for electron scattering on He. *Total*: Kennerly and Bonham (1978); Buckman and Lohmann (1986); Ferch *et al.* (1980); Szmytkowski *et al.* (1995); Kauppila *et al.* (1981); Blaauw *et al.* (1980); Nickel *et al.* (1985); Dalba *et al.* (1979, 1981). *Elastic*: Brunger *et al.* (1992); Shyn (1980); Register *et al.* (1980); Boesten and Tanaka (1992). *Excitation*: de Heer and Jansen (1977) semiempirical; sum of all levels from Cartwright's (1992) first-order many-body theory; sum of three singlet levels from Trajmar *et al.* (1992a, b). *Ionization*: Shah *et al.* (1988); Rapp and Englander-Golden (1965); Krishnakumar and Srivastava (1988); Nagy *et al.* (1980). *Momentum transfer*: Ramanan and Freeman (1990); data of Crompton *et al.* (1970) are superimposed to those of Ramanan and Freeman. *Zero-energy*: Saha (1993) multiconfiguration Hartree-Fock calculations.

at low energies, linearized techniques for intermediate energies (Nickel *et al.*, 1985; Blaauw *et al.*, 1980), curved configurations at intermediate (Kauppila *et al.*, 1981) and high (Dalba *et al.*, 1979, 1981) energies. A very good agreement (within 3%) exists among all these recent data.

TCS for electron scattering on helium diminishes slowly in the zero-energy limit: no minimum, observable for heavier noble gases, exists. On the contrary, for positron-helium scattering a deep minimum of about  $0.05 \cdot 10^{-20} \text{ m}^2$  around 1.5 eV has been observed (Canter *et al.*, 1973; Stein *et al.*, 1978; Sinapius *et al.*, 1980; Mizogawa *et al.*, 1985). This has been explained in terms of a Ramsauer-Townsend effect. It has been already noticed by Holtsmark (1929) that the occurrence of a Ramsauer-Townsend minimum depends on combined effects of scattering on the static and polarization potentials. In the case of electron scattering the two effects compete, since the static interaction is repulsive. For positron scattering, in spite of a very small polarizability of He ( $0.205 \cdot 10^{-20} \text{ m}^2$ ), the summed effect is strong enough to induce a zero value in the *s*-partial-wave shift at low energies (Campeanu and Humberston, 1977, compare also fig. 3 for  $e^-$  experimental phase shifts).

Kauppila *et al.* (1981) noticed a merging between total electron and positron CS at

energies above 250 eV. This would indicate (Kauppila *et al.*, 1981): i) the validity of the Born-Bethe approach, in which the sign of the scattering potential does not influence the cross-section, ii) a negligible influence of the polarization and exchange forces.

*Swarm.* The swarm method has been introduced by Townsend and Bailey (1922). It is based on the measurement of transport coefficients, like mobility and transverse diffusion, of the electron swarm drifting under the influence of an electrostatic field in a relatively high pressure ( $10^3$  Pa) gas target. The transport coefficients are coupled, via Boltzman's equation, with the cross-sections for particular processes (elastic scattering, rotational, vibrational and electron excitations, ionization). Physically similar to swarm are the microwave experiments, in which the temporal evolution of the discharge depends both on the CS as well as on the energy distribution of electrons (see Bederson and Kieffer, 1971 for a review). Swarm methods are effective in deriving momentum transfer CS at low energies and in gases with high threshold for inelastic processes. Due to the expected isotropy of (elastic) scattering in the zero-energy limit, the total and the momentum transfer CS can be directly compared at low energies. Since Townsend and Bailey's time, substantial improvements have been introduced both in the technique and in the mathematical procedure needed to evaluate cross-sections from the original transport data (see Schmidt *et al.*, 1995).

In a recent experiment in helium, Ramanan and Freeman (1990) extended measurements for transport coefficients down to the temperature of 11 K. A good accord of the derived momentum transfer CS with other swarm data (Crompton *et al.*, 1970) and merging with beam experiments has to be acknowledged.

A high accuracy was claimed by Saha (1993) for his calculations of the zero-energy cross-section. The scattering length of Saha ( $+1.178a_0$ ) agrees well with the experimental values of  $1.16a_0$ ,  $1.19a_0$ ,  $1.172a_0$  and  $1.195a_0$  from Buckman and Lohmann (1986), Crompton *et al.* (1970), Andrick and Bitsch (1975) and Ferch *et al.* (1980), respectively. A somewhat lower scattering length of  $1.08a_0$  has been obtained by the Fano method (see Bederson and Kieffer, 1971), *i.e.* from measurements of pressure shift in perturbed molecular photoabsorption (Asaf, 1989; Rupnik, 1990).

*Elastic cross-sections*, due to their importance for normalization procedures, have been measured in numerous experiments. Measurements at low energies include:

- data of Andrick and Bitsch (1975) at 2–19 eV, 15–145° normalized to the effective-range theory; phase shifts are given in their paper;
- 10–150° measurements of Gupta and Rees (1975) at 100 eV, normalized to the data published by Jansen *et al.* in 1976;
- data of McConkey and Preston (1975) at 1.5–100 eV, 20–90° normalized to the experiment of Vriens *et al.* (1968);
- data of Williams (1979) at 0.5–20 eV, 15–150° normalized to resonances in He and Ar; phase shifts have been derived;
- data of Golden *et al.* (1984) at 2–19 eV normalized through a phase-shift analysis (see Steph *et al.*, 1979 for the procedure);
- data of Brunger *et al.* (1992) at 10–125° and 1.5–50 eV normalized to

variational calculations and to the coupled-channels optical model; scattering potentials have been obtained via inversion procedure.

At intermediate energies:

- data of Sethuraman *et al.* (1974) at 30–150° and 100–500 eV, normalized at 500 eV to the data of Bromberg (1974);
- absolute data of Kurepa and Vušković (1975) at 5–150°, 100–200 eV;
- data of Shyn (1980) at 96–156° and 2–400 eV normalized at 10 eV to the extended-polarization-potential calculations (LaBahn and Callaway, 1970);
- the data by Register *et al.* (1980) at 10–140° and 5–200 eV normalized to the TCS by a phase-shift method. This set has been used as reference data for normalization of elastic CS measured in different gases;
- low-angle 0–10° absolute data of Wagenaar *et al.* (1986) at 20–100 eV.

At high energies:

- absolute data of Bromberg (1974) at 2–110°, 200–700 eV;
- data of Jansen (1976) at 5–55°, 100–3000 eV normalized to their absolute N<sub>2</sub> result;
- absolute data of Goruganthu and Bonham (1986) at 30–150°, 200–2000 eV.

Different experimental and theoretical results were used by Boesten and Tanaka (1992) to tabulate differential cross-sections  $d\sigma/d\omega$  as a function of the angle  $\theta$  between 0–180° and 0.1–1000 eV in the form of rational functions  $W(\theta)/V(\theta)$ , where  $W$  and  $V$  are polynomials of the 4th order. Good agreement is observed between parametrized integral elastic CS of Boesten and Tanaka (1992) and Register *et al.* (1980) in the whole 30–1000 eV energy range (see table I). A 15% difference at 500 eV comes probably from a print-out error in Register *et al.* (1980). At 100 eV the independent result of Shyn (1980) is almost 20% higher than the last mentioned sets.

Helium elastic CS at intermediate and high energies present some anomalies with respect to the Born-like behaviour. This is expected on theoretical grounds; in addition it is suggested by the observed merging between  $e^-$  and  $e^+$  TCS. In the Born approximation, the extrapolation to zero of the DCS *vs.* the transferred momentum tends to a value which does not depend on the electron impact energy. Bromberg (1974) pointed out that such a behaviour can be observed for all noble gases except for He. The upper part of fig. 2 demonstrates this for Ar and Ne. The lower part shows the different behaviour of the He DCS. Lines connecting points at the same incident energy, converge close to a transferred momentum value of  $6a_0^{-1}$ , where  $a_0$  is the Bohr radius. A phenomenological explanation (Jansen *et al.*, 1976) points at the importance of exchange and polarization effects in helium.

Register *et al.* (1980) and Wagenaar *et al.* (1986) noticed dips in the DCS at scattering angles below 10° for energies just above the ionization threshold and attributed them to channel-coupling effects. No similar phenomena were observed for other noble gases.

As a final remark, we note that the data of Register *et al.* (1980), of Shyn (1980) as well as the compiled results of Boesten and Tanaka (1992) show an energy dependence of the integral CS slightly more rapid than  $E^{-1}$  in the whole 100–1000 eV energy range.

*Phase shifts and potentials.* Phase-shifts analysis has been frequently used (Golden *et al.*, 1984; Williams, 1979; Andrick and Bitsch, 1975) to extrapolate and normalize experimental CS. Generally, a good agreement exists between phase shifts derived from different experimental CS: in fig. 3 we present them as a function of the wave vector  $k$  (note that the  $\pi$  value has been subtracted for the  $s$  shift). In the region 0.5–20 eV the  $s$ -wave shift diminishes smoothly from  $0.91\pi$  rad to  $0.57\pi$  rad, while  $p$  and  $d$ -wave shifts rise from 0 to  $0.1\pi$  and  $0.02\pi$  rad, respectively (Williams, 1979). The changes in the  $s$ - and  $p$ -wave phase shifts between 1 and 15 eV are almost linear, if plotted against  $E^{1/2}$ .

A complex inversion procedure was used to derive the scattering potential at 2, 5, 12 and 19 eV (Allen, 1986), 30 eV (Allen, 1991) and at 10, 20 and 50 eV (Brunger *et al.*, 1992).

*Electronic excitation.* Electronic excitations in helium were subject to intensive experimental (see summary in Trajmar *et al.*, 1992a for excitations to the  $2^1S$ ,  $2^3S$ ,  $2^3P$ ,  $3^3P$ ,  $3^1S$ ,  $3^3S$  levels and in Trajmar 1992b to  $2^1P$  level) and theoretical work. Due to a good agreement between different experimental results the excitation CS to the  $2^1P$  level has been proposed as a standard for electronic-excitation measurements (Trajmar *et al.*, 1992b). Good accord exists between experimental absolute DCS for excitations into the  $n = 2$  (Brunger *et al.*, 1990; Trajmar *et al.*, 1992a) and  $n = 3$  (Chutjian and Thomas, 1975; Trajmar *et al.*, 1992a; Batelaan *et al.*, 1992) levels.

The integral CS for transitions into singlet states after reaching a maximum is expected to descend slowly with energy, following the Born-Bethe formula (de Heer and Jansen, 1977). On the other hand, excitation into triplet states, amounting at its

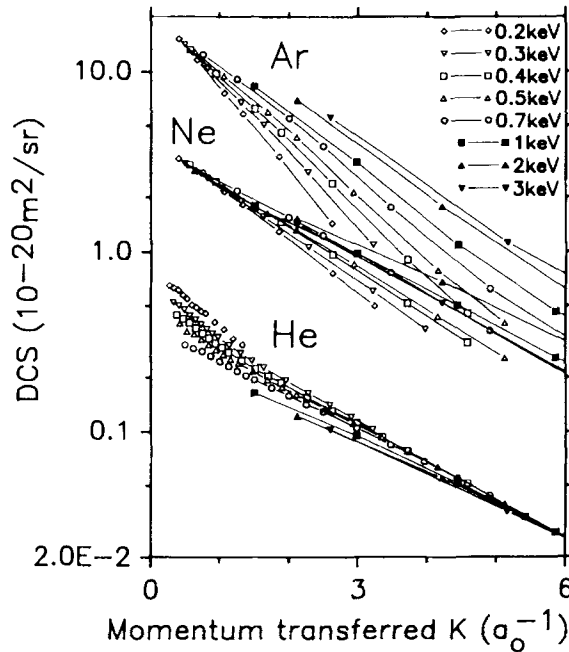


Fig. 2. – Intermediate- and high-energy, low-angle differential elastic cross-sections as a function of transferred momentum for electron scattering on He, Ne and Ar (from Bromberg, 1974 and Jansen *et al.*, 1976).

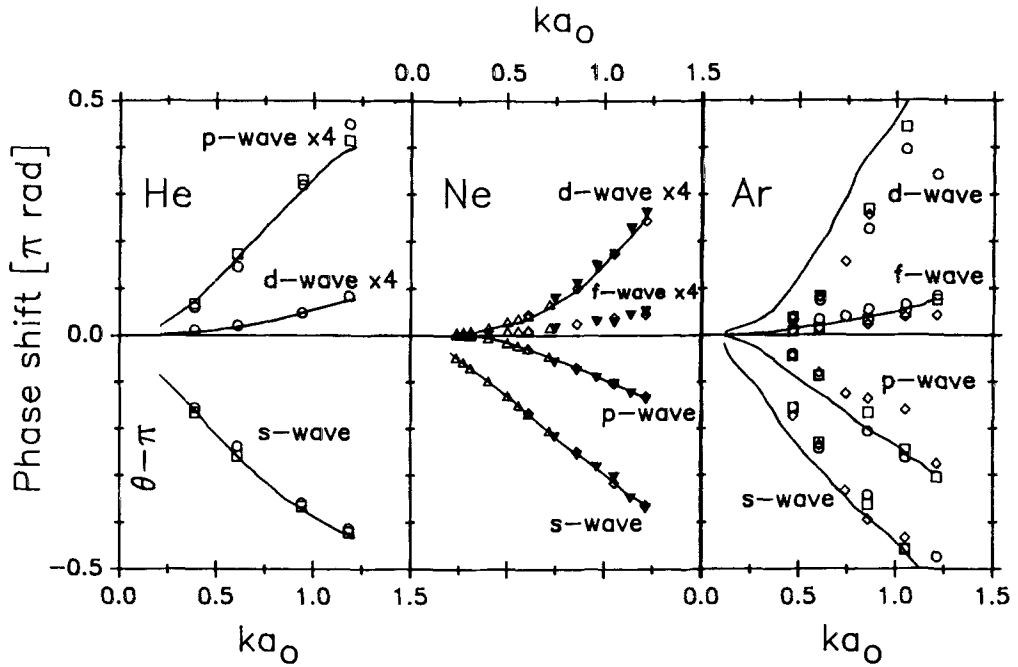


Fig. 3. – Phase shifts for electron scattering on He, Ne and Ar at low energies. Solid lines, Williams (1979); squares, Andrick and Bitsch (1975) for argon as quoted by Furst *et al.* (1989); circles, Golden *et al.* (1984) for He, Furst *et al.* (1989) for Ar; open triangles, Gulley *et al.* (1994); rhombuses, Srivastava *et al.* (1981) for Ar and Register and Trajmar (1984); for Ne full triangles, Brewer *et al.* (1981). References for Ne and Ar are to be found in the respective subsections.

maximum to about 50% of the total excitation (cf. Register *et al.*, 1980), falls rapidly with energy. Recent measurements confirm these conclusions. At 30 eV contributions from both triplet and singlet  $n = 2$  excitations are of similar weights: 3.9, 2.4, 3.7 and  $3.2 \cdot 10^{-22} \text{ m}^2$  for  $2^1S$ ,  $2^3S$ ,  $2^1P$ , and  $2^3P$  states, respectively (Trajmar *et al.*, 1992a, b). Cross-sections for the corresponding  $n = 3$  excitations are roughly lower by a factor of 5 (Trajmar, 1992a; Batelaan *et al.*, 1992). At higher energies the  $2^1P$  excitation dominates, amounting at 100 eV (Trajmar *et al.*, 1992b) to half of the total excitation (de Heer and Jansen, 1976) and 8% of the TCS.

Cross-sections for excitations into singlet states show an  $E^{-1}$  energy dependence between 50 and 100 eV. Cross-sections for  $2^1S$  and  $3^1S$  final states vary from  $2.31 \cdot 10^{-22} \text{ m}^2$  to  $1.24 \cdot 10^{-22} \text{ m}^2$  and from  $0.44 \cdot 10^{-22} \text{ m}^2$  to  $0.25 \cdot 10^{-22} \text{ m}^2$ , respectively (Trajmar *et al.*, 1992a; see also Trajmar, 1973). The sum of triplet states  $2^3S$ ,  $2^3P$ ,  $3^3S$ ,  $3^3P$  fall, in the same energy span, from  $3.31 \cdot 10^{-22} \text{ m}^2$  to merely  $0.40 \cdot 10^{-22} \text{ m}^2$ . A scaling law  $n^3\sigma = \text{const}$  has been indicated (Csanak and Cartwright, 1986) for excitation to higher quantum number  $P$ -states.

A first-order many-body theory is widely used in calculations of electronic-excitation processes (see for example Meneses and Csanak, 1988; Csanak and Cartwright, 1988; Csanak *et al.*, 1992). In the case of helium it reproduces well the semiempirical overall excitation CS from the threshold up to 500 eV (Cartwright *et al.*, 1992) but differs from experiments in predicting particular differential and

integral CS (see Trajmar *et al.*, 1992a). However, in fig. 1 we present the theoretical results rather than a compilation of different experimental data. Following Cartwright *et al.* (1992) the excitation cross-section amounts to as much as 20% of the TCS above 100 eV. We note that a large contribution from inelastic channels is also observable in  $H_2$  and alkali metals.

*Optical emission cross-sections* from early measurements have been summarized by de Heer and Jansen (1977). More recently they have been measured by Shemansky *et al.* (1985) and reviewed by Heddle and Gallagher (1989).

*The metastable  $2^3S_1$  state of He*, due to its high polarizability, is expected to exhibit a high elastic and total CS. Integral CS for the yield of ( $2^1S_0 + 2^3S_1$ ) metastable atoms amounts to 2.5% of TCS at 25 eV (Mason and Newell, 1987, normalized to Borst, 1974). Superelastic DCS for scattering from the  $2^3S_1$  state have been recently studied by Jacka *et al.* (1995).

*Ionization.* Very good agreement (within 2%) from the threshold up to 1000 eV exists between three recent sets of data: Shah *et al.* (1988), Krishnakumar and Srivastava (1988) and Montague *et al.* (1984). Acceptable agreement (see Shah *et al.*, 1988) exists also with the results of Rapp and Englander-Golden (1965) and Wetzell *et al.* (1987). High-energy data of Nagy *et al.* (1980) and Schram *et al.* (1966) are about 15% lower than the measurements of Shah *et al.* and (at 1000 eV and 2000 eV) than data of Goruganthu and Bonham (1986).

The ratio of the double to single ionization of He (Shah *et al.*, 1988; Stephen *et al.*, 1980; Nagy *et al.*, 1980; van der Wiel *et al.*, 1969; Andersen *et al.*, 1987) reaches its maximum of 0.5% at 500 eV. Toward high energies, it tends to an asymptotical value of  $2.4 \cdot 10^{-3}$ , predicted theoretically (McGuire, 1982; Manson and McGuire, 1995) and common for electron, positron, proton and antiproton scattering (Shah and Gilbody, 1985; Charlton *et al.*, 1988; Andersen *et al.*, 1987, respectively).

*Resonances.* After the discovery of a resonance at 19.3 eV by Schulz (1963), several studies have been made on the detailed structure of total and differential CS above the first inelastic threshold (Golden and Bandel, 1965; Kuyatt *et al.*, 1965). The 19.3 eV resonance, having a narrow intrinsic width, has been used as an energy calibration point both in total and differential measurements. Eleven structures have been detected by Kuyatt *et al.* (1965) in the range from 19.3 eV to the ionization threshold. Further resonant structures appear at about 57 eV (Golden and Zecca, 1970).

More recent studies of He resonances include high-resolution measurements in the elastic-scattering (Brunt *et al.*, 1977b), metastables yield (Brunt *et al.*, 1977a; Buckman *et al.*, 1983; Shpenik *et al.*, 1984) and electronic-excitation (Allan, 1992) channels.

*Sum check.* The sum check confirms a good consistency between partial and total cross-sections up to energies of a few hundred eV. A consistent set of partial cross-sections includes the «reference» elastic CS of Register *et al.* (1980); the elastic parametrized values of Boesten and Tanaka (1992); recent ionization data (Shah *et al.*, 1988; Krishnakumar and Srivastava, 1988; Montague *et al.*, 1984); recent excitation measurements by Trajmar (1992a, b). These partial CS sum up to yield values close to



TABLE I. – *Integral cross-sections for electron scattering on helium (in  $10^{-22}$  m<sup>2</sup> units) at selected energies.*

Energy (eV)	Elastic	Excitation	Ionization	Sum	Total
30	217 <sub>B</sub> 230 <sub>BR</sub> 211 <sub>R</sub>	20 <sub>C</sub> (8.3) <sup>1</sup> (6.9) <sup>3</sup>	6.7 <sub>K</sub>	244	239.1 <sub>N</sub>
50	126 <sub>B</sub> 147 <sub>BR</sub> 126 <sub>R</sub>	25 <sub>C</sub> (11.2) <sup>1</sup> (3.3) <sup>3</sup>	23.7 <sub>K</sub>	175	171.5 <sub>N</sub>
100	55.1 <sub>B</sub> 56.1 <sub>R</sub>	20 <sub>C</sub> (11.6) <sup>1</sup> (0.4) <sup>3</sup>	37.0 <sub>K</sub>	112	112.0 <sub>N</sub>
200	25.9 <sub>B</sub> 24.7 <sub>R</sub>	14 <sub>C</sub>	36.0 <sub>K</sub>	76	73.4 <sub>N</sub> 76.6 <sub>D</sub>
400	12.5 <sub>B</sub> 12 <sub>S</sub> 11.5 <sub>R</sub>	8.5 <sub>C</sub>	24.3 <sub>SH</sub> 25.7 <sub>K</sub>	45.3	44.9 <sub>D</sub> 25.7 <sub>K</sub>
500	9.68 <sub>B</sub> 8.4 <sub>R</sub>	6.8 <sub>C</sub>	22.0 <sub>K</sub> 21.0 <sub>SH</sub>	38.5	37.4 <sub>D</sub>
700	6.64 <sub>B</sub> 6.5 <sub>R</sub>	4.8*	17.7 <sub>SH</sub> 17.8 <sub>K</sub>	29.1	34.6 <sub>D</sub>
1000	4.34 <sub>B</sub> 4.1 <sub>R</sub>	3.4*	13.4 <sub>SH</sub>	21.1	21.0 <sub>D</sub> 13.9 <sub>K</sub>
2000	2.17*	1.7*	8.02 <sub>SH</sub> *	11.9	11.1 <sub>D</sub>

\* – Extrapolated data, assuming  $E^{-1}$  high-energy dependence of partial cross-sections.

(<sup>1</sup>) – Sum of experimental excitations into  $2^1P$ ,  $2^1S$ ,  $3^1S$  states from Trajmar *et al.* (1992a,b).

(<sup>3</sup>) – Sum of experimental excitations into  $2^3S$ ,  $2^3P$ ,  $3^3S$   $3^3P$  states from Trajmar *et al.* (1992a,b).

B – Boesten and Tanaka (1992), semiempirical.

BR – Brunger *et al.* (1992).

C – Sum of the partial excitation cross-sections as given in fig. 14 of Cartwright (1992). The error on the  $x$ -scale of the original drawing has been corrected for.

D – Dalba *et al.* (1979, 1981).

K – Krishnakumar and Srivastava (1988).

N – Nickel *et al.* (1985).

S – Shyn (1980).

SH – Shah *et al.* (1988).

R – Register *et al.* (1980).

the TCS of Nickel *et al.* (1985) at low and Dalba *et al.* (1981) at high energies. This is shown for selected energies in table I. The difference between the summed value and the experimental TCS of Dalba *et al.* (1981) is about 3% at 500 eV. This difference increases with energy up to 7% at 2000 eV and can be explained in part on the basis of an angular resolution error in the cited experiment. TCS measurements with a small angular acceptance and energy-loss analysis would be of interest.

It is peculiar for He, compared with other noble gases, that elastic CS at high energies (above 1000 eV) amounts to only 20% of the total one.

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2.2. *Neon (Ne).* – Total and partial CS for electron scattering on Ne have been reviewed among others by Brandsen and McDowell (1978), de Heer *et al.* (1979), Shimamura (1989). Figure 4 depicts the present knowledge on Ne integral CS.

*Total cross-sections.* Different experimental results in neon constitute a congruent set of data. This congruence is close to the limits posed by the experimental errors in each measurement. Two recent results: from a time-of-flight apparatus (Gulley *et al.*, 1994) and from an electrostatic-spectrometer set-up (Szmytkowski *et al.*, 1995) coincide at 0.5 eV. In the 2–5 eV range different measurements (Salop and Nakano, 1970; Stein *et al.*, 1978; Sinapius *et al.*, 1980; Charlton *et al.*, 1984; Nickel *et al.*, 1985; Kumar *et al.*, 1987; Szmytkowski *et al.*, 1995) agree very well. The above-mentioned measurements of Gulley *et al.* (1994) are slightly (from 3% at 2 eV to 5% at 5 eV) higher than other data.

At intermediate energies the scatter between data of Nickel *et al.* (1985), Szmytkowski *et al.* (1995), Zecca *et al.* (1987) remains within a few per cent. A minor deviation downwards (2%) of the data of Kaupilla *et al.* (1981) is within the expected angular resolution error of their measurement; no clear explanation can be given for an upwards (5% at 200 eV) discrepancy between the data of Wagenaar and de Heer (1980) and the remaining measurements. The data of García *et al.* (1986) at 1000 eV are 6% higher than those of Zecca *et al.* (1987). We will find in the following that the measurements of García *et al.* are higher than those of Zecca *et al.* for all gases measured by both groups. This difference is sometimes energy independent (see Ne) and sometimes is larger at high energies (see Kr). Therefore it is difficult to say if it can be attributed to a different pressure evaluation (from optical-emission intensity in the measurements of García *et al.*, 1986 and from capacitance manometry in the work of Zecca *et al.*) or to different angular resolutions of the apparatuses.

*Swarm measurements.* Momentum transfer CS have been derived by O'Malley and Crompton (1980) from swarm measurements of Robertson (1972). Just below 1 eV the momentum transfer CS is higher than TCS (see fig. 4). This finding has also been confirmed by Gulley *et al.* (1994) in their low-energy measurements of DCS. Ultra low-energy microwave measurements of Sol *et al.* (1975) agree very well with the determination of O'Malley and Crompton (1980) above 0.05 eV but exceed the latter for lower energies.

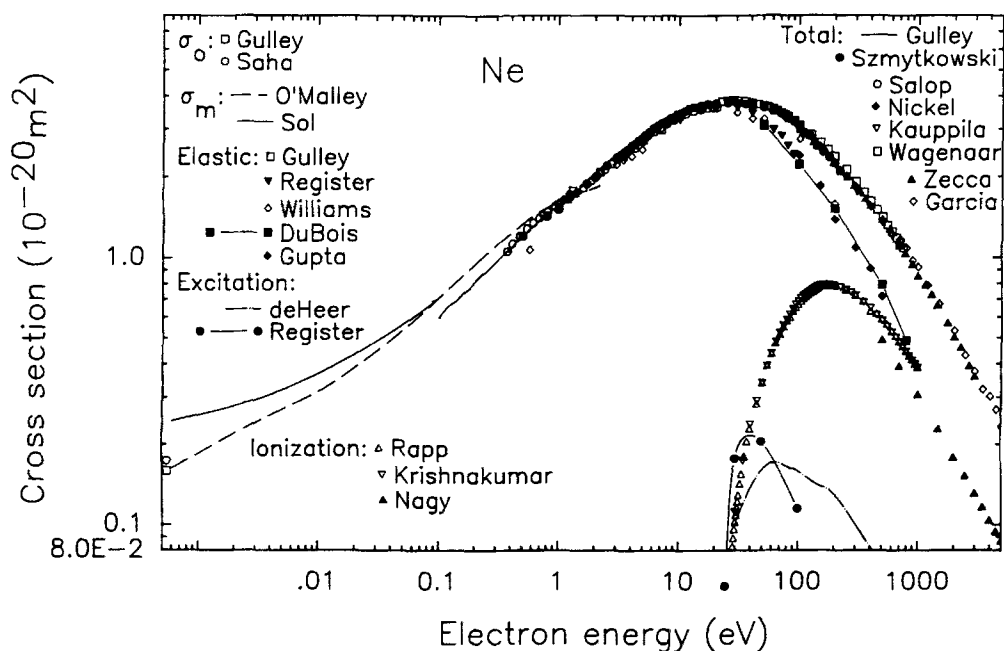


Fig. 4. – Integral cross-sections for electron scattering on Ne. *Total*: Gulley *et al.* (1994) from time-of-flight measurements; Szymtkowski *et al.* (1995); Salop and Nakano (1970); Nickel *et al.* (1985); Kauppila *et al.* (1981); Wagenaar and de Heer (1980); Zecca *et al.* (1987); García *et al.* (1986); the data of Stein *et al.* (1978); Sinapius *et al.* (1980); Charlton *et al.* (1984) and Kumar *et al.* (1987) are not included for clarity. *Elastic*: Gulley *et al.* (1994) from differential CS; «semiempirical» of Register and Trajmar (1984); Williams and Crowe (1975, integral values from de Heer *et al.*, 1979) and Williams (1979); DuBois and Rudd (1976); Gupta and Rees (1975); data of Brewer *et al.* (1981) are not included for clarity. *Momentum transfer*: O'Malley and Crompton (1980) from swarm; Sol *et al.* (1975) microwave. *Zero-energy*: Gulley *et al.* (1994), beam; Saha (1990) theory. *Electronic excitation*: de Heer *et al.* (1979) semiempirical; Register *et al.* (1984) sum of forty excitations. *Ionization*: gross ionization of Rapp and Englander-Golden (1965); counting of Krishnakumar and Srivastava (1988); counting of Nagy *et al.* (1980).

A scattering length value of  $+0.222a_0$  obtained from recent theory (Saha, 1989, 1990) agrees well with the value  $0.214a_0$  derived via a modified-effective-range analysis of swarm measurements (O'Malley and Crompton 1980),  $0.212a_0$  from total cross-sections (Gulley *et al.*, 1994),  $0.2a_0$  and  $0.24a_0$  from microwave measurements (Hoffmann and Skarsgard, 1969 and Sol *et al.*, 1975, respectively) and  $0.16\text{--}0.2a_0$  from perturbed-optical-absorption studies (see Rupnik *et al.*, 1990). We note, however, difficulties of the theory in calculating close-to-zero phase shifts at very low energies (compare Saha, 1989 and 1990) and a scatter of the modified effective-range-theory parameters depending on the energy range used in the fit (compare Gulley *et al.*, 1994).

*Elastic cross-sections* for neon have been measured in the low-energy range by Williams (1979) at 0.5–20 eV, by Shi and Burrow (1992) at 0.25–7.0 eV, by Gulley *et al.*

(1994) at 0.75–7.0 eV; by Brewer *et al.* (1981) at 7.5–20 eV; at intermediate energies by Register and Trajmar (1984) at 5–100 eV, by Williams and Crowe (1975) at 20–400 eV; at high energies by DuBois and Rudd (1976) at 50–800 eV, by Gupta and Rees (1975) at 100–625 eV, by Bromberg (1974) at 200–700 eV and by Jansen *et al.* (1976) at 100–3000 eV. Integral CS when given by these authors are included in fig. 4.

The two recent data sets at low energies (Shi and Burrow, 1992; Gulley *et al.*, 1994) are in excellent agreement (within 2–3%). Note, however, that both measurements were normalized to theoretical helium data (Nesbet, 1979). A similar agreement exists at 50 eV and 100 eV between the integral values of Register and Trajmar (1984) and DuBois and Rudd (1976). DCS of Gupta and Rees (1975) are somewhat scattered with respect to other measurements (Jansen *et al.*, 1976; Williams and Crowe, 1975; Bromberg, 1974); this also reflects in the integral values (compare fig. 4 and table II).

Phase shifts obtained from DCS by Williams (1979), Brewer *et al.* (1981), Register and Trajmar (1984), Gulley *et al.* (1994) are presented in fig. 3. The behaviour of the *s*-wave shift for  $k \rightarrow 0$  indicates that the scattering potential of neon is almost strong enough to induce a Ramsauer-Townsend minimum at near-to-zero energy. We note that microwave and swarm measurements performed until now did not have the potentiality to resolve any hypothetical narrow structure contained within a few meV (compare discussion for  $N_2$ ). Swarm experiments at low temperatures would be of interest.

*Excitation cross-section.* Semiempirical excitation CS of de Heer *et al.* (1979) have been obtained below 200 eV from analysis of optical-emission experiments and between 200–4000 eV from the Born-Bethe approximation.

Extensive measurements of differential and integral CS for the lowest forty electronic levels have been performed by Register *et al.* (1984) between 25 eV and 100 eV. The integral CS of Register *et al.* (1984) agree well with the data set published as «recommended» by Tachibana and Phelps (1987) for  $1s_5$ – $1s_2$  and summed  $2p$  (see Register *et al.*, 1984 for notation) levels. DCS of Register *et al.* (1984) also agree with recent first-order many-body theory (Csanak *et al.*, 1994; Machado *et al.*, 1994).

The sum of integral excitation CS measured by Register *et al.* (1984) reaches a maximum of  $0.21 \cdot 10^{-20} \text{ m}^2$ , *i.e.* merely 7% of the TCS, at 50 eV. This value is 30% higher than the earlier semiempirical data of de Heer *et al.* (1979). On the other hand, at 100 eV the Register *et al.*'s cross-section is lower than the semiempirical value by a similar amount, probably partially due to the lack of contribution from higher excitation levels (see Tachibana and Phelps, 1987).

The excitation of the  $3s'[1/2]_1^0$  ( $^1P_1$ ) ( $1s_2$  in Paschen notation) state amounts to about 50% of the overall excitation CS both at 50 eV (Register *et al.*, 1984) as well as at 500 eV (compare the partial excitation CS of Suzuki *et al.*, 1994 and of Phillips *et al.*, 1985 in table II with overall excitation of de Heer *et al.*, 1979).

The CS for excitation of metastable states  $3s'[1/2]_0^0$  ( $^3P_0$ ) and  $3s[3/2]_2^0$  ( $^3P_2$ ) (in Paschen notation  $1s_3$  and  $1s_5$ , respectively) amounts to about 20% of the overall excitation at 25 eV (Register *et al.*, 1984) but diminishes rapidly with rising energy (to 3% at 50 eV: Phillips *et al.*, 1985; Tachibana and Phelps, 1987). Exact ratios between DCS for  $1s_3$  over  $1s_5$ , and  $1s_4$  over  $1s_2$  levels at 20 eV and 30 eV were recently obtained by Khakoo *et al.* (1992 and 1994).

TABLE II. – *Integral cross-sections for electron scattering on neon (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Excitation	Ionization <sub>K</sub>	Sum	Total
5.0	2.68 <sub>RT</sub> 2.73 <sub>GU</sub>				2.843 <sub>N</sub>
10	3.25 <sub>RT</sub> 3.47 <sub>B</sub>				3.443 <sub>N</sub>
15	3.55 <sub>RT</sub> 3.42 <sub>B</sub>				3.646 <sub>N</sub> *
20	3.61 <sub>RT</sub> 3.81 <sub>B</sub>				3.727 <sub>N</sub>
30	3.61 <sub>RT</sub>	0.18 <sub>R</sub> 0.1 <sub>DH</sub>	0.11	3.90 3.82	3.780 <sub>N</sub>
40	3.43 <sub>RT</sub>	0.20 <sub>R</sub> * 0.16 <sub>DH</sub>	0.24	3.87 3.83	3.709 <sub>N</sub>
50	3.13 <sub>RT</sub> 3.08 <sub>D</sub>	0.21 <sub>R</sub>	0.34	3.68 3.63	3.613 <sub>N</sub>
60	0.20 <sub>R</sub> *	2.98 <sub>RT</sub>	0.44	3.62	3.509 <sub>N</sub>
80	2.60 <sub>RT</sub>	0.17 <sub>R</sub> * (0.11 <sub>P</sub> )	0.58	3.35	3.283 <sub>N</sub>
100	2.23 <sub>RT</sub> 2.21 <sub>D</sub> 2.40 <sub>G</sub> 2.39 <sub>J</sub>	0.12 <sub>R</sub> 0.16 <sub>DH</sub> (0.11 <sub>P</sub> )	0.68	3.03 3.05	3.041 <sub>N</sub> 3.001 <sub>Z</sub>
200	1.51 <sub>D</sub> 1.38 <sub>G</sub> 1.40 <sub>J</sub>	0.12 <sub>DH</sub> (0.07 <sub>P</sub> )	0.79	2.42 2.29	2.250 <sub>N</sub> 2.220 <sub>Z</sub>
300	1.09 <sub>G</sub>	0.10 <sub>DH</sub> (0.053 <sub>S</sub> ) (0.055 <sub>P</sub> )	0.720	1.91	1.827 <sub>N</sub> 1.826 <sub>Z</sub>
400	0.907 <sub>G</sub>	0.083 <sub>DH</sub> (0.043 <sub>S</sub> )	0.645	1.63	1.559 <sub>Z</sub>
500	0.790 <sub>D</sub> 0.714 <sub>G</sub> 0.771 <sub>J</sub>	0.071 <sub>DH</sub> (0.037 <sub>S</sub> )	0.579	1.44 1.36 1.42	1.378 <sub>Z</sub>
800	0.487 <sub>D</sub>	0.051 <sub>DH</sub>	0.444	0.982	1.019 <sub>Z</sub> 1.081 <sub>GA</sub>

\* – Interpolated values.

() – Denominate partial excitation CS not used for summation.

B – Brewer *et al.* (1981).

D – DuBois and Rudd (1975).

DH – de Heer *et al.* (1979) semiempirical sum of all excitations.

G – Gupta and Rees (1975).

GA – Garcia *et al.* (1986).GU – Gulley *et al.* (1994).J – Jansen *et al.* (1976) as integrated by DuBois and Rudd (1976).N – Nickel *et al.* (1985)P – Phillips *et al.* (1985), sum of  $1s_2$  and  $1s_4$  excitations.

RT – Register and Trajmar (1984).

R – Register *et al.* (1984), sum of forty lowest excitation levels.S – Suzuki *et al.* (1994), sum of  $1s_2$  and  $1s_4$  excitations.Z – Zecca *et al.* (1987).

*Optical emission.* Phillips *et al.* (1985) performed extensive measurements of optical emission from both the metastable  $^3P_2$  and  $^3P_0$  ( $1s_5$  and  $1s_3$ ) and mixed resonant  $^3P_1$  and  $^1P_1$  ( $1s_4$  and  $1s_2$ ) levels and evaluated cascading effects. These and earlier investigations have been reviewed by Heddle and Gallagher (1989).

*Metastables.* Excitation to the  $1s_5$  and  $1s_3$  states have also been studied via detection of metastable atoms (Theuws *et al.*, 1982; Teubner *et al.*, 1985; Mason and Newell, 1987). The absolute values (Teubner *et al.*, 1985) agree well with the fluorescence studies (Phillips *et al.*, 1981a, b, 1985). Above 40 eV cascade processes dominate the production of metastable atoms. Cross-sections for metastable excitation have also been obtained from swarm parameters by Sakai *et al.* (1986).

*Ionization cross-section.* Total gross ionization CS of Rapp and Englander-Golden (1965) practically coincide (within 2%) up to 1000 eV with the sum of partial ionization CS of Krishnakumar and Srivastava (1988). This is partially fortuitous, since the multiple ionization in Ne amounts to not more than 5% of the single one (Nagy *et al.*, 1980; Krishnakumar and Srivastava, 1988; Almeida *et al.*, 1995) in the whole energy range presently considered. The measurements extending to high energies (Schram *et al.* 1965; Adamczyk *et al.*, 1966; van der Wiel 1969; Nagy *et al.*, 1980; Almeida *et al.*, 1995) are at the overlap point of 1000 eV, 20–25% lower than the measurements of Rapp and Englander-Golden (1965) and Krishnakumar and Srivastava (1988) (see also fig. 4).

Partial CS for  $\text{Ne}^{2+}$  yield of Krishnakumar and Srivastava (1988) are somewhat (3% at 200 eV) higher than those of Stephan *et al.* (1980) and of Wetzell *et al.* (1987) and 20% higher than the result of Nagy *et al.* (1980), Schram *et al.* (1966a, b) and Adamczyk *et al.* (1966) at 1000 eV.

*Resonances.* ( $^2P_{3/2}^0$  and  $^2P_{1/2}^0$ )  $3s^2 \text{Ne}^-$  resonances in the elastic channel, placed at 16.111 and  $(16.298 \pm 0.008)$  eV (Brunt *et al.*, 1977) were observed in pioneer experiments (Simpson and Fano, 1963). An extensive review has been performed by Buckman and Clark (1994).

*Sum check* indicates an excellent agreement (within 3% for all energies) between total and summed partial cross-sections. Opposite to helium, and similarly to the other noble gases the elastic scattering dominates over inelastic processes, up to 800 eV, even if in a gradually diminishing way.

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2'3. *Argon (Ar)*. – Argon, due to its availability, became a standard target in electron scattering experiments. Discovery of a fall of the  $e^- + \text{Ar}$  total cross-section towards zero energy (Ramsauer, 1921) and successively of a minimum in the momentum transfer (Townsend and Bailey, 1922, 1923) and in the total (Ramsauer and Kollath, 1929) CS stimulated the development of quantum-mechanical computational methods (Holtmark, 1929). Figure 5 shows the integral cross-sections of Ar.

*Total cross-section.* In the region of the Ramsauer-Townsend minimum at about 0.35 eV an excellent agreement between the two time-of-flight experiments of Ferch *et al.* (1985) and Buckman and Lohmann (1986) has to be acknowledged. A much deeper minimum ( $0.16 \cdot 10^{-20} \text{ m}^2$ , compared to  $0.309 \cdot 10^{-20} \text{ m}^2$  of Buckman and Lohmann, 1986) was observed in the time-of-flight experiment of Gus'kov *et al.* (1978). Their measurements also give the lowest reported values for Kr and Xe minima. This peculiarity could be explained in terms of a wrong evaluation of the effective scattering cell length. In the experimental set-up of Gus'kov *et al.* (1978) a source of indetermination can come from the electron source region, which is at the same pressure as the scattering path. Alternatively, a zero shift in the pressure measurement could explain this systematic behaviour.

A larger scatter ( $\pm 10\%$ ) between different results (Sinapius *et al.*, 1980; Ferch *et al.*, 1985; Buckman and Lohmann, 1986; Subramanian and Kumar, 1987; Szmytkowski *et al.*, 1995) can be noticed in the region of rapid rise of TCS (0.5 to 10 eV). The data of Jost *et al.* (1983) are the highest in this region; these authors have corrected upward their original data in order to account for a finite angular resolution of their apparatus. The data of Kauppila (1977), from a magnetic-guided beam experiment, higher than other results at 1.3–10 eV, are probably subject to an energy determination error. They follow the other experimental results if shifted by  $+0.3 \text{ eV}$ .

At the TCS maximum around 14 eV, the best agreement regards the data of Nickel *et al.* (1985), Buckman and Lohmann (1986), Nishimura and Yano (1988) and Szmytkowski *et al.* (1995), while the measurements of Kauppila *et al.* (1977, 1981) are sensibly lower. At collision energies from 100 eV to 700 eV the measurements of Zecca *et al.* (1987) are bounded in a  $\pm 5\%$  strip by those of Wagenaar and de Heer

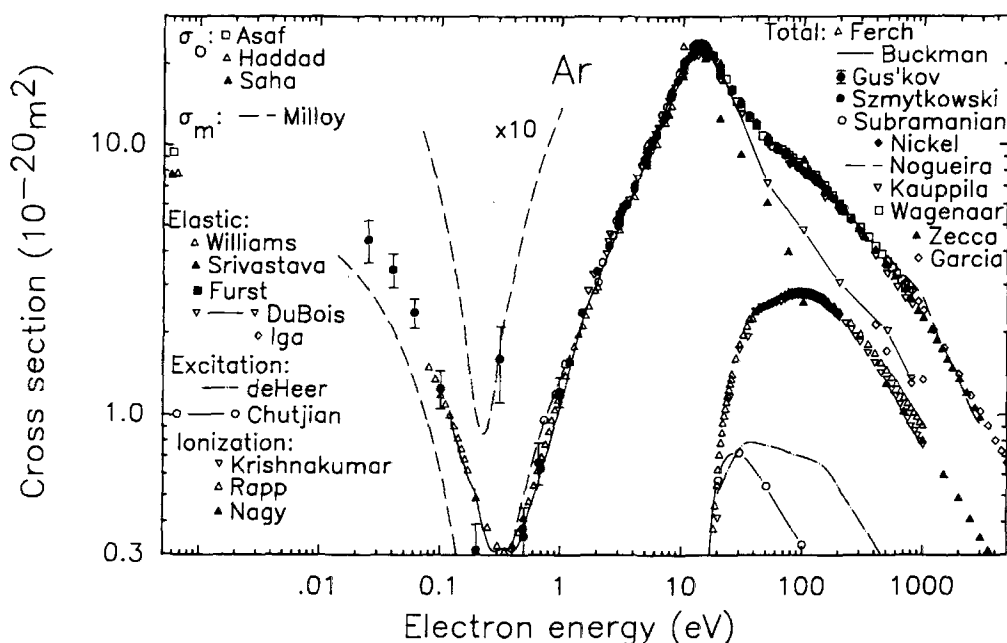


Fig. 5. – Integral cross-section for electron scattering on Ar. *Total*: absolute of Ferch *et al.* (1985); Buckman and Lohmann (1986); Gus'kov *et al.* (1978); Szmytkowski *et al.* (1995); Subramanian and Kumar (1987); Nickel *et al.* (1985); Nogueira *et al.* (1982); Kauppila *et al.* (1977) at 1.3–15.5 eV shifted (this work) by + 0.3 eV; Kauppila *et al.* (1981) at 15–800 eV; Wagenaar and de Heer (1980, 1985); Zecca *et al.* (1987); García *et al.* (1986). Data of Jost *et al.* (1983) at 0.1–60 eV; Sinapius (1980) at 1–6 eV; Nishimura and Yano (1988) at 7–500 eV, Ce Ma *et al.* (1989) at 300 eV are not presented for clarity. *Elastic*: Williams (1979) normalized by two methods, numerical values of CS from Srivastava *et al.* (1981); Srivastava *et al.* (1981) normalized to He; Furst *et al.* (1989) normalized by two methods; DuBois and Rudd (1976) absolute; Iga *et al.* (1987) normalized to N<sub>2</sub>; integral CS of Jansen (1976) given by DuBois and Rudd are not presented. *Momentum transfer*: Milloy *et al.* (1977). Zero-energy points: Asaf *et al.* (1989) from optical absorption; Haddad and O'Malley (1982) from swarm; Saha (1993) theory. *Electronic excitation*: de Heer *et al.* (1979) semiempirical excitation; Chutjian and Cartwright (1981) sum of 23 excitations. *Ionization*: Krishnakumar and Srivastava (1988) and Nagy *et al.* (1980) counting integral CS; Rapp and Englander-Golden (1965) gross integral CS.

(1980, 1985) from the upper side and Kauppila *et al.* (1981) from the lower side. At 3000 eV the TCS of Zecca *et al.* (1987) is 5% lower than the result of García *et al.* (1986) and 5% higher than the one of Nogueira *et al.* (1982).

*Swarm measurements.* Momentum transfer CS obtained (Milloy *et al.*, 1977) from swarm measurements of Milloy and Crompton (1977) merge well with the TCS measurements above 1 eV (see fig. 5). However, as can be expected from the modified-effective-range theory (O'Malley, 1963) the minimum in the momentum transfer CS is deeper ( $0.085 \cdot 10^{-20} \text{ m}^2$ ) and placed at lower energy (0.23 eV) than the minimum observed in TCS.

A scattering length of  $-1.63a_0$  from studies of perturbed optical absorption in gases (Asaf *et al.*, 1989; see also Rupnik *et al.*, 1990) differs somewhat from the values derived from TCS studies ( $-1.492a_0$  and  $-1.449a_0$  according to Buckman and Lohmann, 1986 and Ferch *et al.* 1985, respectively). The last two values are in good agreement with very-low-energy calculations ( $-1.486a_0$  from Saha, 1991, 1993) and with the analysis of swarm data ( $-1.492a_0$  from Haddad and O'Malley, 1982 and  $-1.459a_0$  from Petrović *et al.*, 1995). Phase shifts obtained from elastic CS measurements are compared to those in He and Ne in fig. 3. We note for Ar a much quicker change with energy of all the shifts.

Elastic cross-sections for Ar have been measured by Weyhreter *et al.* (1988) at 0.05–2 eV, Williams (1979) at 0.6–20 eV, Srivastava *et al.* (1981) at 3–100 eV, Furst *et al.* (1989) at 3–20 eV, Lewis *et al.* (1974) at 15–200 eV, DuBois and Rudd (1976) at 20–800 eV, Iga *et al.* (1987) at 400–1000 eV, Wagenaar *et al.* (1986) at 20–100 eV, Bromberg (1974) at 200–700 eV, Jansen *et al.* (1976) at 100–3000 eV. Due to a limited angular range of the measurements, the first and the three last papers do not contain integral CS. Integral values derived from measurements of Williams and Willis (1975) at 20–400 eV and of Jansen *et al.* (1976) were given by de Heer *et al.* (1979).

At very low energies the measurements of Ramsauer and Kollath (1932), Williams (1979) and Weyhreter *et al.* (1988) are, to our knowledge, the only ones extending below 2 eV. The DCS for the five noble gases are compared in fig. 6. DCS at the Ramsauer-Townsend minimum in argon (at 0.3 eV) exhibits a dominating *p*-wave character while in the lowest achieved energy (0.05 eV) the DCS show a rather flat, *s*-wave-like shape (Weyhreter *et al.*, 1988). DCS plotted against the collision energy exhibits a minimum which changes its position as a function of the scattering angle. For the 90° angle the minimum is placed at 0.27 eV; it gets shallower and shifts to higher energies (0.8 eV for 30°) for smaller angles (Weyhreter *et al.*, 1988).

At low energies Srivastava *et al.* (1981) have normalized their relative DCS both by the phase-shifts fit and via relative-flow technique to helium data; both normalization methods have been used to yield a unique set of integral CS by Furst *et al.* (1989); a cross-check method via both the phase-shifts fit and the phase-shifts analysis of resonance in He and Ar was used by Williams (1979). Integral CS of Srivastava *et al.* (1981), if normalized by the phase shifts, agree at 5–20 eV very well (within 10% on average) with the results of Furst *et al.* (1989) and of Williams (1979). The same data of Srivastava if normalized to helium seem to be underestimated above 20 eV (see fig. 5). At 200 eV and 500 eV the absolute data of DuBois and Rudd (1976) coincide with results of Jansen *et al.* (1976, integral values from de Heer *et al.*, 1979); at higher energies they agree well with the measurements of Iga *et al.* (1987) normalized to N<sub>2</sub>.

*Electronic excitation.* Differential and integral CS for excitation of 23 states have been given by Chutjian and Cartwright (1981). According to these data, near the threshold, at 16 eV, the optically allowed  $4s'[1/2]_1^0 \ ^1P_1$  and  $4s[3/2]_1^0 \ ^3P_1$  transitions dominate (by a factor of 2) over the forbidden  $4s[3/2]_1^0 \ ^3P_2$  and  $4s'[1/2]_1^0 \ ^3P_0$  states. The total excitation CS reaches a maximum of  $0.66 \cdot 10^{-20} \text{ m}^2$  at 30 eV, where it amounts to 5% of TCS.

At 100 eV the excitation to the above-mentioned optically allowed  $^1P_1$  and  $^3P_1$  states amounts, respectively, to 40% and 10% of the overall excitation CS. The experimental data of Chutjian and Cartwright (1981) for the  $^3P_2$ ,  $^3P_0$ ,  $^3P_1$ ,  $^1P_1$

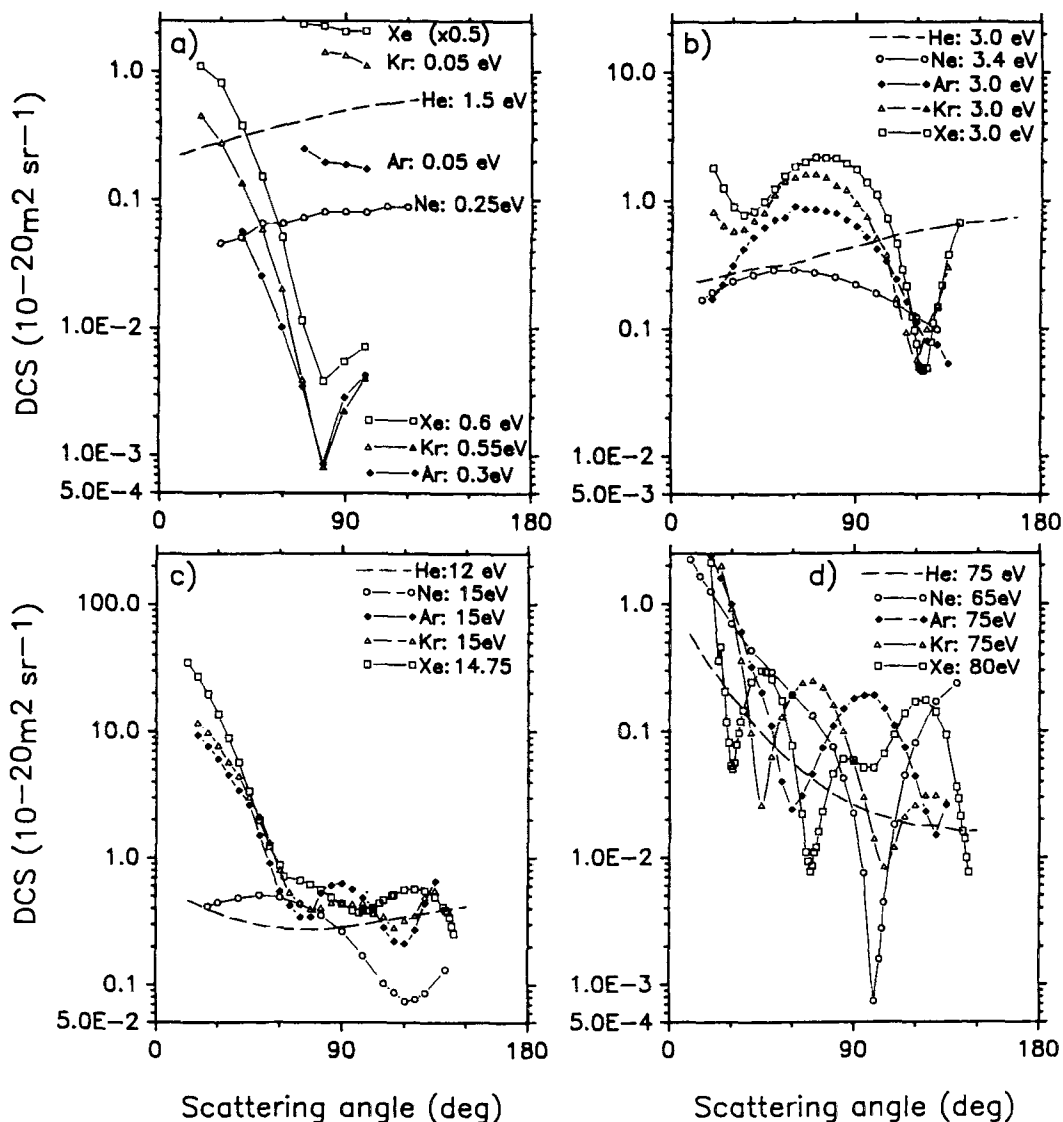


Fig. 6. – Differential cross-sections for electron scattering on noble gases. *a)* Very low energies; He, Brunger *et al.* (1992); Ne, Shi and Burrow (1992); Ar, Kr, Xe, Weyhreter *et al.* (1988). *b)* Low energies; He, Shyn (1980); Ne, Gulley *et al.* (1994); Ar and Kr, Srivastava *et al.* (1981); Xe, Register *et al.* (1984). *c)* and *d)* intermediate energies; He, Register *et al.* (1980); Ne, Register and Trajmar (1984); Ar and Kr, Srivastava *et al.* (1981); Xe, Register *et al.* (1984). References for gases other than Ar are to be found in the respective subsections.

excitations are in good agreement with the first-order many-body theory (Padial *et al.*, 1981; Csanak *et al.*, 1994). High-energy integral CS for excitation to  $^1P_1$  and  $^3P_1$  states (Li *et al.*, 1988) merge well with the results of Chutjian and Cartwright (1981) and amount, summed, to  $0.12 \cdot 10^{-20} \text{ m}^2$  and  $0.10 \cdot 10^{-20} \text{ m}^2$  at 400 eV and 500 eV, respectively.

Exact ratios between DCS for excitations of the two lowest optically allowed,  $^3P_1$  over  $^1P_1$ , and optically forbidden states,  $^3P_2$  over  $^3P_0$ , were studied by Khakoo *et al.* (1992, 1994) at 20 eV and 30 eV. The ratio for the forbidden states is close to the statistical weight value of 5; the one for the allowed states exhibits variation between 0.27 and 0.4, as a function of the scattering angle.

*Optical measurements.* At high energies, the semiempirical excitation CS of de Heer *et al.* (1979) are traditionally used. De Heer *et al.* have evaluated the sum of electronic excitations by normalizing the emission CS for the  $^1P_1$  state 104.8 nm emission line (de Jong, 1971; cited in the review of van der Burgt, 1989) to the Born-Bethe theory. Some arbitrariness in this procedure is to be noticed. More recent extensive absolute measurements in the extreme ultraviolet (Ajello *et al.*, 1990) gave at 200 eV an overall emission CS of  $0.57 \cdot 10^{-20} \text{ m}^2$ , in good agreement with the semiempirical value of  $0.54 \cdot 10^{-20} \text{ m}^2$  (de Heer *et al.*, 1979). More than 50% of this emission comes from  $^1P_1$  and  $^3P_1$  states (Ajello *et al.*, 1990). However, due to cascading effects, the *electronic excitation* CS for these states at 500 eV is lower than the *emission* CS (Ajello *et al.* 1990; Forand *et al.*, 1988) by a factor of 2/3. Cascading is even more important at 100 eV; this fact partially explains a big difference between de Heer *et al.*'s and Chutjian and Cartwright (1981) results. Therefore, in the absence of comprehensive measurements of excitation CS at high energies, we have decided to adopt the sum of  $^1P_1$  and  $^3P_1$  optical-emission CS (Ajello *et al.*, 1990) rather than the semiempirical values of de Heer *et al.* (1979) for our «sum check».

*Metastable states.* CS for production of metastable ( $3p^5 4s$ )  $^3P_{0,2}$  atoms reaches a maximum of  $0.35 \cdot 10^{-20} \text{ m}^2$  at 22 eV (Borst, 1974). This value is frequently used in normalization of relative measurements (Theuws *et al.*, 1982; Mason and Newell, 1987) of metastable noble-atoms yields.

*Ionization cross-section.* The agreement both for the partial and the summed ionization cross-sections from different groups (Rapp and Englander-Golden, 1965; Schram *et al.*, 1966; Kurepa *et al.*, 1974; Nagy *et al.*, 1980; Stephan *et al.*, 1980; Wetzel *et al.*, 1987; Krishnakumar and Srivastava, 1988; McCallion *et al.*, 1992) can be considered exemplary (all results are within a  $\pm 10\%$  belt in the whole energy range).

Selected measurements only are illustrated in fig. 5. The rise of Rapp and Englander-Golden's (1965) points over the values of Krishnakumar and Srivastava (1988) and Nagy *et al.* (1980) reflects the difference between gross and counting ionization CS. In fact, at 1000 eV the double and triple ionizations amount, respectively, to 5.5% and 1.2% of the single ones (Krishnakumar and Srivastava, 1988). At 100 eV the  $\text{Ar}^{2+}/\text{Ar}^+$  ratio amounts to 6.6% (Tarnovsky and Becker, 1992; Weisemann *et al.*, 1987; Syage, 1991).

*Resonances.* Argon presents a richer spectrum of negative-ion resonances than Ne (Buckman and Clark, 1994). The lowest-lying ( $3s^2 3p^5 4s^2$ )  $^2P_{3/2}$  and  $^2P_{1/2}$  states, placed at 11.098 and  $(11.27 \pm 0.010) \text{ eV}$ , respectively (Brunt *et al.*, 1977), decay exclusively into the elastic channel. A phase-shift analysis of the angular distributions of electrons scattered from these resonances is used to normalize DCS measurements (see Williams and Willis, 1975).

TABLE III. – *Integral cross-sections for electron scattering on argon (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Excitation	Ionization <sub>K</sub>	Sum	Total
3.0	5.5 <sub>S</sub> 5.64 <sub>W</sub>				4.99 <sub>SZ</sub> 4.96 <sub>B</sub>
5.0	8.4 <sub>S</sub> 10.1 <sub>S</sub>				8.98 <sub>N</sub> 8.71 <sub>SZ</sub>
10	13.0 <sub>S</sub> 23.3 <sub>W</sub>				20.6 <sub>N</sub>
16	21.0 <sub>S</sub> 23.9 <sub>W</sub>	0.17 <sub>C</sub>			23.1 <sub>N</sub>
20	19.2 <sub>DU</sub> 18.6 <sub>F</sub> (12.5 <sub>S</sub> )	0.57 <sub>C</sub>	0.41	20.2 19.6	19.0 <sub>N</sub> 18.2 <sub>SZ</sub>
30	13.2 <sub>WW</sub> 9.2 <sub>S</sub>	0.66 <sub>C</sub>	1.72	15.6 11.6	14.5 <sub>N</sub>
50	6.1 <sub>S</sub> 7.17 <sub>DU</sub>	0.54 <sub>C</sub>	3.74	10.4 11.5	10.7 <sub>N</sub> 10.3 <sub>SZ</sub>
75	4.0 <sub>S</sub>	0.6*	2.7	7.3	8.6 <sub>N</sub> *
100	2.6 <sub>S</sub> 4.79 <sub>DU</sub>	0.33 <sub>C</sub> (0.70 <sub>DH</sub> )	2.75	5.68 7.87	8.00 <sub>N</sub> 7.95 <sub>SZ</sub>
200	3.05 <sub>DU</sub> 2.75 <sub>WW</sub>	0.54 <sub>DH</sub> (0.57 <sub>A</sub> )	2.29	5.88 5.58	5.83 <sub>N</sub> 5.98 <sub>SZ</sub>
400	2.13 <sub>I</sub> (1.72 <sub>WW</sub> )	0.33 <sub>DH</sub>	1.55	4.01	4.059 <sub>Z</sub>
500	2.02 <sub>DU</sub> 1.71 <sub>I</sub>	0.28 <sub>DH</sub> (0.30 <sub>A1</sub> )	1.35	3.65 3.34	3.574 <sub>Z</sub>
800	1.35 <sub>DU</sub> 1.31 <sub>I</sub>	0.20 <sub>DH</sub> (0.22 <sub>A1</sub> )	0.91	2.46 2.42	2.64 <sub>Z</sub> *
1000	1.35 <sub>I</sub> 1.27 <sub>DH</sub>	0.17 <sub>DH</sub> (0.18 <sub>A1</sub> )	0.77	2.29 2.21	2.269 <sub>Z</sub> 2.41 <sub>G</sub>
3000	0.574 <sub>J</sub>	0.069 <sub>DH</sub>	0.351 <sub>N</sub>	0.994	0.981 <sub>Z</sub> 1.030 <sub>G</sub>

\* – Interpolated value.

() – Not used for summation.

A – Ajello *et al.* (1990) sum of EUV emission CS.A<sub>1</sub> – Ajello *et al.*, sum of  $^1P_1$  and  $^3P_1$  excitations multiplied by a factor 1.74.

B – Buckman and Lohmann (1986).

C – Chutjian and Cartwright (1981), excitation to 23 states.

DH – de Heer *et al.* (1979), semiempirical.

DU – DuBois and Rudd (1976).

G – García *et al.* (1986).I – Iga *et al.* (1987).J – Jansen *et al.* (1976), integral values given by de Heer *et al.* (1979).

K – Krishnakumar and Srivastava (1988).

N – Nagy *et al.* (1980).S – Srivastava *et al.* (1981), from normalization to He.SZ – Szmytkowski *et al.* (1995).W – Williams (1979), numerical values from Srivastava *et al.* (1981).WW – Williams and Willis (1975) integral values from de Heer *et al.* (1979).Z – Zecca *et al.* (1987).

*Sum check* indicates a rather poor agreement between summed and total CS below 100 eV. In particular, the elastic CS of Srivastava *et al.* (1981) obtained by normalization to an old He standard are underestimated, especially at 20, 30, 75 and 100 eV. On the other hand, the absolute elastic cross-sections of DuBois and Rudd (1976) seem to be overestimated at 20 eV and 50 eV. Elastic CS of Williams and Willis (1975, integral values from de Heer *et al.*, 1979) overestimate the summed value in the 20–100 eV range and underestimate it at 200 eV and 400 eV. A better agreement between partial and total CS is to be stressed at high energies. At 1000 eV the elastic CS still amounts to about 60% of TCS.

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2'4. *Krypton (Kr)*. – Electron scattering cross-sections for krypton and argon exhibit numerous analogies in the low and intermediate energy ranges. Although  $e^- + \text{Kr}$  experiments are less numerous than for the Ar counterpart, a pretty consistent picture of the cross-sections at these energies can be drawn. Figure 7 reports the integral cross-sections of krypton, whereas DCS at selected energies have been shown in fig. 6a) to d).

*Total cross-section.* Good agreement exists between TCS measurements in different laboratories at low and intermediate energies. Bigger discrepancies exist in the region of the Ramsauer-Townsend minimum. Buckman and Lohmann (1987) obtained a minimum CS value of  $0.44 \cdot 10^{-20} \text{ m}^2$  at 0.74 eV, while at 0.7 eV Ferch *et al.* (1987) reported  $0.55 \cdot 10^{-20} \text{ m}^2$  and Szmytkowski *et al.* (1995)  $0.64 \cdot 10^{-20} \text{ m}^2$ , which is not far from the value of  $0.74 \cdot 10^{-20} \text{ m}^2$  of Subramanian and Kumar (1987) at 0.73 eV.

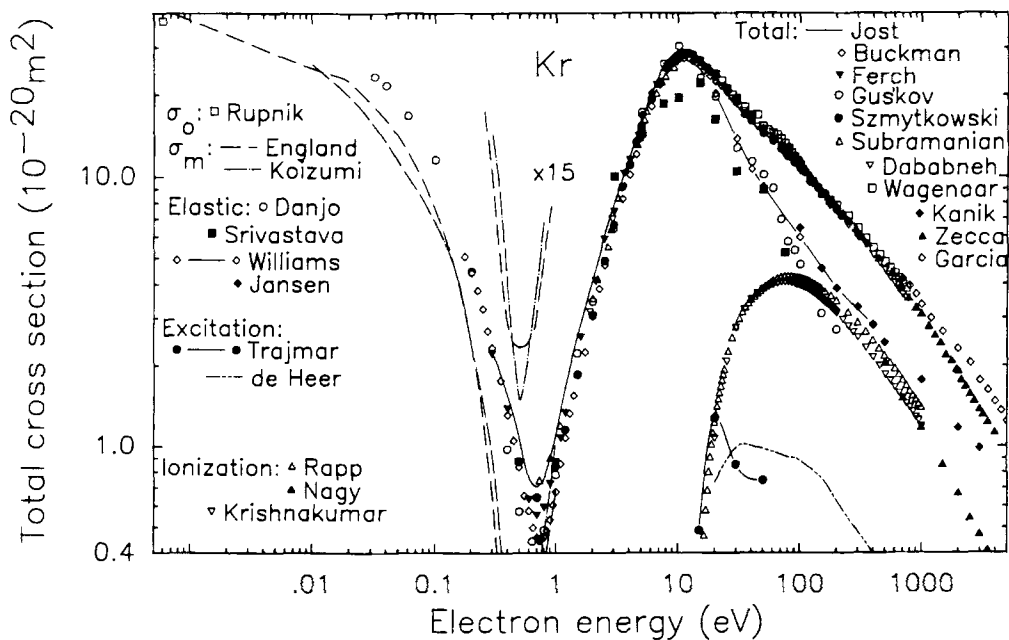


Fig. 7. – Integral cross-sections for electron scattering on Kr. *Total:* Jost *et al.* (1983); Buckman and Lohmann (1987); Ferch *et al.* (1987); Gus'kov *et al.* (1978); Szmytkowski *et al.* (1995); Subramanian and Kumar (1987); Dababneh *et al.* (1980, 1982); Wagenaar and de Heer (1980, 1985); Kanik *et al.* (1992); Zecca *et al.* (1991); García *et al.* (1986); results of Sinapius *et al.* (1980) are not presented for clarity. *Elastic:* Danjo (1988), 5–200 eV; Srivastava *et al.* (1981) from He normalization; Williams and Crowe (1975) and Jansen and de Heer (1976), integral values from de Heer *et al.* (1979). *Momentum transfer:* England and Elford (1988); Koizumi *et al.* (1986). *Zero-energy:* Rupnik *et al.* (1990) from optical absorption in  $\text{C}_6\text{H}_6$ . *Electronic excitation:* Trajmar *et al.* (1981) for 24 states; de Heer *et al.* (1979) semiempirical, scaled from  $e^- + \text{Ar}$ . *Ionization:* Nagy *et al.* (1980) and Krishnakumar and Srivastava (1989) counting total; Rapp and Englander-Golden (1965) gross total; other (El-Sherbini *et al.*, 1970; Stephan *et al.*, 1980; Wetzel *et al.* 1987; Syage, 1992; and Tarnovsky and Becker, 1992) not presented for clarity.

These discrepancies can be attributed only partially to a worse energy resolution of the electrostatic spectrometers (50–70 meV FWHM, for example, in the set-up of Szmytkowski *et al.*, 1995) with respect to the time-of-flight experiment of Buckman and Lohmann (1987). Time-of-flight measurements of Gus'kov *et al.* (1978) gave a value of  $0.44 \cdot 10^{-20} \text{ m}^2$  for the Ramsauer-Townsend minimum in agreement with Buckman and Lohmann's (1987) result but at a lower (0.65 eV) energy.

Between 1 eV and 5 eV the results of Sinapius *et al.* (1980), not presented in fig. 7, of Ferch *et al.* (1987) and of Jost *et al.* (1983) are, as was the case for argon, higher than the results of Buckman and Lohmann (1987) and Szmytkowski *et al.* (1995). TCS reaches a maximum of  $28.5 \cdot 10^{-20} \text{ m}^2$  (Szmytkowski *et al.*, 1995) at 12 eV. The agreement with other data (Kanik, 1992; Dababneh *et al.*, 1980, 1982; Wagenaar and de Heer, 1980, 1985) remains within 2% in this region. At 700 eV the spread between different results (García *et al.*, 1986; Wagenaar and de Heer, 1980, 1985; Zecca *et al.*, 1991; Dababneh *et al.*, 1982) amounts to 20%, with the later data being the lowest.

*Swarm measurements.* The most recent experimental determinations (Schmidt *et al.*, 1994; Brennan and Ness, 1993; Mitroy, 1990) and the older analysis of Koizumi *et al.* (1986) give a deeper Ramsauer-Townsend minimum than earlier determinations (England and Elford, 1988; Hunter *et al.*, 1988). Following these recent data the Ramsauer-Townsend minimum in Kr, as measured in momentum transfer CS, is placed at a higher (0.51 eV) energy and is slightly shallower ( $0.1 \cdot 10^{-20} \text{ m}^2$ ) than that in Ar. We notice a relatively bigger scatter in the determination of the Ramsauer-Townsend minimum in Kr than in Ar or even in Xe: more measurements, including swarm experiments in pure Kr and mixtures (Elford *et al.*, 1992), would be desirable.

*Scattering length.* Optical absorption studies give scattering length values in the  $-3.03a_0$  to  $-3.26a_0$  range, depending on the kind of molecular absorber (see Rupnik *et al.*, 1990 and references therein). A bigger absolute value ( $-3.48a_0$ ) was obtained by Weyhreter *et al.* (1988) via modified-effective-range analysis of their very-low-energy DCS, while a value of  $-3.35a_0$  has been obtained in recent (Brennan and Ness 1993) analysis of swarm coefficients.

*Elastic cross-section.* Srivastava *et al.* (1981) used both the phase-shifts analysis and the normalization to the He standard (Register *et al.*, 1980). Their elastic data from the phase-shifts normalization exceed TCS at 3 eV and 5 eV (Kanik *et al.*, 1992; Szmytkowski *et al.*, 1995) and therefore are not presented in fig. 7. Danjo (1988) used only the He standard. His integral CS in the 15–100 eV range are roughly 15% higher than the helium-normalized data of Srivastava; this difference remains within the limits of normalization uncertainties in the relative-flow technique. At 7.5 and 10 eV the difference between the integral CS of Danjo and of Srivastava *et al.* exceeds +30%. A possible 3° shift towards smaller angles of Srivastava *et al.*'s DCS with respect to other measurements (Williams and Crowe, 1975; Danjo, 1988) would partially explain this discrepancy. This shift will be found to be useful also for sodium. Note, however, that at 5–10 eV the integral elastic CS of Danjo (1988) are also somewhat higher than the absolute TCS values (Kanik *et al.*, 1992).

At intermediate and high energies elastic scattering was studied in the 20–400 eV, 30–200 eV, 200–700 eV and 100–3000 eV ranges, respectively, by Lewis *et al.* (1974,

normalized to an optical model), Bromberg (1974), Williams and Crowe (1975) and Jansen and de Heer (1976). Integral values from the three latter measurements have been given by de Heer *et al.* (1979). Integral CS of Williams and Crowe agree pretty well both with the measurements of Danjo (1988) and of Jansen and de Heer (1976) in the whole energy range of overlap.

Differential elastic CS from 0.05 eV to 2 eV (Weyhreter *et al.*, 1988) exhibit close analogies with argon (see fig. 6a) and b)). At 15 eV DCS in krypton still resembles that in argon, being however higher (fig. 6c)). At 75 eV (fig. 6d)) the two minima observable below  $120^\circ$  in Kr are placed at lower angles than the corresponding ones in Ar; probably Kr develops another minimum above  $140^\circ$ . Differential elastic CS at near-to-zero angles and 20–100 eV energies were studied by Wagenaar *et al.* (1986).

*Excitation cross-section.* Excitations into the 24 lowest electronic states were studied between 15 eV and 100 eV by Trajmar *et al.* (1981). At 30 eV the sum of these states contributes to 5% of the TCS. Excitations to optically allowed  $5s[3/2]_1$  and  $5s'[1/2]_1$  states amount together to almost half of the overall excitation. Integral (and also differential) CS for these two states, as measured by Danjo (1989), are at 30 and 50 eV in very good agreement (within 4%) with the results of Trajmar *et al.* (1981); at 20 eV they are 30% lower. Normalized measurements of the excitation into 9 electronic states have been also performed by Filipović *et al.* (1987), between 20 eV and 80 eV. A good agreement of the relative DCS with the theory (Meneses *et al.*, 1985) has been declared. We also note that the accuracy of Trajmar *et al.*'s (1981) absolute DCS of the four lowest states has been validated by recent first-order many-body calculations (Csanak *et al.*, 1994). The semiempirical excitation CS (de Heer *et al.*, 1979), obtained by a scaling procedure from Ar cross-sections, are lower than the experimental data (Trajmar *et al.*, 1981) at 20 eV, but exceed them substantially (see table IV) at 100 eV.

Branching ratios for two pairs of the lowest excitations were studied by Khakoo *et al.* (1994) at 20 and 30 eV. The ratio between DCS for optically allowed  $5s[3/2]_1$  and  $5s'[1/2]_1$  states diminishes with the scattering angle from about 1.5 at  $0^\circ$  to 1.1 at  $90^\circ$ . The ratio between metastable  $5s[3/2]_2$  and  $5s'[1/2]_0$  states varies between 3.5 and 5 as a function of the angle.

*Metastables.* Integral CS for production of the  $^3P_0$  and  $^3P_2$  metastable states reach a maximum value of  $0.28 \cdot 10^{-20} \text{ m}^2$  at 17 eV (Mason and Newell, 1987, normalized to measurements of Trajmar *et al.*, 1981). This is in agreement with the value of  $0.23 \cdot 10^{-20} \text{ m}^2$  at 18 eV obtained (Theuws *et al.*, 1982) by normalization to Ar metastables yield (Borst 1974).

*Ionization cross-section.* A good agreement ( $\pm 5\%$ ) exists between the early gross total ionization CS of Rapp and Englander-Golden (1965) and more recent partial measurements, if summed to yield the gross values (Wetzel *et al.* 1987; Stephan *et al.*, 1980; Krishnakumar and Srivastava, 1988). Similarly, good agreement exists among partial cross-sections for  $\text{Kr}^+$  and  $\text{Kr}^{2+}$  production (Schram *et al.*, 1966; Stephan *et al.*, 1980; Nagy *et al.*, 1980; Wetzel *et al.*, 1987; Krishnakumar and Srivastava, 1988; Syage, 1992; Tarnovsky and Becker, 1992). Double-to-single-ionization ratio rises from 0.087 at 100 eV (Tarnovsky and Becker, 1992) to 0.13 at

TABLE IV. – *Integral cross-sections for electron scattering on krypton (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Excitation	Ionization <sub>K</sub>	Sum	Total
3	10.0 <sub>S</sub>				6.61 <sub>SZ</sub>
5	14.4 <sub>S</sub> 17.2 <sub>D</sub>				16.7 <sub>K</sub> 15.3 <sub>SZ</sub>
7.5	18.5 <sub>S</sub> 26.0 <sub>D</sub>				23.6* <sub>SZ</sub>
10	19.4 <sub>S</sub> 30.3 <sub>D</sub>				28.2 <sub>K</sub>
15	22.1 <sub>S</sub> 23.0 <sub>D</sub>	0.48 <sub>T</sub>	0.08	22.7 23.6	26.3 <sub>K</sub> 26.8 <sub>SZ</sub>
20	16.2 <sub>S</sub> 19.6 <sub>D</sub> 20.1 <sub>WI</sub>	1.27 <sub>T</sub> (0.73 <sub>D</sub> )	1.07	18.5 21.9 22.4	23.3 <sub>K</sub> 23.5 <sub>SZ</sub>
30	10.4 <sub>S</sub> 12.7 <sub>D</sub> 13.7 <sub>WI</sub>	0.85 <sub>T</sub> 0.98 <sub>DH</sub>	2.74	14.0 16.4 17.4	19.1 <sub>K</sub> 18.7 <sub>SZ</sub>
50	8.9 <sub>S</sub> 10.1 <sub>D</sub> 9.1 <sub>WI</sub>	0.74 <sub>T</sub> 0.98 <sub>DH</sub>	3.81	13.5 14.9 13.9	14.9 <sub>K</sub> 14.4 <sub>SZ</sub>
75	5.2 <sub>S</sub> 6.3 <sub>D</sub>	0.92 <sub>DH</sub>	4.06	10.2 11.3	13.5 <sub>K</sub> 12.2* <sub>SZ</sub>
100	4.0 <sub>S</sub> 4.7 <sub>D</sub> 5.91 <sub>WI</sub>	(0.15 <sub>T</sub> ) 0.88 <sub>DH</sub>	3.94	8.8 9.5 10.7	10.6 <sub>K</sub> 10.7 <sub>SZ</sub>
200	3.65 <sub>WI</sub> 3.84 <sub>J</sub>	0.62 <sub>DH</sub>	3.11	7.38 7.57	7.44 <sub>K</sub> 7.76 <sub>W</sub>
400	2.80 <sub>WI</sub> 2.82 <sub>J</sub>	0.40 <sub>DH</sub>	2.13	5.33 5.35	5.27* <sub>Z</sub> 5.39 <sub>W</sub>
1000	1.76 <sub>J</sub>	0.20 <sub>DH</sub>	1.18	3.14	3.09 <sub>Z</sub> 3.33 <sub>G</sub>
3000	0.977 <sub>J</sub>	0.081 <sub>DH</sub>	0.471 <sub>N</sub>	1.53	1.37 <sub>Z</sub> 1.75 <sub>G</sub>

\* – Interpolated value.

( ) – Not used for summation.

D – Danjo (1988).

DH – de Heer *et al.* (1979).G – García *et al.* (1986).J – Jansen and de Heer (1976), integral values from de Heer *et al.* (1979).K – Kanik *et al.* (1992).S – Srivastava *et al.* (1981) from He normalization.SZ – Szmytkowski *et al.* (1995).T – Trajmar *et al.* (1981).

W – Wagenaar and de Heer (1980, 1985).

WI – Williams and Crowe (1975), integral values from de Heer *et al.* (1979).Z – Zecca *et al.* (1991).

2000 eV (El-Sherbini *et al.*, 1970). Measurements due to Krishnakumar and Srivastava (1988) of multiple ionization ( $\text{Kr}^{3+}$  and  $\text{Kr}^{+4}$ ) are higher than earlier data (Stephan *et al.*, 1980; Mathur and Badrinathan, 1984; Wetzel *et al.*, 1987) below 200 eV. At high energies the counting total CS of Nagy *et al.* merge well with those of Krishnakumar and Srivastava (1988).

*Resonances.* Evidence of numerous resonant states both below (in the 9.5–14.4 eV energy range) the first ionization threshold as well as above it (at 22.7–28.8 eV) has been observed in elastic-scattering (Weingartshofer *et al.*, 1974), transmission (Sanche and Schulz, 1972), metastable yield (Buckman *et al.*, 1983; Dassen *et al.*, 1983), electronic-excitation (Roy *et al.*, 1976) experiments. Systematics of these resonances and an extensive list of references have been given by Buckman and Clark (1994).

*Sum check* indicates that at 15 eV the elastic CS of both Danjo (1988) as well as of Srivastava *et al.* (1981) are slightly (about 10%) underestimated. On the other hand, in the whole 20–400 eV range the elastic CS of Williams and Crowe (1975) sum up very well (within 5% on the average) with other partial CS to the experimental TCS. At 1000 eV a similarly good agreement regards the elastic CS of Jansen and de Heer (1976). At 3000 eV the summed value lies between the two experimental numbers (Zecca *et al.*, 1991; García *et al.*, 1986). We stress, however, existing discrepancies between TCS and different sets of elastic CS (Danjo, 1988; Srivastava *et al.*, 1981) at low energies.

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2.5. Xenon (Xe). – Xenon is used in lighting technology and in excimer lasers. Semiempirical evaluation of total and partial cross-sections has been performed, among others, by Hayashi (1983). The summary of xenon integral cross-sections is reported in fig. 8.

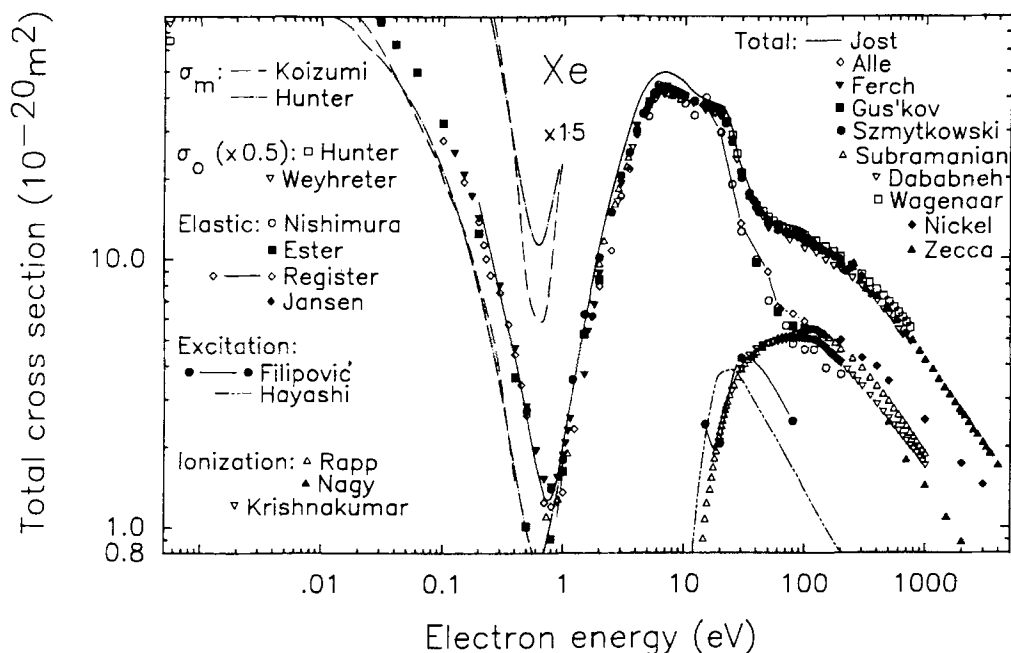


Fig. 8. – Integral cross-sections for electron scattering on Xe. *Total*: Jost *et al.* (1983); Alle *et al.* (1993); Ferch *et al.* (1987); Gus'kov *et al.* (1978); Szmytkowski *et al.* (1995); Subramanian and Kumar (1987); Dababneh *et al.* (1980, 1982); Wagenaar and de Heer (1980, 1985); Nickel *et al.* (1985); Zecca *et al.* (1991); results of Sinapius *et al.* (1980) are not presented for clarity. *Elastic*: Nishimura *et al.* (1987) normalized to He; Ester and Kessler (1994) absolute; Register *et al.* (1984) normalized to total; Jansen and de Heer (1976) absolute, integral values from de Heer *et al.* (1979); data of Williams and Crowe (1975, integrated by de Heer *et al.*) not presented for clarity. *Momentum transfer*: Koizumi *et al.* (1986); Hunter *et al.* (1988). *Zero-energy*: Hunter *et al.* (1988) from swarm; Weyhreter *et al.* (1988) from DCS. *Electronic excitation*: Filipović *et al.* (1988) for 20 states; Hayashi (1983) semiempirical from swarm. *Ionization*: Nagy *et al.* (1980) and Krishnakumar and Srivastava (1989) counting total; Rapp and Englander-Golden (1965) gross total; others (Schram *et al.*, 1966; Stephan and Märk, 1984; Wetzel *et al.*, 1987) are not presented for clarity.

*Total cross-section.* In spite of the fact that less measurements are available for Xe than for other noble gases, a pretty good agreement exists for TCS. In the region of the Ramsauer-Townsend minimum, discrepancies in TCS are smaller than for Kr. Jost *et al.*'s (1983) corrected data from an electrostatic analyser, Szmytkowski *et al.*'s (1995) from a similar apparatus, Alle *et al.*'s (1993), and Ferch *et al.*'s (1987) from a time-of-flight spectrometer give a minimum of about  $1.3 \cdot 10^{-20} \text{ m}^2 \pm 10\%$  at 0.8 eV. Only Gus'kov *et al.* (1978) quoted essentially lower values (see the discussion in the argon subsection).

In the 1–5 eV energy range the results of Szmytkowski *et al.* (1995) and of Jost *et al.* (1983) are higher than other measurements. Between 1 eV and 2 eV the cross-section rises by a factor of 5 and even small energy shifts can cause big differences in TCS. All recent measurements (Sinapius *et al.*, 1980; Dababneh *et al.*, 1980; Wagenaar and de Heer, 1980 and 1985; Nickel *et al.*, 1985; Ferch *et al.*, 1987;



Subramanian and Kumar, 1987; Szmytkowski *et al.*, 1995) but that of Jost *et al.* (1983) give a similar—within  $\pm 5\%$ —maximum CS value at 7 eV (equal to  $41.7 \cdot 10^{-20} \text{ m}^2$ , according to Nickel *et al.*, 1985).

Above 100 eV the agreement between TCS of Nickel *et al.* (1985) and Zecca *et al.* (1991) remains within 3%, while the data of Wagenaar and de Heer (1980, 1985) and Dababneh *et al.* (1982) differ, respectively, by  $-4\%$  and  $+6\%$  on the average, with respect to the above two.

*Swarm measurements* in pure xenon are extremely sensitive to impurities, even at the p.p.m. level. Momentum transfer CS derived by Hayashi (1983), Koizumi *et al.* (1986) and Hunter *et al.* (1988) coincide between 0.05 eV and 0.5 eV. However, Koizumi *et al.* (1986) obtained a deeper Ramsauer-Townsend minimum of  $0.4 \cdot 10^{-20} \text{ m}^2$  at 0.62 eV with respect to other swarm (Hayashi, 1983; Hunter *et al.*, 1988) or microwave (Hoffmann and Skarsgard, 1969) determinations. An even deeper minimum of  $0.22 \cdot 10^{-20} \text{ m}^2$  has been measured by Schmidt *et al.* (1994). Measurements of very-low-energy DCS (Weyhreter *et al.*, 1988) set upper and lower limits on the momentum transfer CS. These coincide with Koizumi *et al.*'s and Schmidt *et al.*'s values, respectively. More measurements, for pure Xe and mixtures with molecular gases would be desired (Elford *et al.*, 1994; Schmidt *et al.*, 1994). At the energy of 1 eV the momentum transfer CS merges with the total one.

*A scattering length* of  $-5.83a_0$  from optical absorption in cesium vapours (Rupnik *et al.*, 1990 and references therein) is, similarly as for other noble gases, smaller in its absolute value than the results from swarm analysis ( $-6.08a_0$ , Hunter *et al.*, 1988) and from very-low-energy elastic DCS measurements ( $-6.53a_0$ , Weyhreter *et al.*, 1988).

*Elastic cross-section.* Differential elastic CS were measured in the range  $15\text{--}145^\circ$  and at energies from 1 eV to 100 eV by Register *et al.* (1986). These data were put on an absolute scale by normalization to integral elastic values obtained as the difference between absolute TCS (Jost *et al.*, 1983; Nickel *et al.*, 1985) and semiempirical inelastic (from de Heer *et al.*, 1979 and Hayashi *et al.*, 1983) CS. In the range 40–100 eV, the normalized data of Register *et al.* (1984) are less than 10% higher than the absolute integral CS of Ester and Kessler (1994). The results of Register *et al.* at 5–30 eV are also in good agreement with integral CS of Nishimura *et al.* (1987) obtained by normalization to the He standard. However, at 50–100 eV these two sets of data differ by 20% on the average.

Xenon elastic DCS, compared to other noble gases, exhibit a much richer pattern at intermediate energies (see fig. 6d)). This indicates a contribution from several (up to seven at 50 eV, according to Register *et al.*, 1984) partial waves to the overall scattering amplitude. Relative DCS at 2–300 eV,  $30\text{--}120^\circ$  were given by Klewer *et al.* (1980). Absolute DCS of Bromberg (1974) at 300–700 eV, Wagenaar *et al.* (1986) at 20–100 eV, Jansen and de Heer (1976) have been obtained, similarly as for krypton, only for small scattering angles. DCS of Williams and Crowe (1975), integrated by de Heer *et al.* (1979), coincide at 200 eV and 400 eV with values of Jansen and de Heer (1976) but are somewhat scattered at lower energies.

*Excitation cross-section.* Electronic excitation to the twenty lowest states was studied by Filipović *et al.* (1988) at 15–80 eV. Integral CS are presented in fig. 8. More

recent measurements at 15–100 eV for unresolved  $6s[3/2]_2$  and  $6s[3/2]_1$  (Ester and Kessler, 1994) and at 100–500 eV for  $6s[3/2]_1$  and for  $6s'[1/2]_1$  states (Suzuki *et al.*, 1991) indicate that the measurements of Filipović *et al.* are overestimated. Above 30 eV they are also higher than the semiempirical, swarm-derived values of Hayashi (1983). On the other hand, early studies at 20 eV (Williams *et al.*, 1975) yielded integral excitation CS underestimated by almost one order of magnitude.

Semiempirical values in the review of de Heer *et al.* (1979) have been obtained from scaling of argon (optical emission) CS and are substantially lower (see table V) than Hayashi's recommended set. Branching ratios as a function of the scattering angle for the two lowest optically allowed and two optically forbidden states have been recently studied by Khakoo *et al.* (1994). Swarm analysis of excitation CS has been performed by Sakai *et al.* (1991). More measurements of electronic excitation and optical emission from Xe would be desirable.

*Metastables.* Mason and Newell (1987) have normalized their measurements of the  $(5p^5 6s)^3P_{0,2}$  metastables yield by the method of Blagoev *et al.* (1984). A maximum value of  $1.2 \cdot 10^{-20} \text{ m}^2$  at 15 eV has been obtained. We note that this value corresponds to as much as 5% of TCS while the same ratio in Kr amounts to only 1%.

*Ionization cross-section.* Absolute measurements for  $e^- + \text{Xe}$  ionization were performed by Rapp and Englander-Golden (1965) up to 1000 eV, Stephan and Märk (1984) up to 180 eV, Wetzel *et al.* (1987) up to 200 eV, Krishnakumar and Srivastava (1988) up to 1000 eV, Syage (1992) up to 470 eV, Schram *et al.* (1966) at 0.5–16 keV, Nagy *et al.* (1980) at 0.5–5 keV. Additionally, only relative, partial CS were obtained by Mathur and Badrinathan (1986) up to 150 eV and by El-Sherbini *et al.* (1970) at 2–14 keV. Good agreement between gross and partial ( $\text{Xe}^+$  and  $\text{Xe}^{2+}$ ) CS has to be acknowledged.

At 200 eV yields of  $\text{Xe}^{2+}$ ,  $\text{Xe}^{3+}$  and  $\text{Xe}^{4+}$  equal to 10%, 5% and 2% of the value for single ionization (Krishnakumar and Srivastava, 1988). Partial  $\text{Xe}^+$  and  $\text{Xe}^{2+}$  CS exhibit (Mathur and Badrinathan 1986; Syage, 1992) shoulders at the thresholds for inner-shell ionizations.

*Resonances.* Resonant features between 7.9 eV and 13.1 eV have been observed in transmission spectra (Sanche and Schulz 1972), elastic scattering (Heindorff *et al.*, 1976), metastables yield (Brunt *et al.*, 1976; Buckman *et al.*, 1983) and optical emission (Brunt *et al.*, 1977). Features about the first ionization threshold were investigated in the transmission studies (Sanche and Schulz, 1972) and in the excitation functions (Delâge *et al.*, 1977).

*Sum check.* The most complete measurements of elastic cross-sections (Register *et al.*, 1986) are normalized to TCS. Therefore a sum based on these elastic CS has a limited meaning. However, absolute elastic CS of Ester and Kessler (1994) sum up almost perfectly with other partial CS (Hayashi, 1983 for the excitation and Krishnakumar and Srivastava, 1988 for the ionization), to yield the experimental TCS (Nickel *et al.*, 1985).

A peculiar feature in Xe, with respect to other noble gases, is the energy dependence of TCS (cf. fig. 7 and 8 for Kr and Xe, respectively). After the Ramsauer-Townsend minimum, the TCS in xenon shows a large maximum at about 7.0 eV. Going to higher energies, the TCS drop is modulated by a shoulder at about

TABLE V. – *Integral cross-sections for electron scattering on xenon (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Excitation	Ionization <sub>K</sub>	Sum	Total
1.0					1.79 <sub>SZ</sub>
2.0					10.0 <sub>SZ</sub>
5.0	33.9 <sub>N</sub>				36.8 <sub>N</sub>
10	37.8 <sub>N</sub>	0.18 <sub>H</sub>			40.12 <sub>N</sub>
15	39.8 <sub>N</sub>	2.14 <sub>H</sub> (2.41 <sub>F</sub> )	0.55	42.5	37.1 <sub>N</sub> 36.7 <sub>SZ</sub>
20	29.2 <sub>R</sub> 29.5 <sub>NI</sub>	3.73 <sub>H</sub> (2.05 <sub>F</sub> )	2.07	35.0 35.3	35.8 <sub>N</sub>
30	13.1 <sub>R</sub> 12.6 <sub>NI</sub>	3.57 <sub>H</sub> (4.25 <sub>F</sub> )	3.85	20.5 20.0	20.8 <sub>N</sub>
40	9.63 <sub>E</sub>	2.85 <sub>H</sub>	4.59	17.1	15.7 <sub>N</sub>
50	8.83 <sub>R</sub> 6.96 <sub>NI</sub>	2.40 <sub>H</sub> (1.27 <sub>DH</sub> )	4.80	16.0 14.2	14.0 <sub>N</sub>
60	6.33 <sub>E</sub> (4.59 <sub>W</sub> )	2.10 <sub>H</sub>	4.90	13.3	13.2 <sub>N</sub>
80	6.21 <sub>R</sub> 5.60 <sub>E</sub>	1.66 <sub>H</sub> (2.48 <sub>F</sub> )	5.01	12.9 12.3	12.4 <sub>N</sub>
100	5.82 <sub>R</sub> 5.49 <sub>E</sub> 5.05 <sub>J</sub>	1.38 <sub>H</sub> (1.13 <sub>DH</sub> )	5.02	12.2 11.9 11.5	11.9 <sub>N</sub>
200	3.68 <sub>NI</sub> 4.95 <sub>J</sub>	0.80 <sub>H</sub>	4.04	8.52 9.79	9.92 <sub>N</sub> 9.42 <sub>Z</sub>
400	4.05 <sub>W</sub> 3.94 <sub>J</sub>	0.465 <sub>H</sub>	2.86	7.38 7.26	7.24 <sub>Z</sub>
500	3.49 <sub>J</sub>	0.395 <sub>H</sub> (0.201 <sub>S</sub> )	2.53	6.41	6.47 <sub>Z</sub>
1000	2.50 <sub>J</sub>	0.231 <sub>H</sub>	1.70 1.43 <sub>NA</sub>	4.43 4.16	4.17 <sub>Z</sub>
3000	1.44 <sub>J</sub>	0.095 <sub>H</sub>	0.631 <sub>NA</sub>	2.17	2.078 <sub>Z</sub>

\* – Interpolated value.

() – Not used for summation.

DH – de Heer *et al.* (1979), semiempirical scaled from Ar data.

E – Ester and Kessler (1994), absolute.

F – Filipović *et al.* (1988).

H – Hayashi (1983), semiempirical from swarm data.

J – Jansen and Wagenaar (1976), integral values from de Heer *et al.* (1979).

K – Krishnakumar and Srivastava (1988).

N – Nickel *et al.* (1985).NA – Nagy *et al.* (1980).NI – Nishimura *et al.* (1987).R – Register *et al.* (1986).S – Suzuki *et al.* (1991), sum of  $6s[3/2]_1$  and  $6s'[1/2]_1$  excitations.SZ – Szymkowski *et al.* (1995).

22 eV. This is easily attributed to a similar feature in the elastic CS and possibly to the contribution of the excitation channels. Between 25 eV and 40 eV, both TCS and the integral elastic CS fall like  $E^{-1}$ . A second wider shoulder around 100 eV looks to be due both to the contribution of the ionization CS and to a change in the slope of the elastic CS. This shoulder has been indicated by the elastic CS measurements of Williams and Crowe (1975), Jansen and de Heer (1976), Ester and Kessler (1994). We note that, due to the rapid fall of the elastic CS between 20 eV and 80 eV, TCS in xenon at 100 eV is smaller than the corresponding value in Kr. We also note for Xe, in analogy with other heavier noble gases, a high contribution (60%) from elastic scattering even at 1000 eV.

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### 3. – Metal vapours

TCS for numerous metals, including alkali metals, mercury, zinc, tellurium, cadmium have been measured by Brode (see a summary paper: Brode, 1933). An updated review is given here for alkali metals (subsect. 3'1-3'5) and mercury (subsect. 3'6). In subsect. 3'7 the recent measurements for other metals are mentioned.

Alkali metals, having the electronic configuration of noble gas atoms with an *s*-electron added, are targets with very high polarizability ( $24.3 \cdot 10^{-30} \text{ m}^3$  and  $23.6 \cdot 10^{-30} \text{ m}^3$  for Li and Na,  $43.4 \cdot 10^{-30} \text{ m}^3$  and  $47.3 \cdot 10^{-30} \text{ m}^3$  for K and Rb,  $59.6 \cdot 10^{-30} \text{ m}^3$  for Cs, respectively, Weast 1986). The interest for alkali metals was triggered in the sixties by their possible applications for laser excitation, in magneto-hydrodynamic generators and in the nuclear-energy industry. Due to the cited electronic configuration, alkali metals are of obvious interest for theoreticians. Among these atoms, Li and Cs have received very little experimental attention. Total and partial cross-sections are available for Na and K, although the measurements are confined to energies lower than 200 eV. This scarcity of measured data can be easily attributed to the experimental difficulties involved in dealing with these metal vapours.

**3'1. Lithium (Li).** – Integral cross-sections for lithium are presented in fig. 9 and in table VI.

*Total cross-section.* Perel *et al.* (1962) reported TCS for Li at 0.25–10 eV using a

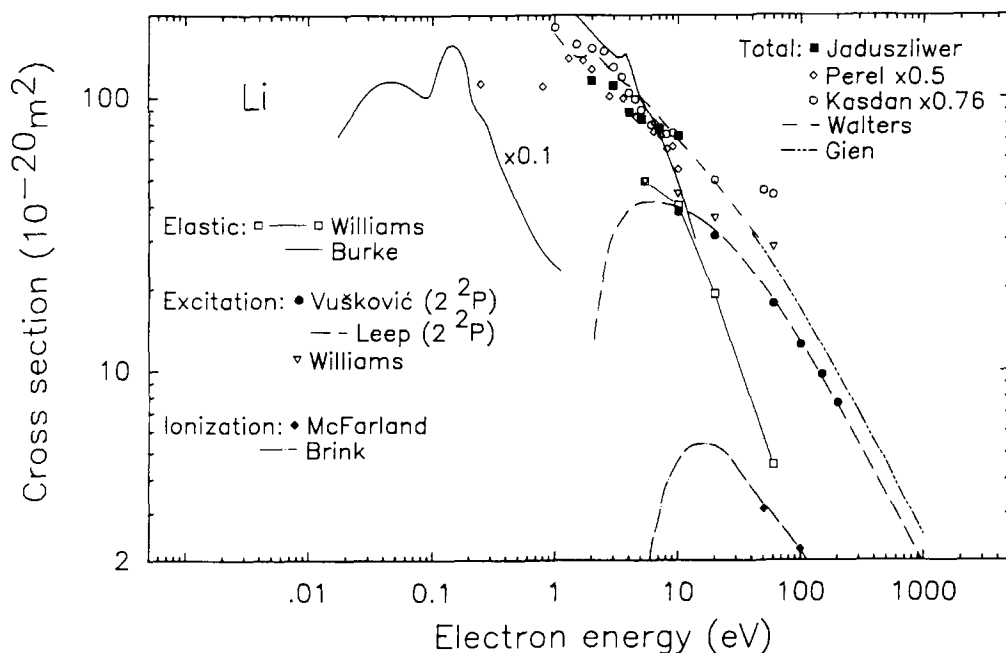


Fig. 9. – Integral cross-sections for electron scattering on Li. *Total*: Jaduszliwer *et al.* (1981) recoil beam; Perel *et al.* (1962) recoil beam, normalized (this work) by a factor of 0.5; Kasdan *et al.* (1971) recoil beam, normalized as in Walters (1976) by a factor of 0.76, numerical values from Walters (1976) and Williams *et al.* (1976); Walters (1976), polarization potential with non-adiabatic effects and absorption; Gien (1987) modified Glauber approximation with a model potential; theory of Burke and Taylor above the inelastic threshold not shown for clarity. *Elastic*: Williams *et al.* (1976) beam, normalized to TCS; Burke and Taylor (1969) close-coupling. *Excitation*: Williams *et al.* (1976) (sum of four states), normalized to TCS; Vušković *et al.* (1982) for  $2P^2P$  state; Leep and Gallagher (1974), optical for  $2p^2P$  state. *Ionization*: McFarland and Kinney (1965); Brink (1962) normalized at 200 eV to McFarland and Kinney (1965); data of Jalin *et al.* (1973) are out of Y-scale; data of Zapesoschnyi and Aleksakhin (1969) not shown for clarity.

recoil-beam method and normalization to their potassium data (see subsect. 3'3). Bederson and Kieffer (1971) later indicated a possible overestimation of Perel *et al.*'s TCS due to this normalization. The results of Perel *et al.* present a broad maximum centred around 1.5 eV and are higher than the more recent determination of Jaduszliwer *et al.* (1981) up to 10 eV. In fig. 9 we present TCS of Perel *et al.* renormalized by a factor of 0.5; this brings the two TCS in agreement at 5 eV. Another recoil-beam measurement was obtained by Kasdan *et al.* (1971) up to 60 eV (we have collected the numerical values from figures published by Walters, 1976 and Williams *et al.*, 1976). As indicated by Inokuti and McDowell (1974) and by Walters (1976) the data of Kasdan *et al.* need to be renormalized by a factor 0.76. It is worth noting that the recoil method does not require an evaluation of the absolute density in the target beam. However, the systematic discrepancies can be attributed to difficulties in the exact determination of the scattering geometry and of the collection efficiency. The renormalized data of Kasdan *et al.* and Perel *et al.* agree, within their declared 20% error bars, with the TCS of Jaduszliwer *et al.*

The close-coupling Hartree-Fock calculation (Burke and Taylor, 1969) predicts a pronounced maximum of TCS of  $1500 \cdot 10^{-20} \text{ m}^2$  at about 0.15 eV and another—weaker—at 0.05 eV. It also indicates for a shoulder structure at the electronic-excitation threshold. However, the theory of Burke and Taylor somewhat exceeds the experimental TCS at low energies and is by as much as 40% higher above the inelastic threshold. A theoretical model of scattering on a polarization potential (Inokuti and McDowell, 1974), modified for non-adiabatic effects and with a semiempirical absorption added (Walters, 1976), is in better agreement with the experimental TCS between 1 and 20 eV (see fig. 9). In the figure we also present a modified-Glauber approximation with a model-potential (Gien, 1987) at intermediate energies: no experimental data exist to confront with.

*Elastic cross-section.* Williams *et al.* (1976) have measured relative elastic (and excitation) DCS at  $10\text{--}130^\circ$  from 5.4 to 60 eV. They have determined the absolute scale, with an overall 35% error bar, by normalizing the integral values to the difference between TCS of Kasdan *et al.* (1971) and the ionization CS of Zapesoschný and Aleksakhin (1969). In the 10–60 eV range the integral elastic CS possibly follows, within the errors, a  $1/E$ -dependence (see fig. 9). The elastic theoretical CS of Burke and Taylor (1969) above 10 eV agree, within the experimental error bars, with the data of Williams *et al.* (1976).

TABLE VI. – *Integral cross-sections for electron scattering on lithium (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic <sub>W</sub>	Excitation		Ionization	Sum	Total
		$2P^2$	other <sub>W</sub>			
5.4	49	49 <sub>W</sub>	—		98	82 <sub>J</sub> *
10	40	38.0 <sub>V</sub>	5.2	4.6 <sub>B</sub>	88	72 <sub>J</sub>
		44 <sub>W</sub>			94	90 <sub>K</sub>
20	19	31.1 <sub>V</sub>	5.3	5.3 <sub>B</sub>	61	62 <sub>K</sub>
		36 <sub>W</sub>			66	
60	4.5	17.5 <sub>V</sub>	3.2	2.9 <sub>B</sub>	28	44 <sub>K</sub>
		28 <sub>W</sub>			39	
100		12.4 <sub>V</sub>		2.2 <sub>M</sub>		
				1.0 <sub>JA</sub>		
150		9.63 <sub>V</sub>				
200		7.56 <sub>V</sub>		1.5 <sub>M</sub>		
				0.76 <sub>JA</sub>		

\* – Interpolated value.

B – Brink (1962) normalized at 200 eV by McFarland and Kinney (1965).

J – Jaduszliwer *et al.* (1981).

JA – Jalin *et al.* (1973).

K – Kasdan *et al.* (1971), numerical values obtained by digitizing the figure from Williams *et al.* (1976).

M – McFarland and Kinney (1965).

V – Vušković *et al.* (1982).

W – Williams *et al.* (1976).

*Excitation cross-section.* Williams *et al.* (1976) have measured relative CS for excitations to  $3s^2S$ ,  $2p^2P$ ,  $3p^2P$  and  $4p^2P$  states. These CS have been normalized in the way described for the elastic part. More recently, Vušković *et al.* (1982) have obtained absolute values for  $2p^2P$  excitation by normalization to the optical oscillator strength. Both Williams *et al.*'s as well as Vušković *et al.*'s results are in pretty good agreement (better than 10% for most of the points) with optical-emission CS (Leep and Gallagher, 1974; Zapesoschnyi *et al.*, 1976). Williams *et al.*'s CS jump over the other data at 60 eV; this can derive from a possible overestimation of TCS in the recoil-beam experiment used for normalization.

*Ionization cross-section.* Relative ionization CS for  $\text{Li}^+$  production were measured by Brink (1962) from threshold to 500 eV and put on an absolute scale in the 50–500 eV experiment of McFarland and Kinney (1965). These data are reported in fig. 9 and agree within 10% with the absolute results of Zapesoschnyi and Aleksakhin (1969) up to 30 eV. Measurements of Jalin *et al.* (1973) from 100 eV to 2000 eV are by a factor of 2 lower than those of McFarland and Kinney and are out of scale in fig. 9. We have no way to judge on this discrepancy.

*Sum check* is of little use with the available data. A reasonable agreement between summed values and TCS (Jaduszliwer *et al.*, 1981; Kasdan *et al.*, 1971) is found at 10 and 20 eV. At 60 eV the recoil-beam TCS (Kasdan *et al.*, 1971) is probably overestimated, as for other alkali metals at intermediate energies. At 60 eV the electronic excitation (Vušković *et al.*, 1982 for the  $2pP^2$  state, Williams *et al.* (1976) for the others) amounts to almost 75% of the summed value. More precise measurements, first of all of total and elastic CS at higher energies, would be of interest.

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**3.2. Sodium (Na).** – Electron scattering on sodium vapours has been extensively studied by different groups. Applicative interest has been triggered by the extensive use of sodium in lighting technologies. Integral cross-sections are given in fig. 10.

*Total cross-section.* Pioneering TCS of Brode (1929) from a Ramsauer-type transmission experiment, as well as the recoil beam measurements of Perel *et al.* (1962) presented a resonant-like maximum at energies between 1 and 2 eV. The existence of such a maximum has not been confirmed by the successive recoil beam experiment (Kasdan *et al.*, 1973). Furthermore, both the absolute values of Brode (1929) and the results of Perel *et al.* normalized to Brode's data are more than a factor of 2 higher than the more recent determinations (Kasdan *et al.*, 1973; Kwan *et al.*,

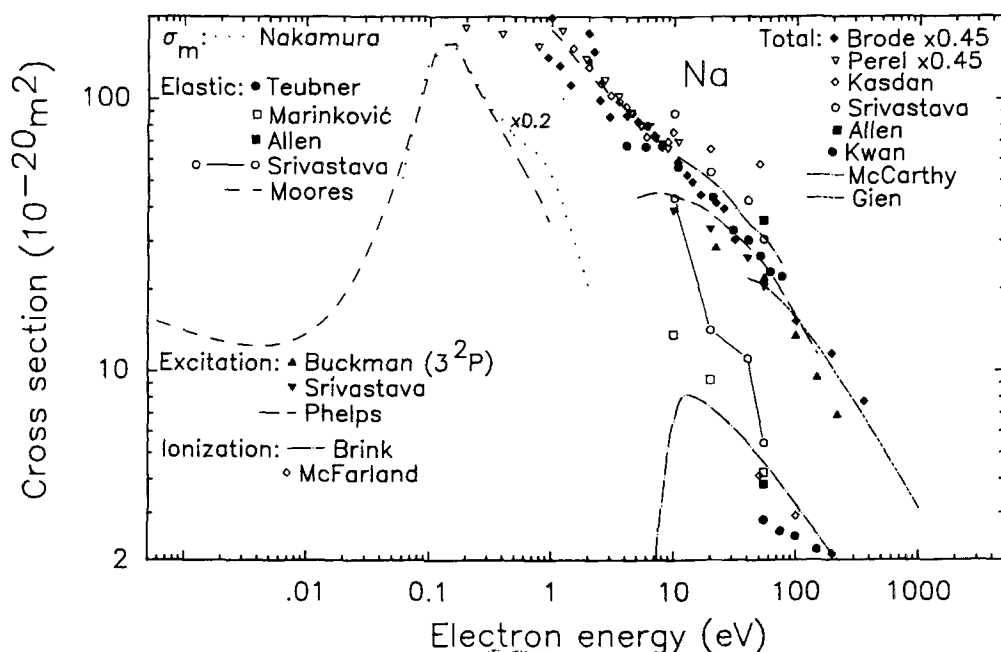


Fig. 10. – Integral cross-sections for electron scattering on Na. *Total:* Brode (1929) beam, normalized by 0.45, digitized from the original figure; Perel *et al.* (1962) and Kasdan *et al.* (1973), recoil-beam; Srivastava and Vušković (1980) summed; Allen *et al.* (1987) semiempirical via complex potential; Kwan *et al.* (1991) absolute, beam; McCarthy *et al.* (1993) coupled-channels optical method; Gien (1987), modified-Glauber. *Elastic:* Teubner *et al.* (1978) normalized to inelastic and integrated in this work ( $\pm 20\%$  possible extrapolation error); Marinković *et al.* (1992) normalized to the optical strength; Allen *et al.* (1987) normalized via complex phase-shift analysis, Srivastava and Vušković (1980) normalized to inelastic; Moores and Norcross (1972) close-coupling. *Momentum transfer:* Nakamura and Lucas (1978b), digitized from the original figure. *Electronic excitation:*  $3^2P$  excitation, Buckman and Teubner (1979); Teubner *et al.* (1986) at 22.1 eV integrated in this work; Srivastava and Vušković (1980) overall excitation; Phelps and Lin (1981) optical, overall excitation. *Ionization:* Brink (1962) normalized at 200 eV to Brink (1964); McFarland and Kinney (1965).

1991). In fig. 10 Brode's and Perel's results have been renormalized by a factor of 0.45 to the value of Kasdan *et al.* (1973) at 5 eV. This normalization can be justified on the basis of the characteristics of Brode's apparatus. This was built as a modification of the successful apparatus of Ramsauer (1921). In Brode's apparatus the sample gas was admitted on the entire electron beam trajectory. With this choice, both the energy and angular selection were poor. The definition of the interaction chamber length was subject to a large error. Furthermore, large ambiguities in determining the pressure of metals vapour from the temperature existed in those times.

Kwan *et al.* (1991), using a short (3 inches) scattering cell with a longitudinal guiding magnetic field (0.15–0.35 T) and determining the vapour pressure precisely, have measured electron and positron TCS from 4 eV to 100 eV. Their data in the 10–50 eV range agree, within experimental errors, with the normalized measurements of Brode. At higher energies the data of Brode tend to be lower than those of Kwan *et al.*; this can be attributed to the poor angular resolution of Brode's apparatus. At energies above the ionization threshold the beam-recoil experiment (Kasdan *et al.*, 1973) tends to give TCS values higher than those obtained by the transmission method (Kwan *et al.*, 1991).

TCS, obtained by Walters (1976) by summing the theoretical elastic CS from his non-adiabatic, polarization model and semiempirical inelastic CS, agree at 1–10 eV with the results of Kasdan *et al.* within the declared error bars. The coupled-channels optical method (Bray and McCarthy, 1993; McCarthy *et al.*, 1993) overestimate the recent beam data (Kwan *et al.*, 1991) while the modified-Glauber calculation (Gien, 1987) underestimates them.

*Swarm measurements.* Analysis (Nakamura and Lucas, 1978b) of swarm measurements (Nakamura and Lucas, 1978a) indicates a maximum of  $800 \cdot 10^{-20} \text{ m}^2$  in the momentum transfer CS at 0.13 eV, in agreement with four-state close-coupling calculations (Norcross, 1971; Moores and Norcross, 1972). At higher energies, the momentum transfer CS merges well with TCS of Kasdan *et al.* (1973); at 0.05 eV it falls down to about  $270 \cdot 10^{-20} \text{ m}^2$  (values have been digitized from the figure of Nakamura and Lucas, 1978b). Additional measurements, especially with transmission beam techniques, would be of utility to confirm the existence of the maximum predicted by swarm analysis and theory.

*Elastic cross-section.* Elastic DCS measurements from different laboratories agree generally in shape (see fig. 11). Srivastava and Vušković (1980) normalized their measurements to electronic excitation CS from optical measurements (Enemark and Gallagher, 1972). Teubner *et al.* (1978) used a normalization to the electronic excitation CS from distorted-wave calculations (Keneddy *et al.*, 1977); in a later work (Teubner *et al.*, 1986) they used the normalization to the values given by Enemark and Gallagher (1972).

Integral elastic CS of Teubner *et al.* (1978) and Allen *et al.* (1987) at 54.4 eV are lower than those of Srivastava and Vušković (1980); as indicated by Teubner *et al.* (1986) the discrepancy could have been caused by a shift in the determination of the angular position in DCS measurements of Srivastava and Vušković. A  $3^\circ$  shift has been indicated as possible. Marinković *et al.* (1992) have presented three alternative normalizations of their relative DCS. These data normalized to optical oscillator strength are at 10 and 20 eV substantially lower than the measurements of Srivastava and Vušković (1980) but agree with the latter at 54.4 eV (see table VII). DCS of

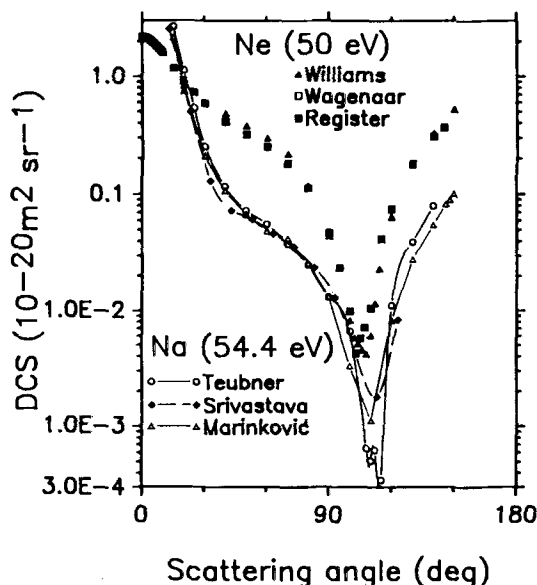


Fig. 11. – Comparison of differential elastic cross-sections for electron scattering on Ne and Na. Sodium data: Teubner *et al.* (1978); Srivastava and Vušković (1980), have been shifted by  $+3^\circ$  in this work, following Allen *et al.* (1987); relative data of Marinković *et al.* (1992) have been normalized in this work to those of Teubner *et al.* (1978) at  $80^\circ$ . Neon data: Williams and Crowe (1975), Wagenaar *et al.* (1986), Register and Trajmar (1983).

Lorenz and Miller (1989) are in apparent agreement with those of Srivastava and Vušković (1980), but the absolute values have been obtained by normalization to close-coupling calculations of Mitroy *et al.* (1987).

In fig. 11 we compare elastic DCS for sodium and neon at two nearby energies. The elastic DCS for Na is strongly forward peaked. The Ne cross-section is definitely flat at small angles. Crossing of the two DCS is observed at  $20^\circ$  scattering angle. At  $60^\circ$  the sodium DCS (Teubner *et al.*, 1978) is almost one order of magnitude smaller than that of Ne. It is worth stressing that the optical model (Teubner *et al.*, 1978; see also the discussion in Mitroy *et al.*, 1987) predicts the magnitude of these CS properly. The static-exchange calculations (Mitroy *et al.*, 1987; McCarthy *et al.*, 1991) do not include the absorption channel and therefore fail to reproduce the experimental DCS at intermediate angles. This suggests that the difference between neon and sodium could be attributed to absorption effects in the elastic electron-sodium scattering. Note also that the measurements of Srivastava and Vušković (1980) suggest a rapid fall (from  $11 \cdot 10^{-20} \text{ m}^2$  to  $5.4 \cdot 10^{-20} \text{ m}^2$ ) of the integral elastic CS between 40 and 54.4 eV. This could be caused by the phenomenon of channel coupling, as indicated for positron scattering on argon and krypton by Dou *et al.* (1992a, b). A similar effect has been hypothesized for electron scattering on  $\text{H}_2$  molecules (Karwasz *et al.*, 1995). In the 54.4–150 eV range the integral elastic  $e^- + \text{Na}$  cross-section (Teubner *et al.*, 1978, as integrated by us with a  $\pm 20\%$  extrapolation uncertainty) varies much more slowly (see fig. 10).

Relative angular distributions for elastic scattering were obtained by Gehenn and Reichert (1972) at 0.5–20 eV, for angles between  $25^\circ$  and  $150^\circ$ . At low energies

TABLE VII. – *Integral cross-sections for electron scattering on sodium (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Excitation		Ionization	Sum	Total <sub>K</sub>
		$3P^2$	other			
5.4						66.7*
10	43 <sub>S</sub>	31.7 <sub>E</sub>	6.9 <sub>S</sub>	6.8 <sub>B</sub>	88.4	57.5*
	13.5 <sub>M</sub>	29.4 <sub>M</sub>			56.6	
20	14 <sub>S</sub>	29.0 <sub>E</sub>	3.9 <sub>S</sub>	6.5 <sub>B</sub>	53.4	44.0*
		35.6 <sub>M</sub>			60.0	
	9.2 <sub>M</sub>	23 ± 6 <sub>J</sub>			42.6	
22.1		28.4 <sub>T1</sub>				
40	11.0 <sub>S</sub>	21.8 <sub>E</sub>	3.9 <sub>S</sub>	5.2 <sub>B</sub>	41.9	30.2*
54.4	5.4 <sub>S</sub>	18.6 <sub>E</sub>	1.6 <sub>S</sub>	4.7 <sub>B</sub>	30.3	25.0*
	4.2 <sub>M</sub>	19.8 <sub>M</sub>			30.3	
	(3.8 <sub>A</sub> )				35.6 <sub>A1</sub>	
	2.8 <sub>T</sub>	21.9 <sub>B</sub>			31.0	
75	2.6 <sub>T</sub>	17.3 <sub>P</sub>	2.3 <sub>P</sub>	3.8 <sub>B</sub>	26.0	22.1
100	2.4 <sub>T</sub>	13.4 <sub>B</sub>	1.8 <sub>P</sub>	2.9 <sub>MF</sub>	20.5	
		13.9 <sub>P</sub>			21.0	
150	2.2 <sub>T</sub>	9.41 <sub>B</sub>	1.2 <sub>P</sub>	2.5 <sub>MF</sub> *	15.3	
		10.2 <sub>F</sub>			16.1	

\* – Interpolated value.

() – Not used for summation.

A – Allen *et al.* (1987).A1 – Total (elastic + reaction) from complex phase shift analysis (Allen *et al.*, 1987).

B – Buckman and Teubner (1979).

E – Enemark and Gallagher (1972), from optical measurements.

J – Jiang *et al.* (1990).K – Kwan *et al.* (1991).M – Marinković *et al.* (1992) normalized to optical strength.

MF – McFarland and Kinney (1965).

P – Phelps and Lin (1981), optical measurements.

S – Srivastava and Vučković (1980).

T – Data of Teubner *et al.* (1978), integrated in this work ( $\pm 15\%$  possible extrapolation error).T1 – Data of Teubner *et al.* (1986),  $\pm 10\%$  possible extrapolation error, integrated in this work.

(0.5–1.5 eV) the DCS exhibits a minimum at 110°, while at 12 eV assumes a *d*-wave character with minima at 55° and 140°.

Eyb and Hofmann (1975), studying the energy dependence of elastic DCS between 1.0 and 2.5 eV, have noticed cusp structures and maxima at different scattering angles, centred around 2.1 eV and have related them to the opening of the  $3^2P_{1/2, 3/2}$  excitation channel.

At high energies, relative angular distributions normalized to unity at a scattering angle of 30° have been measured by Rao and Bharathi (1987). The distributions exhibit minima at 100°, which become shallower (0.011, 0.024, 0.036, relative units) with rising energy (150, 300, 400 eV, respectively).

*Excitation cross-section.* Differential CS at angles from  $10^\circ$  to  $120^\circ$  for excitation from the ground state to  $3^2P$ ,  $4^2S$ ,  $3^2D + 4^2P$  and  $4^2D + 4^2F + 5^2P + 5^2S$  states have been studied by Srivastava and Vučković (1980). These data were normalized to optical measurements (Enemark and Gallagher, 1972). Shuttleworth *et al.* (1977) normalized their small angle (below  $20^\circ$ ) DCS for  $3^2P$  excitation at 54.4–200 eV to a Born calculation, similarly as was done by Buckman and Teubner (1979) with their  $2$ – $145^\circ$ , 54.4–217.7 eV DCS for the same state. Marinković *et al.* (1992) normalized their  $2$ – $150^\circ$ , 10–54.4 eV DCS for the  $3^2P$  state to the optical oscillator strength and presented three alternative normalization modes for  $4^2S$ ,  $3^2D$  and  $4^2P$  states.

In spite of the apparent good matching between integral excitation CS of Srivastava and Vučković (1980) and those of Buckman and Teubner (1979), see fig. 10, the angular distributions for excitation to the  $3^2P$  state from these two experiments differ at some angles by more than a factor of 2. This discrepancy can be corrected (Teubner *et al.*, 1986) assuming a  $+3^\circ$  shift of Srivastava and Vučković's data and normalizing them to the optical CS.

Integral electronic excitation CS obtained from normalized differential measurements (Buckman and Teubner, 1979; Teubner *et al.*, 1986; Srivastava and Vučković, 1980) are in good accord with optical-excitation experiments: Phelps and Lin (1981) for 14 states, Enemark and Gallagher (1972) and Zapesochnyi *et al.* (1975) for the  $3^2P$  state. Independent, absolute, small-angle ( $1$ – $20^\circ$ ) measurements of  $3^2P$  excitation at 10 eV (Jiang *et al.*, 1990) yielded an integral excitation CS in good agreement with optical data (see table VII).

Small-angle ( $0$ – $20^\circ$ ) relative DCS for  $3^2P$  excitation at 54–250 eV were obtained by Shuttleworth *et al.* (1977). Alkali metals excitation cross-sections are extremely forward peaked: the DCS of sodium for  $3^2S \rightarrow 3^2P$  excitation decreases by four orders of magnitude between  $10^\circ$  and  $40^\circ$  at 50 eV (Srivastava and Vučković, 1980); at higher energies, a similar decrease takes place between  $0^\circ$  and  $20^\circ$  (Shuttleworth *et al.*, 1977). The  $0$ – $10^\circ$  angular range contributes to 90% of the integral electronic excitation CS at 54.4 eV (Teubner *et al.*, 1986). For the elastic part, this forward scattering could be attributed to long-range forces, *i.e.* the polarization interaction in the case of alkali metals. From the experimental point of view, it introduces large extrapolation errors while deriving the integral CS. Due to this feature, extreme angular resolution should be used both in TCS and DCS measurements to avoid systematic errors.

Scattering from excited Na atoms has been studied by Hanne *et al.* (1982), Riley *et al.* (1985), Farrell *et al.* (1985) and Scholten *et al.* (1993).

*Ionization cross-sections* were measured by Brink (1962) as relative values from threshold to 500 eV and by Brink (1964) in an absolute mode between 200 and 500 eV, by McFarland and Kinney (1965) between 50 and 500 eV and by Zapesochnyi and Aleksakhin (1969) from threshold to 30 eV. These measurements form a pretty consistent set of data; therefore only selected data are presented in fig. 10. The maximum value of the integral ionization CS is of the order  $7.7 \cdot 10^{-20} \text{ m}^2$  (an average between Zapesochnyi and Aleksakhin's (1969) and Brink's (1964) values) and placed at a relatively low energy (14 eV). Double  $\text{Na}^{2+}$  ionization amounts at 500 eV to about 10% of the overall ionization (Tate and Smith, 1934).

*Resonances.* Johnston and Burrow (1982) in electron transmission experiments have observed a  $3s3p\ ^3P$  shape resonance located at 0.08 eV. This resonance has been predicated theoretically by Moores and Norcross (1972). Only broad structures were observed in the elastic channel (Eyb and Hofmann, 1975) around 2.1 eV, i.e. near the threshold for excitation of the  $3^2P_{1/2, 3/2}$  states. The assignment of a resonant state to this observation is not clear (see the review of Buckman and Clark, 1994).

*Semiempirical total cross-sections* of Srivastava and Vučković (1980) were obtained by summing their elastic CS with the excitation (Enemark and Gallagher, 1972) and the ionization contribution (Zapesochnyí and Aleksakhin, 1969 and Brink, 1964). These semiempirical CS are 10–30% higher than the experimental values (Kwan *et al.*, 1991) in the 10–54.4 eV range. The value of total (elasticreaction) CS at 54.4 eV, obtained via a complex phase-shift analysis of elastic DCS (Allen *et al.*, 1987), is higher than the experimental TCS (Kwan *et al.*, 1991), with the difference remaining however within the error bar of the analysis.

*Sum check* for Na indicates that the elastic data of Marinković *et al.* (1992) normalized to the optical oscillator strength and the data of Teubner and collaborators (1978,1986) are possibly more reliable than the measurements of Srivastava and Vučković (1980). The latter seem to be overestimated below 40 eV. Inelastic CS from different groups show a relatively smaller scatter. Characteristic for all alkali metals is a high contribution to the TCS from the resonant electron excitation. In sodium, the transition to the  $3^2P$  state contributes 66% to the TCS at 100 eV.

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**3'3. Potassium (K).** – Electron scattering on potassium atoms has received so much attention as sodium. Experimental integral CS are presented in fig. 12. A few theoretical results have been inserted in order to give a more complete picture of these cross-sections.

*Total cross-sections* for potassium were measured in several experiments starting from the work of Brode (1929). It has already been stressed that the magnetic spectrometer used by this author suffered from a poor, difficult to define, angular resolution.

Rubin *et al.* (1960) and Perel *et al.* (1962) used a recoil beam technique and normalized their results to those of Brode at 5 eV. As in the case of Na, this normalization led to overestimation of TCS. In fig. 12 we have renormalized the results of Brode by the same multiplicative factor as for sodium (0.45). Perel *et al.* have observed a maximum in the TCS at 1.2 eV similar to the one reported by Brode. Subsequent recoil-beam experiments (Collins *et al.*, 1971; Visconti *et al.*, 1971; Kasdan *et al.*, 1973) covering altogether the 0.2–50 eV energy range

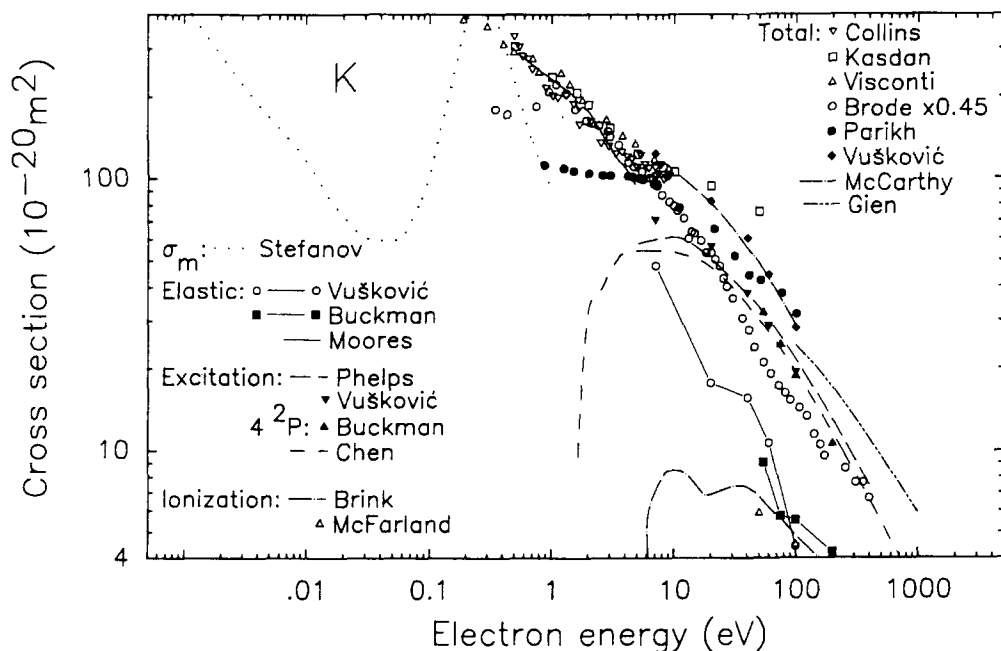


Fig. 12. – Electron-potassium cross-sections. *Total*: Collins *et al.* (1971) recoil; Kasdan *et al.* (1973) recoil; Visconti *et al.* (1971) recoil; Brode (1929) beam, normalized by a factor 0.45 (this work), digitized from the original figure; Vušković and Srivastava (1980) summed; Parikh *et al.* (1993) absolute from beam experiment (part of the data of Kwan *et al.*, 1991, are plotted under the same symbol); McCarthy *et al.* (1993) coupled-channels, partial-wave polarization potential; Gien (1987) Glauber approximation, shown above 100 eV for clarity (points from 50 to 100 eV tend to be lower than other data); data of Perel *et al.* (1962), not shown. *Elastic*: Vušković and Srivastava (1980); Buckman *et al.* (1979) integrated in this work ( $\pm 20\%$  possible extrapolation error); Moores (1976) close-coupling. *Momentum transfer*: Stefanov and Zarkova (1987), digitized from the original figure at very low energies. *Electronic excitation*:  $2p4^2P$  Buckman *et al.* (1979) beam experiment;  $2p4^2P$  Chen and Gallagher (1978) optical with cascading; overall excitation, Phelps *et al.* (1979) optical direct for 24 states; Vušković and Srivastava (1980), beam experiment for 11 states. *Ionization*: gross total of Brink (1962) normalized at 200 eV to Brink (1964); counting total of McFarland and Kinney (1965); Nygaard (1976) and Zapesochnyi and Aleksakhin (1969) are not shown.

and in relatively good mutual agreement, did not confirm the existence of the maximum at 1.2 eV.

Recent beam measurements of the Detroit group Stein *et al.* (1985) at 5–50 eV, Kwan *et al.* (1991) at 4–100 eV and Parikh *et al.* (1993) at 1–100 eV merge pretty well with the recoil measurements at 10 eV but at 2 eV are lower as much as 50%. Parikh *et al.* have discussed extensively possible systematic errors, including the role of the magnetic field used to guide their electron beam. This is likely to worsen the effective angular resolution in their apparatus, but such a big discrepancy remains without explanation. We may also note smaller discrepancies among «direct» and «relative» TCS of Parikh *et al.* (1993) and earlier absolute values of Kwan *et al.* (1991) from the same laboratory.

Close-coupling calculations at 0.5–5 eV with a semiempirical potential (Moores,



1976) reproduce a rising trend of TCS towards low energies but do not give any indication about the possible existence of a maximum at lower energies. At intermediate energies a close-coupled optical model (McCarthy *et al.*, 1993) overestimate the experimental TCS (Kwan *et al.*, 1991) at 10–100 eV. On the other hand, the Glauber approximation (Gien, 1987) underestimates it (for clarity reasons, in fig. 12 the points of Gien (1987) are shown above 100 eV only).

*Swarm measurements.* The analysis performed by Stefanov and Zarkova (1987) on plasma experiments indicates a maximum in the momentum transfer CS of about  $460 \cdot 10^{-20} \text{ m}^2$  at 0.25 eV, a minimum of about  $50 \cdot 10^{-20} \text{ m}^2$  at 0.05 eV and an additional rise to about  $500 \cdot 10^{-20} \text{ m}^2$  at zero energy. No confirmation of such a behaviour has been given until now from beam experiments nor theoretical work.

*Elastic cross-section.* Relative elastic DCS between 0.9 eV and 15 eV have been measured in a wide angular range (25–150°) by Gehenn and Wilmers (1971). With respect to Na, the potassium angular distributions at a given energy indicate that more partial waves are involved in the scattering process. A well-defined *d*-wave pattern is already observable at 3.1 eV for K (Gehenn and Wilmers, 1971; Eyb, 1976), compared with 6.0 eV for Na. The integral (relative) elastic CS of Eyb and Hofmann (1975) presents a step-like fall of the order of 15% around 1.5 eV, *i.e.* at the first inelastic threshold.

The recoil method has been used to obtain absolute DCS for elastic scattering at 3.3–5.2 eV (Slevin *et al.*, 1972). A crossed beam method has been used to measure relative elastic (and electron excitation to 3 states) DCS at 6.7, 16 and 60 eV by Williams and Trajmar (1977). They normalized the summed (elastic excitation) values to the difference between TCS (Kasdan *et al.*, 1973) and the ionization CS (McFarland and Kinney, 1965 and Korchevoí and Przonski, 1967). Their integral elastic CS at the two lower energies agrees well with more recent determinations (see fig. 12) but overestimates them at 60 eV. This is probably due to the choice of the data used for normalization. Therefore, Vušković and Srivastava (1980), in the same laboratory, first normalized their  $4^2P$  excitation data to the optical oscillator strength and then used these values to derive the absolute amplitude of elastic DCS. A two-step fall of the integral CS of Vušković and Srivastava in the 7–100 eV region is well visible in fig. 12. The same normalization procedure was used by Buckman *et al.* (1979) in the 54.4–217.7 eV range. Although these measurements were performed at different energy points than those of Vušković and Srivastava (1980), the two sets of data are in reasonable agreement (see fig. 13a)). Also the integral CS as given by Vušković *et al.* (1979) are in good agreement with the data of Buckman *et al.* (1979) integrated by us.

In fig. 13a) and b) the differential elastic CS for potassium and argon are compared at 50 eV and 100 eV. A possible absorption effect in the elastic channel is less clear for potassium than for sodium. At high energies the angular distributions of elastically scattered electrons (Rao and Bharathi, 1987), normalized to unity at 30°, resemble those in sodium, both as far as the angular position of the minimum (100°) and its depth (0.023, 0.034, 0.052 at 300, 400 and 500 eV, respectively) are concerned.

*Excitation cross-section.* Crossed beam studies of DCS for electronic excitation in the 6.7–60 eV energy range have been initiated by Williams and Trajmar (1977) and continued in the 7–100 eV range by the same group (Vušković and Srivastava, 1980) and by Buckman *et al.* (1979) at 54.4–217.7 eV. The latter two papers normalized their

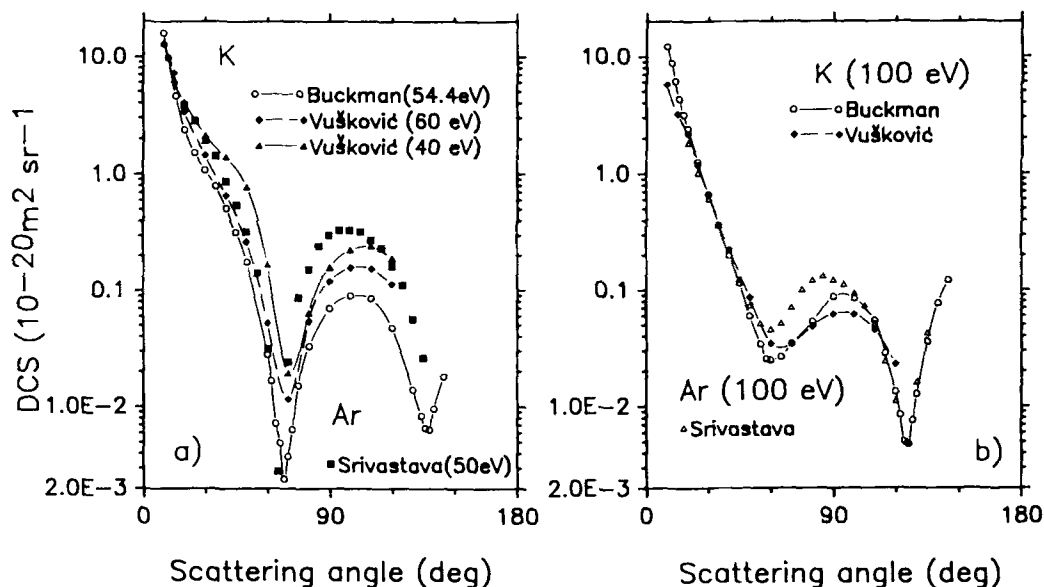


Fig. 13. – Comparison of differential elastic cross-sections for electron scattering on Ar and K at 50 eV (a) and 100 eV (b). *Potassium* cross-sections: Buckman *et al.* (1979); Vušković and Srivastava (1980). *Argon*: Srivastava *et al.* (1981).

zero-angle  $4^2P$  differential CS to the optical oscillator strength. At overlapping energies the integral  $4^2P$  values of Vušković and Srivastava (1980) and Buckman *et al.* (1979) coincide within 5%. The  $4^2P$  state is the most important one, amounting to 70% at 7 eV and to as much as 90% at 100 eV of the overall (Vušković and Srivastava, 1980) excitation CS. Scattering from the excited  $4^2P$  state has been studied by Matterstock *et al.* (1995).

*Optical emission.* Optical measurements include works of Chen and Gallagher (1978) who normalized their measurements of the  $4^2P$  line to the Born approximation calculation, absolute data of Zapesochnyí *et al.* (1976) for the same transition and absolute measurements of direct excitations (*i.e.* with cascading effects subtracted) for 24 transitions of Phelps *et al.* (1979). Integral values for the overall excitation from the beam experiment (Vušković and Srivastava, 1980) agree well both with the summed direct optical excitation (Phelps *et al.*, 1979) as well as with the cascade-including  $4^2P$  excitation (Chen and Gallagher, 1978), see fig. 12. Optical data (Chen and Gallagher) agree also well with the trapped electron measurements of the excitation in the threshold region (1.5–2.5 eV) (Korchevoi and Przonski 1967).

*Ionization cross-section* was measured by Tate and Smith (1934) in a relative way from threshold to 30 eV and then by Brink (1962 and 1964) from threshold to 500 eV in relative and from 200 eV to 500 eV in absolute ways, respectively. Absolute measurements were also performed by McFarland and Kinney (1965) at 50–500 eV, Korchevoi and Przonski (1967) up to 25 eV, by Zapesochnyí and Aleksakhin (1969) up to 30 eV and by Nygaard (1975) from threshold to 30 eV. All these measurements agree well, putting a lower limit of  $7.9 \cdot 10^{-20} \text{ m}^2$  (Nygaard, 1976; Zapesochnyí and

Aleksakhin, 1969) and an upper limit of  $9.0 \cdot 10^{-20} \text{ m}^2$  (Brink, 1964; Korchevoï and Przonski, 1967) on the maximum value of the ionization CS at 8.5 eV. Autoionizing excited and metastable states contribute to a broad maximum in the ionization CS around 30 eV (Nygaard, 1976) and smaller structures at 20 eV (Marmet and Proulx, 1987). Double ( $K^2+$ ) ionization constitutes 13% of the overall one at 100 eV (Brink, 1962).

*Resonances.* Resonant structures were observed in the excitation functions for elastic and  $4^2P$  inelastic scattering around 2.5 eV (Eyb, 1976). No structures in the very low-energy transmission spectra down to 0.1 eV were observed (Johnston and Burrow, 1982). For more details about resonant phenomena, the reader is referred to the recent review by Buckman and Clark (1994).

*Sum check.* Values obtained by summing ionization CS with elastic and excitation CS from the two most complete measurements (Buckman *et al.*, 1979; Vušković and Srivastava, 1980) are higher than the beam measurements of TCS (Kwan *et al.*, 1991) in the whole 7–60 eV energy range, the difference exceeding 30%. This discrepancy cannot be explained in terms of non-discriminated forward scattering in the measurements of Kwan *et al.* (1991). We cannot discard the possibility that the choice of normalization data for elastic and excitation CS contributes to the discrepancy. Total and summed values agree well at 75 eV and 100 eV.

We also note, as observed for Na, that the recoil experiment (Kasdan *et al.*, 1973) tends to overestimate the TCS at energies above the ionization threshold (see fig. 12). New TCS measurements at low energies and a cross-check of normalization procedures for elastic scattering at intermediate energies would be of interest.

TABLE VIII. – *Integral cross-sections for electron scattering on potassium (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Excitation		Ionization	Sum	Total <sub>K</sub>
		$4P^2$	other			
7	47.7 <sub>V</sub>	50.3 <sub>V</sub>	20.0 <sub>V</sub>	5.4 <sub>BR</sub>	123	87.6*
20	17.6 <sub>V</sub>	45.9 <sub>V</sub>	10.1 <sub>V</sub>	8.2 <sub>BR</sub>	81.8	66.6*
40	15.5 <sub>V</sub>	31.5 <sub>V</sub>	6.3 <sub>V</sub>	6.7 <sub>BR</sub>	60.0	45.0
54.4	9.4 <sub>B</sub>	32.3 <sub>B</sub>	4.2 <sub>V</sub> *	5.8 <sub>MF</sub> *	51.7	41.5*
60	10.6 <sub>V</sub>	24.5 <sub>V</sub>	3.4 <sub>V</sub>	5.5 <sub>BR</sub>	44.0	40.5*
75	5.7 <sub>B</sub>	24.4 <sub>B</sub>	2.6 <sub>V</sub> *	5.2 <sub>MF</sub> *	37.9	37.8*
100	4.41 <sub>V</sub>	17.4 <sub>V</sub>	1.7 <sub>V</sub>	4.5 <sub>MF</sub>	28.0	31.6*
	5.5 <sub>L</sub>	18.8 <sub>B</sub>			30.5	
200	4.2 <sub>B</sub>	10.6 <sub>B</sub>	0.1 <sub>P</sub>	3.5 <sub>MF</sub>	18.4	

\* – Interpolated value.

B – Buckman *et al.* (1979), integrated in this work ( $\pm 20\%$  extrapolation uncertainty).

BR – Brink (1962) normalized to Brink (1964).

K – Kwan *et al.* (1991).

MF – McFarland and Kinney (1965).

P – Phelps *et al.* (1979).

V – Vušković and Srivastava (1980).

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3'4. *Rubidium* (Rb). – A limited number of total and partial CS measurements exist for rubidium. The ionization CS has received more attention. The theory meets essential difficulties in *ab initio* treatment of heavy, open-shell targets at low energies, where the exchange processes contribute in a substantial way to the TCS.

A set of experimental integral CS is presented in fig. 14. A few theoretical results have been inserted to complement the scarce experimental data.

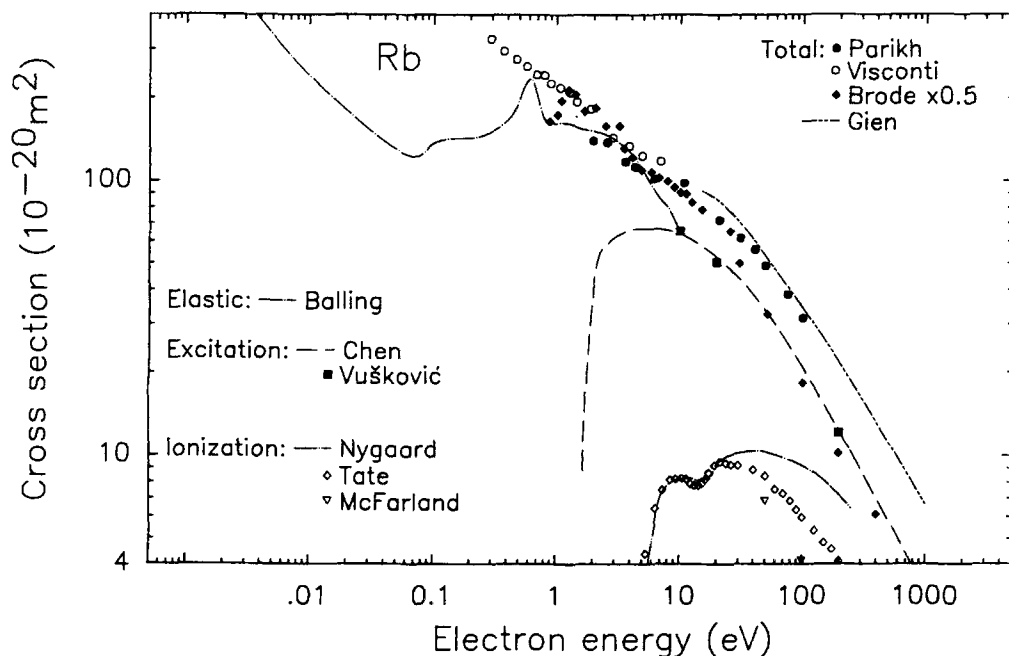


Fig. 14. – Integral cross-sections for electron scattering on Rb. *Total*: Parikh *et al.* (1993) beam; Visconti *et al.* (1971) recoil; Brode (1929) beam, normalized by a factor 0.5, digitized from the original figure; Gien (1992) 3-state, modified-Glauber calculation. *Elastic*: Balling (1969), Hartree-Fock with polarization adjusted to fit the experiment. *2p5<sup>2</sup>P excitation*: Chen and Gallagher (1978) optical; Vušković *et al.* (1984). *Ionization*: gross total of Nygaard and Hahn (1973); counting integral of Tate and Smith (1934) normalized at 10 eV to Nygaard and Hahn (1973); counting total of McFarland and Kinney (1965); gross integral values of Brink (1964) are out of scale.

**Total cross-section.** As for other alkali metals, rubidium was measured in a beam experiment by Brode (1929), and recently by Parikh *et al.* (1993). A recoil-beam set-up has been used by Visconti *et al.* (1971). Brode's results suffer from a large uncertainty («by as much as 2 or 3 fold» in Brode's words) in the pressure determination. This has been remarked also for Na and K. However, his results for rubidium, if divided by a factor of 2, are in reasonable agreement with both the data of Parikh *et al.* as well as those of Visconti *et al.* (1971) up to about 20 eV (see fig. 14). The agreement between the low-energy tail of Parikh *et al.*'s TCS and the data from the recoil experiment is much better than for potassium. It is worth noting that the dependence of the rubidium TCS in the 1–100 eV range (Visconti *et al.*, 1971 and Parikh *et al.*, 1993) is, contrary to lighter alkali metals, less steep than  $1/\sqrt{E}$ . This dependence is reproduced between 1 eV and 5 eV by the calculations of Balling (1969) who used Herman-Skillman atomic orbitals and an adjustable polarization potential. Additionally, he predicted a shape resonance at about 0.6 eV and a rise of the TCS in the zero-energy limit. However, due to the use of an adjustable value for the atomic polarization, these features could be an artifact. At intermediate energies a modified-Glauber, 3-state calculation (Gien, 1990, 1992) approaches the experimental TCS of Parikh *et al.* from above.

*Elastic cross-sections* at 10 and 20 eV, normalized via  $5^2P$  excitation to the optical oscillator strength, were measured at Pasadena laboratory (Vušković *et al.*, 1984). No integral CS are given in this paper. Elastic DCS for rubidium at low energies (Vušković *et al.*, 1984) are even more forward-peaked than those for potassium, regardless of any possible systematic error. Potassium and rubidium DCS at  $20^\circ$  measured at 10 eV and at 7 eV amount to  $19 \cdot 10^{-20} \text{ m}^2 \text{ sr}^{-1}$  and  $45 \cdot 10^{-20} \text{ m}^2 \text{ sr}^{-1}$ , respectively; while at  $90^\circ$  they are approximately equal ( $1.08$  and  $0.85 \cdot 10^{-20}$ , respectively). Similar proportions hold for DCS measured at 20 eV.

At 300 eV the relative DCS (Rao and Bharathi, 1987) exhibits a minimum much narrower and deeper (relative value of 0.01 if the DCS is normalized to 1 at  $30^\circ$ ) and at a lower angle ( $79^\circ$ ) than those at the same energy in Na and K.

*Excitation cross-section* to  $5^2P$  and  $4^2D + 6^2S$  states was studied in electron energy loss measurements by Vušković *et al.* (1984) at 10, 20, 200 eV and in the  $5\text{--}120^\circ$  angular range. Integral values were given for the  $5^2P$  state. Integral values of Vušković *et al.* (1984) are in excellent agreement with optical-emission CS for the  $5^2P$  line, with no cascading subtracted (Zapesochnyí *et al.*, 1976; Chen and Gallagher, 1978). As has been noticed for potassium (see fig. 12) the non-corrected  $^2P$  emission CS forms by itself a close, lower bound for the direct overall excitation CS.

*Ionization cross-section.* The list of integral ionization CS measurements for Rb includes the relative data of Tate and Smith (1934), relative (1962) and subsequently (1964) absolute data of Brink, absolute measurements of McFarland and Kinney (1965), Korchevoi and Przonski (1967), Zapesochnyí and Aleksakhin (1969) and of Nygaard and Hahn (1973). The ionization CS of Rb shows, in analogy with potassium, two maxima: the first one at 10 eV, the second at about 30 eV. The first maximum is only slightly (less than 20%) higher than those for Na and K, and amounts to  $8.8 \cdot 10^{-20} \text{ m}^2$  (McFarland and Kinney, Zapesochnyí and Aleksakhin). Korchevoi and Przonski (1967) in a trapped-electron experiment obtained, as for potassium, slightly higher values for the ionization CS. Their values are in agreement with the maximum value of  $9.6 \cdot 10^{-20} \text{ m}^2$  given by Brink (1964).

Multiply charged ions ( $\text{Rb}^{2+}$ ,  $\text{Rb}^{3+}$ ) amount to a substantial part of the overall ionization at high energies. Tate and Smith in relative measurements reported that the sum of  $\text{Rb}^{2+}$  and  $\text{Rb}^{3+}$  yields is equal to one half of the  $\text{Rb}^+$  production at 300 eV; however, they were aware of different collection efficiencies for different ions in their apparatus.

Large discrepancies between gross ionization CS are found at 200 eV where Brink (1964) and McFarland and Kinney (1965) report  $3.0 \cdot 10^{-20} \text{ m}^2$ , while Nygaard and Hahn (1973) give  $7.5 \cdot 10^{-20} \text{ m}^2$ . We have obtained a gross CS of  $6 \cdot 10^{-20}$  at this energy, normalizing at 10 eV the relative data of Tate and Smith (1934) to the value of Nygaard and Hahn (1973).

*Resonances.* Johnston and Burrow (1982) have observed a structure in their transmission spectra below 0.05 eV; the authors state that this structure was close to the limits of observability of their apparatus. For an extensive summary on resonant states in Rb we refer the reader again to Buckman and Clark (1994).

TABLE IX. – *Integral cross-sections for electron scattering on rubidium (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Excitation $5^2P$	Emission $5^2P$	Ionization	Total
10	65.3 <sub>V</sub>	63.6 <sub>C</sub>	8.2 <sub>N</sub>	87 <sub>VI</sub> <sup>*</sup> 100 <sub>P</sub>
20	50.0 <sub>V</sub>	52.2 <sub>C</sub>	9.1 <sub>N</sub>	72.2 <sub>P</sub> <sup>*</sup>
100		20.7 <sub>C</sub>	4.1 <sub>MF</sub>	31.2 <sub>P</sub>
200	12.0 <sub>V</sub>	14.5 <sub>C</sub> <sup>*</sup>	7.2 <sub>N</sub> 3.0 <sub>B</sub> 4.1 <sub>T</sub>	

\* – Interpolated value.

B – Brink (1964), gross ionization.

C – Chen and Gallagher (1978).

MF – McFarland and Kinney (1965), counting ionization.

N – Nygaard and Hahn (1973), gross ionization.

P – Parikh *et al.* (1993).

T – Counting ionization cross-section of Tate and Smith (1934) normalized at 10 eV to the value of Nygaard and Hahn (1973).

V – Vušković *et al.* (1984).

VI – Visconti *et al.* (1971).

*Sum check.* The status of measurements on rubidium does not allow any significant check on the sum of partial CS. Elastic measurements, especially at small angles, are needed. Calculations over an extended range would be useful.

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3.5. *Cesium (Cs)*. – Cesium is used in atomic clock standards as well as in studies of thermo-ionic conversion in plasma (Kuehn *et al.*, 1978). Integral CS for electron scattering in cesium are presented in fig. 15.

*Total cross-section.* Brode's (1929) beam measurements exhibit a peak in the TCS around 2.5 eV. No such structure has been observed in recoil-beam experiments (Visconti *et al.*, 1971; Jaduszliwer and Chan, 1992). The two latter experiments agree well on the absolute value of the TCS, while the original measurements of Brode are systematically higher in the whole 2–18 eV energy range. The data of Brode presented in fig. 15 have been normalized by a factor of 0.45, similarly as we have done for other alkali metals. We notice that the normalized data of Brode are lower than the latest electronic excitation CS at energies above 70 eV. This can be caused by the poor angular resolution of his Ramsauer-like apparatus, not suitable for high energies.

*Elastic scattering.* We are unaware of published experimental integral elastic CS in cesium. Gehenn and Reichert (1977) have measured relative elastic DCS for 35–145° scattering angles at 1–2 eV. They observed structures with shapes dependent on the

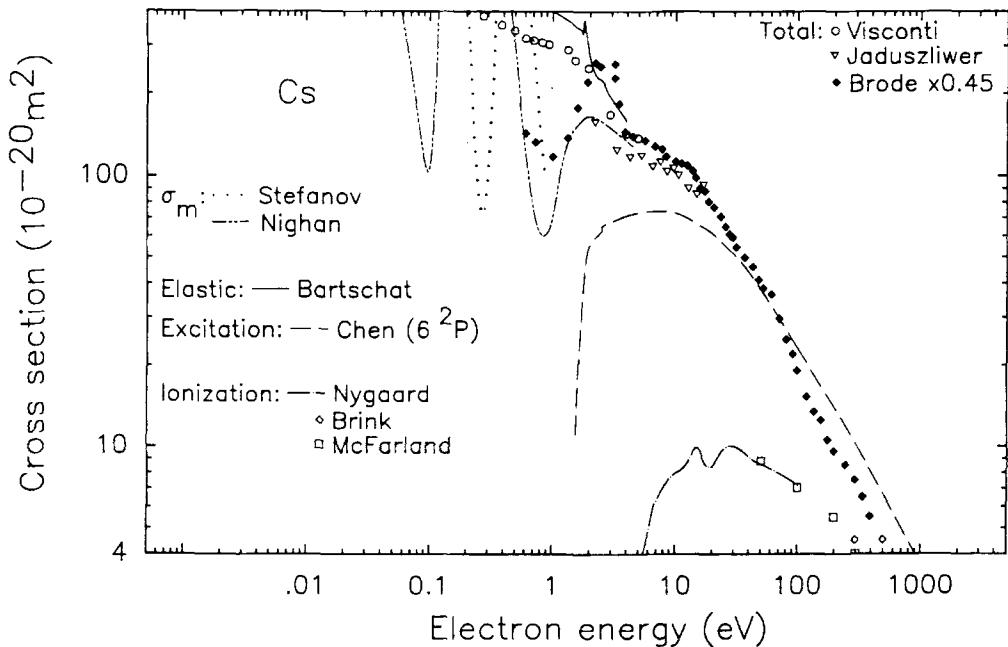


Fig. 15. – Integral cross-sections for electron scattering on Cs. *Total*: Visconti *et al.* (1971) recoil; Jaduszliwer and Chan (1992) recoil; Brode (1929) beam, renormalized by a factor of 0.45, digitized from the original figure. *Elastic*: Bartschat (1993) relativistic *R*-matrix. *Momentum transfer*: Stefanov (1980), Nighan and Postma (1972). *2p 6<sup>2</sup>P excitation*: Chen and Gallagher (1978) optical. *Ionization*: Nygaard (1968) gross total; Brink (1964) gross total; McFarland and Kinney (1965) counting total.



scattering angle at energies around the thresholds for  $^2P_{1/2}$  and  $^2P_{3/2}$  excitations. Relativistic  $R$ -matrix calculations (Scott *et al.*, 1984) at 0.5–2.0 eV, not shown in fig.15, indicate a wide structure in the integral elastic CS just below the first excitation thresholds. Recent  $R$ -matrix calculations (Bartschat, 1993) point for the existence of a shape resonance at 1.8 eV, but much narrower and weaker than the structure in Brode's measurements (see fig.15). In Bartschat's results three additional resonances show up below 0.02 eV.

Experimental angular distributions in the 0.8–2.0 eV range (Gehenn and Reichert, 1977) present just above 1.0 eV a well-developed  $d$ -wave pattern.

*Swarm analysis* in cesium has a relatively weak experimental basis. Stefanov (1980) used only plasma electrical conductivity and disregarded microwave and electron drift velocity measurements. Nighan and Postma (1972) on the basis of early drift velocity data have obtained a maximum of about  $2500 \cdot 10^{-20} \text{ m}^2$  at 0.25 eV, preceded by a Ramsauer-Townsend minimum of  $100 \cdot 10^{-20} \text{ m}^2$  at 0.1 eV. Saelee and Lucas (1979) obtained a momentum transfer CS similar in shape to that of Nighan and Postma, but higher by a factor of 3. A similar shape has been obtained in the first-order perturbative calculation by Crown and Russek (1965). This contrasts with findings of Stefanov (1980) who puts a minimum at 0.25 and two maxima at 0.15 eV and 0.45 eV (see fig. 15). We are unaware of more recent developments of swarm analysis for cesium. The overall situation of swarm measurements in cesium is quite unsatisfactory: the present data are in full disagreement. They are also conflicting with the beam data. These in turn are in strong disagreement below a few eV.

*Excitation cross-section.* We are aware only of optical measurements of the electronic excitation to the  $6^2P$  state. Chen and Gallagher (1978) have measured relative excitation functions for the  $6^2P_{3/2}$  sub-state. They have multiplied their results by 1.5, in order to account for the non-measured component of the doublet (a statistical branching ratio of 2:1 for  $P_{3/2}:P_{1/2}$  states was assumed). These figures were then normalized to the Born value at 1500 eV; a 7% was added to allow for cascading. Emission cross-sections obtained in this way are, however, much lower (with difference of 50% at the maximum of the cross-section) than the absolute measurements of Zapesochnyí *et al.* (1976). The reason for this discrepancy, much higher for cesium than for potassium and rubidium, is unclear. The agreement between the two data sets is better at higher energies, where the Born approximation is valid. Recent relativistic distorted-wave calculations (Zeman *et al.*, 1994) produced integral CS even higher (20% at 100 eV) than the measurements of Zapesochnyí *et al.* (1976).

We also note a different relative scaling of maxima in the emission CS of the  $^2P$  resonant doublets in heavier alkali metals. While Chen and Gallagher indicate an iso-distant scaling of maxima ( $74:66:54 \cdot 10^{-20} \text{ m}^2$  for Cs, Rb, K, respectively), the measurements of Zapesochnyí *et al.* for Cs are much higher than for Rb and K ( $145:89:81 \cdot 10^{-20} \text{ m}^2$  at the maximum for Cs, Rb and K, respectively). Excitation to autoionizing states was studied by Pejčev and Ross (1977) but no absolute cross-sections were given.

*Ionization cross-sections* were measured by Tate and Smith (1934), Brink (1962, 1964), McFarland and Kinney (1965), Zapesochnyí and Aleksakhin (1969) together

with other alkali metals. For the details on energy ranges and normalization procedures we refer to the preceding subsections. Exclusively cesium has been studied by Nygaard (1968) and Heil and Scott (1966). Integral CS exhibits three maxima (Zapesochnyi and Aleksakhin, 1969): at 9.5 eV (only a shoulder was seen by other authors), at 15 eV and at 25 eV, not exceeding  $10 \cdot 10^{-20} \text{ m}^2$  (Nygaard, 1968; McFarland and Kinney). Trapped-electron data (Korchevoi and Przonski, 1967) seem to be overestimated, in contrast to the measurements of Heil and Scott which are about 30% lower than those of Nygaard. Structures visible in the ionization CS are attributable to ionization into metastable states (Nygaard and Hahn, 1973). Ionization of polarized cesium atoms was studied by Baum *et al.* (1993).

Comparing ionization CS for the five alkali metals we note a rather weak dependence on the atomic number, in accordance with other atomic targets (see Freund *et al.*, 1990). More measurements would be required at high energies where only two (McFarland and Kinney, 1965 and Brink, 1964), somewhat confused, absolute results exist.

*Resonances.* Johnston and Burrow (1982) in their transmission experiment between 0.1 and 1 eV did not report any resonant structure for cesium as seen, for example, in Na or Mg. Recent calculations (Bartschat, 1993) would indicate the presence of resonant states at much lower energies ( $< 0.02 \text{ eV}$ ). For a detailed discussion we refer to the review of Buckman and Clark (1994).

*Sum check.* Values of  $20 \cdot 10^{-20} \text{ m}^2$  and  $10 \cdot 10^{-20} \text{ m}^2$  at 10 eV and 20 eV, respectively, can be deduced for the integral elastic CS by subtracting ionization (Nygaard, 1968) and electronic excitation (Chen and Gallagher, 1978) from the TCS (Jaduszliwer and Chan, 1992). It would be of interest to know, even in an approximative way, the partitioning of the TCS in cesium. The present knowledge is such that we have an indication only about the role of different processes.

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**3'6. Mercury (Hg).** – The historical importance of mercury for atomic-physics concepts descends from Franck and Hertz's (1914) experiment on electron transport which evidenced existence of threshold energies for excitation through electron collisions. Mercury light sources with emission spectra extending to the ultraviolet have been used for many decades. Mercury vapour is also used in facilitating gas discharges via the Penning ionization (Sawada *et al.*, 1989; Sakai *et al.*, 1991). In spite of its practical importance, the cross-sections for electron scattering have been studied rather sporadically. Figure 16 shows the cross-sections collected in this work.

*Total cross-sections* have been measured by Jost and Ohnemus (1979) between 0.1 and 400 eV. These data are frequently used to normalize or to derive other partial cross-sections (Holtkamp *et al.*, 1987; Peitzmann and Kessler, 1990b). The data of Jost and Ohnemus are systematically higher than the earlier measurements, dating to the twenties (consult Jost and Ohnemus, 1979 for a complete list of references). In particular, they are about 40% higher than the data of Brode (1929). In the whole 1–400 eV energy range we hypothesize two factors which could have led to these discrepancies. First, at the time of Brode's experiment no well-established values of vapour pressure were known. Secondly, Brode's experiment was performed with a rather poor angular resolution. Both elastic as well as electron excitation DCS are forward-peaked for Hg and can contribute substantially to the angular resolution error. On the other hand, in spite of a much better, angular acceptance of the Jost and Ohnemus' apparatus (0.03 sr as seen from the centre of the scattering cell) their published CS have been increased with respect to the measured data by as much as 30% at 20 eV. This has been done to account for a possible forward-scattering error.

The measurements of Jost and Ohnemus evidence a pretty wide maximum of the TCS of  $265 \cdot 10^{-20} \text{ m}^2$  centred around 0.4 eV. This maximum was also seen in electron transmission spectra (Burrow *et al.*, 1976; Johnston and Burrow, 1982) and has been attributed to a  $^2P_{1/2}$  shape resonance (Walker, 1975). Another wide maximum in the TCS is observed in the region where the electronic excitation CS peaks (about 20 to 50 eV). Jost and Ohnemus also observed two series of sharp, resonant structures in the TCS between 4.5–5.5 eV and 8.2–11.5 eV, the strongest one amounting to 4% of the

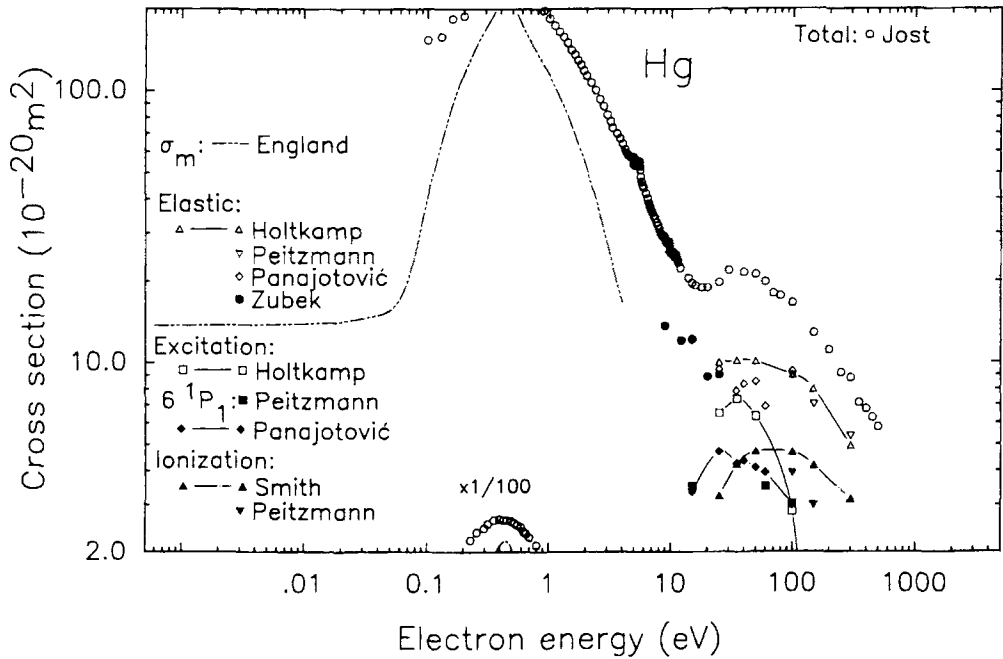


Fig. 16. – Integral cross-sections for electron scattering on Hg. *Total*: absolute corrected for angular resolution by Jost and Ohnemus (1979). Please note that points from 0.3 to 0.7 eV have been drawn at the bottom of the figure. This has been done to maintain a two-decade span on the vertical axis of the figure. *Elastic*: absolute of Holtkamp *et al.* (1987); Peitzmann and Kessler (1990b) normalized to total; Panajotović *et al.* (1993) normalized to oscillator strength; Zubek *et al.* (1995) normalized to Holtkamp *et al.* (1987) at 25 eV. *Momentum transfer*: England and Elford (1991). *Excitation*: Holtkamp *et al.* (1987) overall, from difference between total and elastic-plus-ionization; Peitzmann and Kessler (1990a)  $6^1P_1$ , absolute; Panajotović *et al.* (1993)  $6^1P_1$ , normalized to optical oscillator strength. *Ionization*: counting ionization of Smith (1931) as corrected by Holtkamp *et al.* (1987); Peitzmann and Kessler (1990b) normalized to total.

total value. These series can be barely seen in fig.16 as a gathering of the data points.

*Swarm measurements.* The absence of inelastic processes at low energies and a number of transport coefficients measurements facilitate the evaluation of the momentum transfer CS. However, as noticed by England and Elford (1991), the diffusion effects and the presence of mercury dimers can falsify the results. In fact, their recent analysis gave a maximum CS 10% to 30% higher than earlier results (Rockwood, 1973; Nakamura and Lucas, 1978; Sakai *et al.*, 1989; Elford, 1980). We also note a discrepancy in the very-low-energy limit between the analysis of Nakamura and Lucas, who indicate the presence of a Ramsauer-Townsend minimum at 0.25 eV, and other results giving a constant value of the CS towards zero energy. The relativistic, exchange calculation (Walker, 1970) has been performed only above 0.2 eV, so it gives no hint on the minimum. On the other hand, a Ramsauer-Townsend minimum has been predicted for positron-Hg scattering (Sin Fai Lam, 1980).

*Elastic cross-section.* Absolute differential and integral elastic CS (from a direct determination of vapour pressure and scattering geometry) were obtained by Holtkamp *et al.* (1987) between 25 and 300 eV in a scattering cell experiment. Differential and integral values normalized to the TCS were obtained at 100, 150 and 300 eV by Peitzmann and Kessler (1990b). At overlapping energies the two results agree within 8% on the average. According to Holtkamp *et al.* (1987) the integrated CS exhibits a flat plateau between 25–50 eV and then descends smoothly at higher energies.

The DCS at intermediate energies are forward-peaked but less than for alkali metals, dropping at 50 eV by a factor of 50 when the scattering angle is varied from  $4^\circ$  to  $40^\circ$ . It is peculiar that the DCS at 25 eV resembles an  $f$ -wave distribution with minima at  $35^\circ$ ,  $87^\circ$  and  $132^\circ$ ; at 50 eV it shows only two minima; whilst at 300 eV three minima are visible once more between  $2^\circ$  and  $135^\circ$  (Holtkamp *et al.*, 1987).

Relative DCS of Panajotović *et al.* (1993) normalized to optical-oscillator strength at 15–100 eV are in vague agreement with the absolute data of Holtkamp *et al.* However, their integral CS suffer from a big scatter (see fig. 16). Zubek *et al.* (1995) have obtained elastic DCS at the incident energy range from 9 eV to 25 eV and the angular range from  $10^\circ$  to  $120^\circ$ . They have normalized the relative data to the absolute value of Holtkamp *et al.* (1987) at  $60^\circ$ , 25 eV. The measurements of Zubek *et al.* indicate for a rapid fall of the integral elastic CS between 9 eV and 25 eV.

Bromberg (1969) at 300, 400 and 500 eV observed an energy-independent, linear relation between the logarithm of the elastic DCS and the transferred momentum (consult fig. 2 for noble gases). Bromberg attributed this peculiarity as due to scattering on a polarization potential. In the successive discussion, the importance of static and absorption effects was pointed out (Huo, 1972; Bonham and Fink, 1971).

At low energies (1.4–3.9 eV) relative angular distributions have been measured by Düweke *et al.* (1976) at  $40$ – $120^\circ$ . Elastic DCS at the reported energies exhibit a single minimum at  $110^\circ$ , in agreement with calculations of Walker (1975).

*Excitation cross-section.* Absolute electron excitation CS for the  $6^1S_0$ – $6^1P_1$  transition were obtained by Peitzmann and Kessler (1990a) at 15, 60 and 100 eV. Their data agree well at 15 and 100 eV with the semiempirical analysis of overall electronic excitation performed by Holtkamp *et al.* (1987) but are somewhat lower than this at 60 eV. On the other hand, we note that the rapid fall of the overall excitation between 50 and 300 eV can be an artifact in the analysis of Holtkamp *et al.*, due to the accumulation of the evaluation uncertainties, with a possible error bar of 200% at 300 eV.

Panajotović *et al.* (1993) obtained differential and integral CS for excitation to the  $6^1P_1$  at 15–100 eV and to  $6^3P_1$ ,  $7^1S_0$ ,  $7^1P_1$  at 60 eV. They normalized the relative CS to the  $6^1P_1$  generalized oscillator strength (Skerbele and Lassettre, 1970). The disagreement between integral CS of Peitzmann and Kessler (1990a, b) and of Panajotović *et al.* is less marked for the  $6^1P_1$  excitation than for elastic scattering. According to the integral data of Panajotović *et al.* the excitation to the  $6^1P_1$  state constitutes 20% of the TCS (Jost and Ohnemus, 1979) at 60 eV, while the other three contribute 3% altogether. The ratio between the  $6^1P_1$  and other excitations seem to be the same also at 100 eV (Peitzmann and Kessler, 1990b). Theoretical models (see Panajotović *et al.* and Srivastava *et al.*, 1993) tend to overestimate the experimental elastic and inelastic CS.

The inelastic DCS are much more forward-peaked than the elastic counterpart: at 60 eV the  $6^1P_1$  DCS falls down by three orders of magnitude between  $4^\circ$  and  $50^\circ$  (Peitzmann and Kessler, 1990a). Also excitation to the  $6^3P_1$  state is forward-peaked, even at low energies, due to a mixing of triplet and singlet contributions (Srivastava *et al.*, 1993). More homogeneous angular distributions were observed at 15 eV for  $7^1P_1$ ,  $6^3P_2$  and  $6^3P_0$  states (data of Kessler as cited by Srivastava *et al.*, 1993; Danjo *et al.*, 1993).

Excitation at high energies was studied experimentally by Yamazaki *et al.* (1978).

*Optical-emission cross-section* measurements are rather scarce and incongruent (see Heddle and Gallagher, 1989 for a review). Post (1984) on the basis of low-pressure discharge and some earlier experiments obtained CS values of  $(2.1 \pm 0.6) \cdot 10^{-20} \text{ m}^2$  at 15 eV for the  $6^1P_1 \rightarrow 6^1S_0$  transition, somewhat lower than the electron excitation CS to this state.

*Metastables.* Production of metastable  $6p^3P_{0,2}$  and  $6p'^3D_3$  excited states was extensively studied (Borst, 1969; Newman *et al.*, 1985; Hanne *et al.*, 1985). Excitation into the  $6^3P_2$  metastable state in its maximum at 5.75 eV, where the maximum is located, contributes to almost 7% of the TCS (Borst, 1969). A new, high-lying  $6p^2D_{5/2}$  (Cowan *et al.*, 1988; Zubek and King, 1990) state was observed by Zubek and King (1987).

*Ionization cross-sections* were measured by several groups in the thirties (see review of Kieffer and Dunn, 1966); according to Holtkamp *et al.* (1987) the most reliable remain the gross ionization data of Smith (1931), although being on the average 20% lower than other data. Following Smith, the gross ionization CS reaches a maximum of  $5.49 \cdot 10^{-20} \text{ m}^2$  at 85 eV. The counting ionization CS presented in fig. 16 were derived from Smith's data by Holtkamp *et al.* (1987). Differential CS for ionization were measured at 100–300 eV by Peitzmann and Kessler (1990b).

Multiple ionization at 200 eV scale as 1:0.2:0.06:0.01 for  $\text{Hg}^+$ ,  $\text{Hg}^{2+}$ ,  $\text{Hg}^{3+}$  and  $\text{Hg}^{4+}$  ion yields, respectively (Bleakney, 1930).

*Resonances.* At very low energies the positions of the  $^2P_{1/2} \text{Hg}^-$  shape resonances obtained in TCS (Jost and Ohnemus, 1979) agree well with the values obtained in transmission experiments by Johnston and Burrow (1982).

A rich pattern of resonances has been observed in the vicinity of the inelastic thresholds in Hg. In particular they were observed in TCS (Jost and Ohnemus, 1979), electron transmission spectra (Kuyatt *et al.*, 1965; Burrow *et al.*, 1976), DCS (Düweke *et al.*, 1976; Kazakov *et al.*, 1981), in optical emission (Shpenik *et al.*, 1976), in metastable excitation functions (Newman *et al.*, 1985; Zubek and King, 1987, 1990), in the threshold electron excitation spectra (Zubek *et al.*, 1991) and in scattering with polarized electrons (Wolcke *et al.*, 1983). Assignment of these states was discussed among others by Fano and Cooper (1965), Heddle (1975) and reviewed recently by Buckman and Clark (1994).

*Polarized scattering.* Mercury, due to its high atomic number, is an attractive target for Mott-scattering polarized-electrons sources and detectors. Scattering of polarized electrons on Hg was studied in the elastic channel by Kaussen *et al.* (1987),

Dümmmler *et al.* (1992) and in the electron excitation channel by Wolcke *et al.* (1983), Goeke *et al.* (1989) and Hegemann *et al.* (1991).

*Sum check* for Hg indicates a good agreement between partial and total CS at 15, 60 and 100 eV (see table X). Discrepancies at other energies are probably not intrinsic, since they come from the lack of integral values for excitations other than  $6^1P$ . The sum check suggests in particular that the elastic CS of Panajotović *et al.* at 25–60 eV are probably underestimated. We stress a strong need for more elastic CS measurements, especially at low energies. As indicated by the semiempirical analysis of Peitzmann and Kessler (1990b), the relative contributions from elastic, ionization and excitation channels remain roughly constant between 100 and 300 eV, amounting respectively, to 60%, 20% and 20%. In this

TABLE X. – *Integral cross-sections for electron scattering on mercury (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Excitation		Ionization	Sum <sup>+</sup>	Total <sub>J</sub>
		$6^1P$	other			
15	12.2 <sub>PA</sub>	3.5 <sub>P</sub>	2.07 <sub>SR</sub>	0.97 <sub>S</sub>	18.7	19.5
	12.1 <sub>Z</sub>	3.33 <sub>PA</sub>			18.5	
25	9.97 <sub>H</sub>	4.70 <sub>PA</sub>		3.22 <sub>S</sub>	17.9	19.7
	9.37 <sub>PA</sub>				17.3	
	9.0 <sub>Z</sub>				16.9	
35	10.1 <sub>H</sub>	4.25 <sub>PA</sub>		4.23 <sub>S</sub>	18.6	21.7
	7.85 <sub>PA</sub>				16.3	
50	10.0 <sub>H</sub>	4.10 <sub>PA</sub>		4.70 <sub>S</sub>	18.8	21.1
	8.48 <sub>PA</sub>				17.3	
60	9.8 <sub>H</sub> *	3.5 <sub>P</sub>	0.67 <sub>SR</sub>	4.83 <sub>S</sub>	18.8	19.8
	6.86 <sub>PA</sub>	3.93 <sub>PA</sub>	0.64 <sub>PA</sub>		16.3	
100	8.99 <sub>H</sub>	3.02 <sub>P</sub>		4.68 <sub>S</sub>	16.7	16.5
	9.27 <sub>PA</sub>	2.99 <sub>PA</sub>		3.92 <sub>K</sub>	16.2	
	(8.90 <sub>K</sub> )	(3.70 <sub>K</sub> )				
150	7.95 <sub>H</sub>	2.0**		4.17	14.1	12.8
	(6.97 <sub>K</sub> )	(2.86 <sub>K</sub> )		2.97 <sub>K</sub>	12.9	
300	4.93 <sub>H</sub>	1.0**		3.14	9.07	8.76
	(5.35 <sub>K</sub> )	(1.76 <sub>K</sub> )		1.65 <sub>K</sub>	7.58	

+ – The summed values include all excitations only at 15 and 60 eV.

() – Not used for summation.

\* – Interpolated value.

\*\* – Extrapolated, assuming a  $1/E$  dependence of the cross-section.

H – Holtkamp *et al.* (1987) absolute, from cell experiment.

K – Peitzmann and Kessler (1990b) elastic, overall excitation and ionization normalized to TCS.

P – Peitzmann and Kessler (1990a), absolute.

PA – Panajotović *et al.* (1993).

S – Smith (1931) corrected by Holtkamp *et al.* (1987) for multiple ionization.

SR – Srivastava *et al.* (1993), theoretical.

Z – Zubek *et al.* (1995).

respect, mercury differs essentially from alkali metals, for which electronic excitation is a dominant process at intermediate energies.

We remember however, that: i) the total CS of Jost and Ohnemus (1979) have been obtained using a somewhat arbitrary correction of the measured data to a «zero angular acceptance» of their apparatus; ii) swarm measurements in Hg are performed at high temperatures, *i.e.* very-low-energy momentum transfer CS has to be obtained by extrapolation; iii) the ionization CS of Smith (1931) are in disagreement with other work performed in the thirties; iv) we are unaware of published integral experimental CS for other than  $6^1P$  excitation. Table X gives partial, summed and measured total CS for selected energies.

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### 3.7. Other metals.

#### *Total cross-sections.*

Zinc, cadmium and thallium. Absolute TCS were measured by Brode in the 1–400 eV energy range for Zn and Cd (Brode, 1930) and Tl (1931). TCS for zinc and cadmium descend monotonically with energy, amounting to  $225 \cdot 10^{-20} \text{ m}^2$  and  $140 \cdot 10^{-20} \text{ m}^2$  at 1 eV, respectively. Thallium TCS is much lower, descending from  $14 \cdot 10^{-20} \text{ m}^2$  at 5 eV to  $5.7 \cdot 10^{-20} \text{ m}^2$  at 100 eV and exhibiting a Ramsauer-Townsend minimum of  $4.2 \cdot 10^{-20} \text{ m}^2$  at 1.5 eV (numbers were digitized from the original figures). However, analysis (Nakamura and Lucas, 1978b) of drift velocity measurements (Nakamura and Lucas, 1978a) indicate that the result of Brode (1931) in thallium could be underestimated by a factor of 10, exactly. A pressure evaluation error has been already hypothesized by Brode, but a misprint error is also possible. Brode (1930) noticed for Cd, Zn and Hg that the TCS at 100 eV ( $26 \cdot 10^{-20} \text{ m}^2$ ,  $18 \cdot 10^{-20} \text{ m}^2$ ,  $13 \cdot 10^{-20} \text{ m}^2$ , respectively) scale rather with polarizabilities ( $7.2$ ,  $6.4$ ,  $5.4 \cdot 10^{-30} \text{ m}^3$ , Weast, 1986) than with atomic numbers (30, 48, 80).

Calcium, strontium and barium. Romanyuk *et al.* (1980) used a trapped-electron method to measure low-energy TCS for Ca, Sr, Ba. Strontium and barium exhibit a monotonically descending TCS above 0.1 eV, while calcium shows a maximum of about  $250 \cdot 10^{-20} \text{ m}^2$  at 0.7 eV. A constant, independent of the gas, «saturation» value of the TCS towards 10 eV and a disagreement with a recent optical model (Kelemen *et al.*, 1995) would indicate some systematic error in the measurements of Romanyuk *et al.* (1980).

*Theoretical elastic cross-section* evaluations are numerous especially for alkali-earth metals: Mg, Ca, Sr, Ba. At low energies the theories generally agree in

predicting maxima of the integral CS at about 1 eV and Ramsauer-Townsend minima at tenths of an electron volt (see, for example, Yuan and Zhang, 1989, 1990, 1993; Dzuba *et al.*, 1991; Gribakin *et al.*, 1992; Kelemen *et al.*, 1995). A relativistic-polarization model for these metals has been recently applied by Szmytkowski and Sienkiewicz (1994). A semi-relativistic model has been developed by Kumar *et al.* (1994).

*Elastic scattering* and excitation cross-sections were usually measured in the same experiments. The following targets have been examined.

Magnesium at 10–130°, 10 eV to 40 eV (Williams and Trajmar, 1978), normalized to the optical oscillator strength. Integral CS falls from  $29 \cdot 10^{-20} \text{ m}^2$  at 10 eV to  $16 \cdot 10^{-20} \text{ m}^2$  at 20 eV and then abruptly to  $6.6 \cdot 10^{-20} \text{ m}^2$  at 40 eV.

Barium at 3–130°, 20 eV to 100 eV was measured by Jensen *et al.* (1978) with  $\pm 50\%$  uncertainty in the absolute values and by Wang *et al.* (1994) at 10–130°, 15 eV to 20 eV with a  $\pm 25\%$  claimed error bar. In spite of the fact that both experiments come from the same laboratory and used the same normalization procedure to the optical emission CS (Chen and Gallagher, 1976), at the only point of overlap (20 eV) the reported integral values differ by a factor of 2. A closer look into DCS from the two experiments shows that the biggest discrepancy is at 80°. The agreement with theory (Fabrikant, 1980) gives more credit to the recent measurements (Wang *et al.*, 1994), which report  $35 \cdot 10^{-20} \text{ m}^2$  at 15 eV and  $27 \cdot 10^{-20} \text{ m}^2$  at 20 eV. On the other hand, at 30 eV also the integral CS of Jensen agrees with the theory, within 20%. Only a cautious conclusion on the slow fall of the integral CS in the 20–100 eV region can be drawn.

Manganese at 20 eV, 10–130° (Williams *et al.*, 1978). A forward-peaked angular distribution, showing two minima at 40° and 100°, resembles somewhat the one in barium and magnesium at the same energy. The integral elastic CS for Mn at 20 eV lies between the corresponding values for Mg and Ba, indicating that the elastic CS of these metal could scale with atomic numbers, rather than with the polarizabilities.

Copper at 15–120°, 6 eV to 100 eV (Trajmar *et al.*, 1977), normalized via electronic excitation to the optical oscillator strength. Integral absolute CS rises from  $50 \cdot 10^{-20} \text{ m}^2$  at 6 eV to  $85 \cdot 10^{-20} \text{ m}^2$  at 20 eV and falls down to  $16 \cdot 10^{-20} \text{ m}^2$  at 100 eV. These data are at 20 eV and 60 eV lower by a factor of 2 lower than the earlier, normalized to a theory measurements of Williams and Trajmar (1974), but are still too high with respect to more recent calculations (Msezane and Henry, 1986).

Cadmium DCS at 10–70°, 60 eV to 150 eV, normalized to optical oscillator strength were measured by Nogueira *et al.* (1987). The angular range has been extended to 10–150° at 3.4–85 eV by Marinković *et al.* (1991) but only relative CS normalized separately to unity at 90° for each energy were given. The shape of the two experimental results agrees well with theories (Pangantiwar and Srivastava, 1989; Nahar, 1991; Madison *et al.*, 1991). However, the integral values of Nahar (1991) are 40% higher than those of Pangantiwar and Srivastava (1989) at 40–150 eV; no integral values were given by Madison *et al.* (1991). Nahar (1991) obtained  $13.6 \cdot 10^{-20} \text{ m}^2$  for the elastic CS and  $16.0 \cdot 10^{-20} \text{ m}^2$  for the TCS at 40 eV.

TABLE XI. – *Integral cross-sections for electron scattering on metals at 20 eV and 40 eV (in  $10^{-20} \text{ m}^2$  units).*

Metal	Atomic number	Polar. CRC	Ground state	Excited state	Cross-section					Ref.
					elas.	exc. main	exc. rest	ion.	sum	
Mg 20 eV	12	10.6	$^1S$	$3^1P$	16	15	7.8	$5.3_F$	44.1	WT <sub>78</sub>
Mg 40 eV					6.6	14	2.8	$4.3_F$	27.7	
Ba 20 eV	56	39.7	$^1S_0$	$^1P_1$	27	31	2.3	$10.0_V$	70.3	W <sub>94</sub>
Ba 40 eV					28	21	2.3	$12.0_V$	63.3	J <sub>78</sub>
Cu 20 eV	29	6.7 <sup>+</sup>		$^2P$	49.4	44.3	1.6	$3.7_F$	99.0	T <sub>77</sub>
Cu 40* eV					2.3 <sub>M</sub>	8.57				I
					36.6	31.0	1.91	$4.0_F$	73.5	T <sub>77</sub>
					3.0 <sub>M</sub>	6.80				I
Mn 20 eV	25	9.4	$^6S_{5/2}$	$a^6D@$	22	52	15	$5.1^\#$	94.1	W <sub>78</sub>
Pb 40 eV	82	6.8	$^3P_0$	$^3P_{0,1}$	44.0	8.4	1.7	$9.2_F$	63.3	WT <sub>75</sub>
Bi 40 eV	83	7.4	$^4S_{3/2}$	$^4P_{1/2}$	45.0	3.8	0.9	$8.8_F$	58.5	W <sub>75</sub>

+ – Mean of several values.

\* – Linearly interpolated between 20 eV and 60 eV.

# – Cross-section for Fe value; the Mn cross-sections can be slightly higher (see Freund *et al.*, 1990 for scaling rules).

@ – We note an incongruence between graphically presented DCS and tabulated integral values in Williams *et al.* (1978) as regards the assignment of the states.

CRC – CRC Handbook (Weast, 1986).

F – Freund *et al.* (1990).

I – Ismail and Teubner (1995).

J<sub>78</sub> – Jensen *et al.* (1978), see also Wang *et al.* (1994).

M – Msezane and Henry (1986), close-coupling calculation.

T<sub>77</sub> – Trajmar *et al.* (1977).

V – Vainshtein *et al.* (1972).

W<sub>75</sub> – Williams *et al.* (1975).

WT<sub>75</sub> – Williams and Trajmar (1975).

W<sub>78</sub> – Williams *et al.* (1978).

WT<sub>78</sub> – Williams and Trajmar (1978).

W<sub>94</sub> – Wang *et al.* (1994).

Bismuth DCS at 40 eV,  $10^\circ$  to  $130^\circ$ , normalized to optical-oscillator strength have been measured by Williams *et al.* (1975). These authors have declared an error bar of 20% for angular distributions and of a factor of 2 for absolute integral CS. The beam contained 14% of Bi<sub>2</sub>. DCS exhibit two minima at  $40^\circ$  and  $95^\circ$  and probably develop one more minimum at angles above  $130^\circ$ . An integral elastic CS value of  $45 \cdot 10^{-20} \text{ m}^2$  has been reported at 40 eV.

Lead at 40 eV,  $10^\circ$  to  $130^\circ$ , normalized to optical-oscillator strength was examined by Williams and Trajmar (1975). The vicinity of the atomic parameters (see table XI) with Bi reflects in the similarity of angular distributions. An integral elastic CS value of  $44 \cdot 10^{-20} \text{ m}^2$  has been reported at 40 eV.

*Polarization* of elastically scattered electrons was studied by Kaussen *et al.* (1987) for Hg, Tl, Pb and Bi, by Bartsch *et al.* (1992) for Zn, Cd and In, by Dümmler *et al.* (1992) for Hg, Tl and Pb.

*Electron excitation* was measured in the same experiments as elastic CS for:

Magnesium for the  $3^3P$ ,  $3^1P$ ,  $3^1D$ ,  $4^1S$ ,  $4^1P$  and  $3^3D + 4^3P$  states between 10 eV and 40 eV (Williams and Trajmar, 1978) and for the  $3^1P$  state by Brunger *et al.* (1988) at the same energies,  $5^\circ$  to  $130^\circ$  angular range. A good agreement exists between the two experiments while the five-state close-coupling calculation (McCarthy *et al.*, 1989) overestimates the DCS at 40 eV. The  $3^1P$  excitation is the most important with the integral CS amounting to  $(14-15) \cdot 10^{-20} \text{ m}^2$  in the energy range studied. This excitation channel dominates (by a factor of 2) over the elastic scattering at 40 eV (Williams and Trajmar, 1978). On the other hand, integral CS for the  $3^3P$  excitation falls down rapidly with energy from  $3.5 \cdot 10^{-20} \text{ m}^2$  at 10 eV to roughly  $0.5 \cdot 10^{-20} \text{ m}^2$  at 20 eV (Williams and Trajmar, 1978; Houghton *et al.*, 1994).

Barium excitation CS were studied by Jensen *et al.* (1978) at 20–100 eV,  $3^\circ$  to  $130^\circ$  for transitions from the  $6s^2^1S_0$  state to  $6s6p^1P_1$ , and to partially unresolved  $^1D$ ,  $^3D$ , and  $^3P$  states. Integral CS for the  $^1P$  excitation is comparable with the elastic counterpart, while those for the  $^1D$  and ( $^3D, ^3P$ ) states are one and two orders of magnitude smaller, respectively. Superelastic scattering from  $^1P_1$  state was studied by Register *et al.* (1983) and Li and Zetner (1995).

Manganese at 20 eV,  $10^\circ$  to  $130^\circ$  (Williams *et al.*, 1978). In the ground electronic state  $3p^6 3d^5 4s^2 ^6S_{5/2}$  all five  $d$  electrons have parallel spins. DCS for transitions not changing the multiplicity (to  $a^6D$ ,  $z^6P$ ,  $y^6P$  states) are forward-peaked and the integral excitation CS are comparable with the elastic part. Angular distributions for sextet-octet and sextet-quartet excitations ( $z^8P$ ,  $a^4D$ ,  $a^4P$ ,  $z^4P$ ) are more uniform.

Copper for  $3d^{10} 4p^2 P_{1/2, 3/2}$ ,  $3d^9 4s^2 D_{5/2}$  and  $3d^9 4s^2 D_{3/2}$  states (Trajmar *et al.*, 1977) between 6 eV and 100 eV and at  $15-120^\circ$  angular range. Following Trajmar *et al.*, at 10 eV the excitation to the  $^2P$  state would amount to 30% of the TCS (summed from partial CS), while the other two excitations would contribute to merely 3%. However, as recently indicated by the experiment of Ismail and Teubner (1995), the integral CS for the  $^2P$  excitation given by Trajmar *et al.* are, due to the limited angular range of measurements, overestimated by a factor of about 4. However, as we are unaware of newer experimental elastic CS in copper, in table XI we give both the data of Trajmar *et al.* (1977) and of Ismail and Teubner (1995).

Cadmium excitations from the ground  $5^1S_0$  state to  $5^3P_1$ ,  $5^3P_2$ ,  $5^1P_1$ ,  $6^3S_1$ ,  $6^1S_0$ ,  $5^1D_2$ ,  $6^1P_1$ ,  $7^1S_0$ , ( $6^1D_2 + 7^1P_1$ ),  $8^1S_0$  and ( $7^1D_2 + 8^1P_1$ ) states were studied by Marinković *et al.* (1991) between  $0^\circ$  to  $130^\circ$  at 3.4–85 eV but no absolute values were given. The angular distributions are in good agreement with first-order distorted-wave calculations of Madison *et al.* (1991).

Bismuth DCS at 40 eV for quartet-doublet and quartet-quartet transitions from the ground  $6p^3 ^4S_{3/2}$  state to  $6p^3 ^2D_{3/2}$ ,  $6p^3 ^2D_{5/2}$ ,  $6p^3 ^2P_{1/2}$  and  $6p^2 7s ^4P_{1/2}$  states (Williams *et al.*, 1975). DCS for all these transition fall rapidly from  $0^\circ$  to  $20^\circ$  by two and a half orders of magnitude and exhibit a broad, well-like plateau between  $50^\circ$  and  $130^\circ$ . Integral CS for the transition into the  $^4P_{1/2}$  state is one order of magnitude higher than transitions in which spin-multiplicity changes.

Lead integral CS for the transition from the ground  $6p^2 ^3P_0$  state to the  $6p^2 ^3P_1$ ,  $6p^2 ^3P_2$ ,  $6p^2 ^1D_2$ , and unresolved  $6p 7s ^3P_{0,1}$  states at 40 eV amount to 0.15, 1.5, 0.05,

and  $8.4 \cdot 10^{-20} \text{ m}^2$ , respectively. DCS for transition to the  $6p^2 1S_0$  vanishes at zero scattering angle, according to a general theory of  $P$ - $S$  transitions (Goddard *et al.*, 1971). (We note a similar case experimentally documented for a symmetry inverting  $X^3\Sigma_g^- \rightarrow b^1\Sigma_g^+$  transition in molecular oxygen.).

Total (elastic + absorption) CS have been calculated at 100–5000 eV by Jain *et al.* (1994).

*Ionization.* An important contribution to systematic measurements of ionization CS for metals has been given by Freund *et al.* (1990). As for alkali metals and Hg, measurements of ionization CS have been performed for Mg, Ca, Sr, Ba, Fe, Cu, Ag, Au, Al, Ga, In, Tl, Sn, Pb, Sb, Bi (see Freund *et al.*, 1990 and references therein). Recent measurements from Belfast University for Mg (McCallion *et al.*, 1992), Cu (Bolorizadeh *et al.*, 1994), Fe (Shah *et al.*, 1993) are somewhat lower (15%) than those of Freund *et al.* (1990).

*Resonances.* High-resolution transmitted-electrons spectra in Mg, Zn, Cd (Burrow and Comer, 1975; Burrow *et al.*, 1976) revealed the formation of temporarily negative ions of the  $(ns^2 np)^2P$  configuration (Sin Fai Lam, 1981) at very low energies, of the order of 0.15–0.50 eV. Resonant states in Ca were studied by Johnston *et al.* (1989). Classification of these resonant states and comparison with theoretical predictions have been reviewed by Buckman and Clark (1994).

*Sum check* is not possible with the sparse data available for metal atoms. A sum of partial CS can be obtained at several energies for magnesium, barium and copper. Since no TCS are available, these summed values can give a suggestion about possible TCS values. Summed CS at 20 and 40 eV are given in table XI.

**Magnesium:** by summing elastic and inelastic CS of Williams and Trajmar (1978) with the ionization of Freund *et al.* (1990) one gets  $50 \cdot 10^{-20} \text{ m}^2$  (at 10 eV),  $44 \cdot 10^{-20} \text{ m}^2$  (at 20 eV),  $28 \cdot 10^{-20} \text{ m}^2$  (at 40 eV).

**Barium:** by summing elastic CS of Wang *et al.* (1994),  $6p^1P$  excitation of Chen and Gallagher (1976),  $5s5d^1D$  excitation of Jensen *et al.* (1978) and ionization of Vainshstein *et al.* (1972), we obtain  $71 \cdot 10^{-20} \text{ m}^2$  at 20 eV. Jensen *et al.* (1978) have, measured elastic and inelastic CS up to 100 eV. However, as we have stressed above, their elastic CS at 20 eV is overestimated both with respect to the re-measured values (Wang *et al.*, 1994) as well as to the theory (Fabrikant, 1980). Therefore, the summed value given in table XI at 40 eV (from Jensen *et al.*, 1978) can be overestimated.

**Copper:** by summing elastic and electron excitation measurements of Trajmar *et al.* (1977) and ionization CS of Freund *et al.* (1990), one obtains  $59 \cdot 10^{-20} \text{ m}^2$  (at 6 eV),  $129 \cdot 10^{-20} \text{ m}^2$  (at 10 eV),  $99 \cdot 10^{-20} \text{ m}^2$  (at 20 eV) and  $45 \cdot 10^{-20} \text{ m}^2$  (at 60 eV).

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#### 4. – Diatomic gases

Diatomic gases, due to their presence in Earth's atmosphere, were a preferred subject of experimental investigations of electron scattering during the sixties. Partial CS for specific processes, like rotational and vibrational excitations, molecular dissociation, electron attachment, have been studied in detail for these targets. New phenomena, like shape resonances, have been discovered.

4.1. *Molecular hydrogen* ( $H_2$ ). – Due to their importance, both theoretical as well practical, for interstellar-medium and plasma modelling (see, for example, Cacciatore *et al.*, 1990), the cross-sections for scattering on molecular hydrogen are among those most frequently measured. In spite of this, the overall agreement between the total

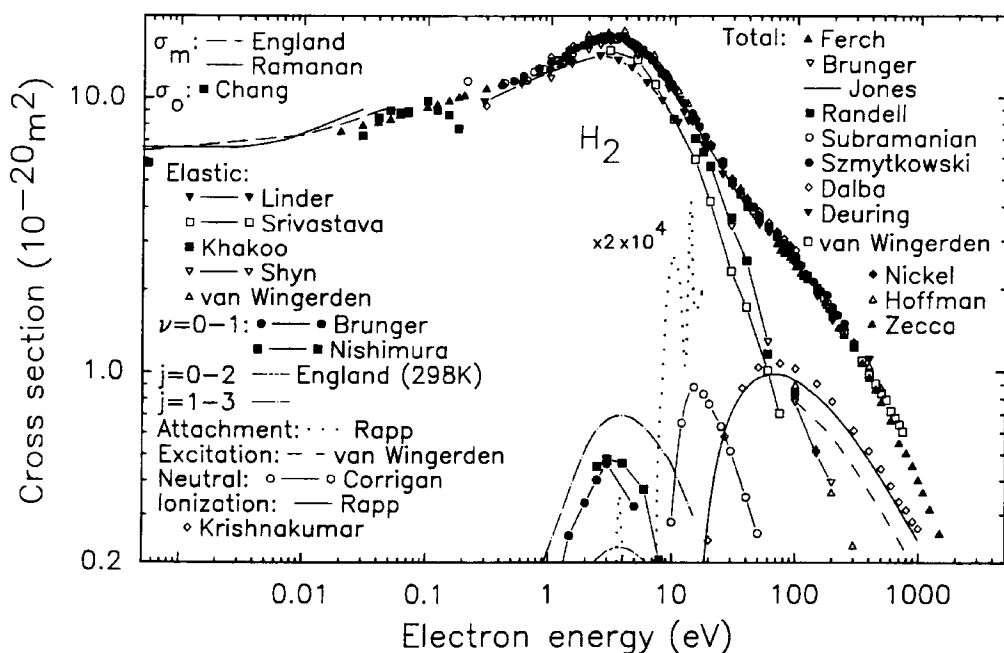


Fig. 17. – Integral cross-sections for electron scattering in  $H_2$ . *Total absolute*: Ferch *et al.* (1980); Jones (1985); Subramanian and Kumar (1989); Szymkowski *et al.* (1995); Dalba *et al.* (1980); Deuring *et al.* (1983); Nickel *et al.* (1992); Hoffman *et al.* (1982); van Wingerden *et al.* (1980); Zecca *et al.* (1995); total as the sum of elastic and vibrational excitation: Brunger *et al.* (1991); total from «backward scattering»: Randell *et al.* (1994). *Elastic* (apart from Linder and Schmidt (1971) vibrationally elastic, *i.e.* the rotational excitation included): Srivastava *et al.* (1975a); Khakoo and Trajmar (1986a); Shyn and Sharp (1981); van Wingerden *et al.* (1977). *Momentum transfer*: England *et al.* (1988); Ramanan and Freeman (1991). *Rotational excitations* averaged over the relative population of the initial levels: England *et al.* (1988). *Vibrational*: Brunger *et al.* (1991); Nishimura *et al.* (1985). *Ionization*: Rapp and Englander-Golden (1965), gross integral; Krishnakumar and Srivastava (1994), counting integral. *Electronic excitation* (summed): semiempirical data of van Wingerden *et al.* (1980). *Dissociation into neutrals*: obtained by subtracting the total ionization cross-section of Rapp and Englander-Golden (1965) from the total dissociation values of Corrigan (1965), compare also Nishimura and Danjo (1986). *Dissociative attachment*: Rapp *et al.* (1965). *Zero-energy cross-section*: Chang (1981) modified-effective-range analysis of experiments.

and partial (elastic and ionization, specifically) CS cannot be considered satisfactory. Extensive reviews and tabulations of  $H_2$  total and partial CS have been performed among others by van Wingerden *et al.* (1980), Trajmar *et al.* (1983), Shimamura (1989) and Tawara *et al.* (1990). Integral CS for  $H_2$  from selected measurements are presented in fig. 17.

*Total cross-sections.* A set of reliable TCS can be chosen between 0.02 eV and 1000 eV. At the very-low-energy limit the time-of-flight measurements of Ferch *et al.* (1980) merge well with momentum transfer CS of Ramanan and Freeman (1991) and England *et al.* (1988). The TCS from a magnetically-guided-beam experiment which uses synchrotron radiation as an electron source (Randell *et al.*, 1994) are somewhat scattered with respect to the data of Ferch *et al.* (see fig. 17).

Between 1 and 10 eV the absolute measurements of Jones (1985) agree well with those of Subramanian and Kumar (1989) and of Szmytkowski *et al.* (1995) while the summed (elastic plus vibrational) CS of Brunger *et al.* (1991) are somewhat lower. Up to 400 eV the data of Nickel *et al.* (1992), van Wingerden *et al.* (1980), Zecca *et al.* (1995), and Hoffman *et al.* (1982) agree within 4%, leaving slightly (less than 5%) beneath the measurements of Deuring *et al.* (1983). By comparing data from different groups, it is possible to point out that TCS become overestimated at the high-energy limits of each apparatus (Dalba *et al.* near 100 eV, Szmytkowski *et al.* close to 200 eV, Deuring *et al.* 400 eV, Hoffman *et al.* 500 eV and van Wingerden *et al.* 750 eV). It is difficult to make an assessment about the reason of this recurrent effect, but such problems as vacuum impurities are not to be excluded. On the other hand the data of Zecca *et al.* (1995) above 1000 eV are probably underestimated, due to inelastic scattering into small angles, for which the quoted apparatus does not perform a complete screening. In the case of  $H_2$  this error can be much higher than for other targets: experimental studies at 25 keV (Ulsh *et al.*, 1974) as well as the theory (Koios *et al.*, 1982) indicate that the small-angle (less than  $1^\circ$ ) inelastic cross-section is higher than the elastic counterpart by a factor larger than 5. This peculiarity can explain the high sensitivity of the measured  $H_2$  TCS to the apparatus angular resolution.

*Elastic cross-sections* from different laboratories form a somewhat confused set of data; the main reason for this may reside in the difference of the normalization procedures. Figure 18 shows a larger set of elastic CS than the one presented in fig. 17: a selected set of total cross-sections is also plotted to allow a comparison. Please note that the energy scale in fig. 18 spans a smaller range than the standard one used in this paper. The data of Linder and Schmidt (1971) between 0.3 eV and 3 eV agree well with the TCS of Ferch *et al.* (1980) and with those of Brunger *et al.* (1991) but are somewhat lower than other sets of data at higher energies. The data of Furst *et al.* (1984) at 4 eV agree well with the data of Srivastava *et al.* (1975a) as renormalized by Trajmar *et al.* (1983) and with the measurements repeated in the same laboratory (Khakoo and Trajmar, 1986a) but both exceed the TCS at their low- and high-energy limits. A similar discrepancy regards the low-energy limits of measurements of Shyn and Sharp (1981) and of Nishimura *et al.* (1985). Between 20 and 200 eV the scatter between the different data sets is as high as 20% (see fig. 18). Quite serious discrepancies also exist with recent optical-model calculations (Jain and Baluja, 1992), see fig. 18.

At high energies, relative DCS have been obtained between  $3^\circ$  and  $130^\circ$ , 100–1000 eV by Fink *et al.* (1975) and absolute ones between  $5^\circ$  and  $50^\circ$  by van



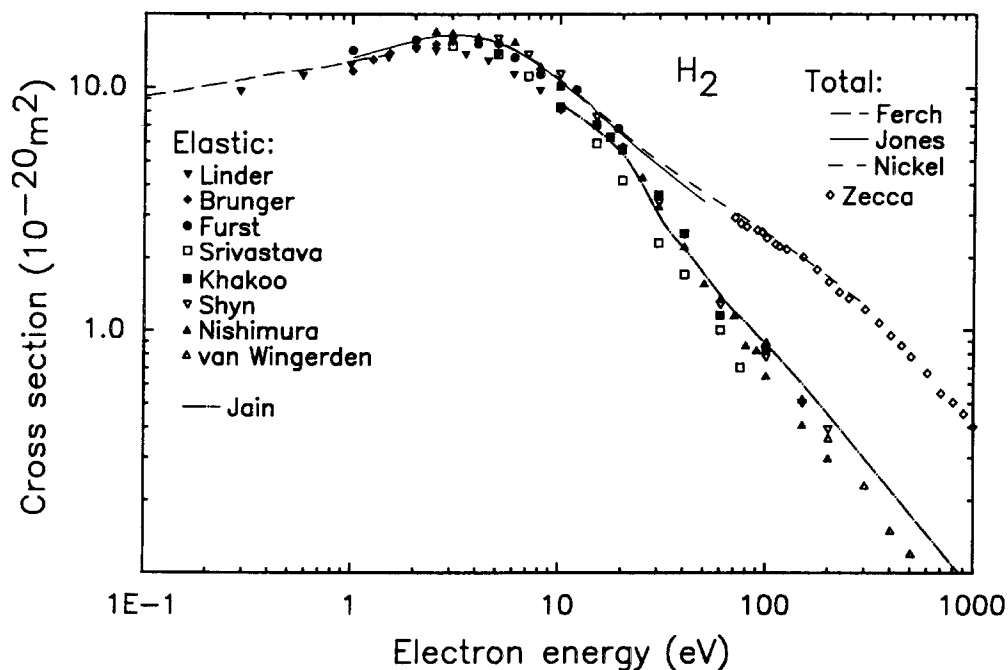


Fig. 18. – Integral elastic cross-section for electron scattering in  $H_2$ . Please note that the energy axis spans from 0.1 to 1000 eV. *Pure elastic*: Linder and Schmidt (1971). *Vibrationally elastic* (include rotational excitation): Brunger *et al.* (1991) normalized to He; Srivastava *et al.* (1975a) normalized to old He standard (see Trajmar *et al.*, 1983 for renormalization); Khakoo and Trajmar (1986a) normalized to their own elastic CS in He and Ne; Shyn and Sharp (1981) normalized at 10 eV to theoretical CS in He; Nishimura *et al.* (1985) normalized to He; van Wingerden *et al.* (1977) normalized to their own  $N_2$  elastic CS at 500 eV. *Electronically elastic*: Furst *et al.* (1984) normalized to their own data in He; Jain and Baluja (1992) optical model. *Total* for reference: Ferch *et al.* (1980); Jones (1985); Nickel *et al.* (1992); Zecca *et al.* (1995).

Wingerden *et al.* (1977) at 100–2000 eV. Similarly as in He (compare fig. 2), the zero-angle differential cross-section in  $H_2$  between 100 eV and 1000 eV diminishes with rising energy (Fink *et al.*, 1975), in contrast with the Born approximation. In the same energy range the integral elastic CS (van Wingerden *et al.*, 1977) falls more rapidly than  $E^{-1}$ .

*Swarm experiments.* The hydrogen molecule, starting from early analysis of drift coefficients (Pack and Phelps, 1961), became a cross-check between swarm and beam experiments (Morrison *et al.*, 1987; Crompton and Morisson, 1993). Molecular hydrogen is also frequently used as an admixture while measuring momentum transfer CS in other gases (noble, for instance). Thanks to the relatively high thresholds for rotational and vibrational excitations, the swarm-derived partial CS have narrower confidence limits than for other molecules. In spite of this, some discrepancies persist between the two types of experiments, in particular on vibrational-excitation CS (see Buckman *et al.*, 1990). A good agreement between

recently obtained momentum transfer CS (England *et al.*, 1988; Ramanan and Freeman, 1991) as well a merging of these CS with TCS from beam experiments (see fig. 17) have to be acknowledged. At 0.1 eV the momentum transfer CS exceeds the total value: this results from the particular, backward-dominated DCS in  $H_2$  at low energies (see Linder and Schmidt, 1971; Furst *et al.*, 1984).

*Scattering length and potentials.* Chang (1981) proposed a modified-effective-range theory for diatomic molecules. A scattering length of  $1.27a_0$  (zero-energy TCS of  $5.75 \cdot 10^{-20} \text{ m}^2$ ) has been obtained by him from Ferch *et al.*'s (1980) total and Crompton *et al.*'s (1969) momentum transfer CS.

It has been recently indicated (Karwasz *et al.*, 1995) that elastic DCS of Shyn and Sharp's can be well approximated above 10 eV by Born's formula for scattering on a Yukawa potential with  $Z_{\text{eff}} = 1.23$  and a range of  $a = 1.3a_0$ . At high energies (25 keV) the zero-angle elastic DCS (Bonham and Fink, 1986; Zhang *et al.*, 1991) amounts to  $(1.37a_0)^2/\text{sr}$ .

*Vibrational excitation.* The vibrational-excitation CS measured in beam experiments (Ehrhardt *et al.*, 1968; Linder and Schmidt, 1971; Nishimura *et al.*, 1985; Brunger *et al.*, 1991) are in good mutual agreement and agree also with the theory (Buckman *et al.*, 1990) in the near-to-threshold region. They are somewhat higher (30% at 1.0 eV) than those derived from swarm experiments (England *et al.*, 1988).

A wide maximum in the integral vibrational CS occurs at about 3.0 eV, in correspondence to the TCS maximum. The existence of a broad  $^2\Sigma_u^+$  shape resonance in this region has been documented in early experiments (Schulz and Asundi, 1967; Ehrhardt *et al.*, 1968). However, in its maximum, the vibrational excitation (Nishimura *et al.*, 1985; Brunger *et al.*, 1991) contributes 3% only to the TCS.

In the region of the  $^2\Sigma_u^+$  shape resonance the CS for excitation of vibrational levels with higher quantum numbers  $\nu$  diminish with rising  $\nu$  much more rapidly for  $H_2$  (Wong and Schulz, 1974; Hall and Andrić, 1984; Allan, 1985) than for  $N_2$  and CO at their resonance energies (see fig. 19). As noticed by Wong and Schulz (1974) the angular distribution of the vibrational excitation at 4.5 eV exhibits a  $p$ -wave behaviour. Due to the short lifetime of the collision interaction, no structures (like observed in  $N_2$ , compare fig. 22) were visible in the energy dependencies for the excitation of low-order vibrational levels. A structure appears for excitations of  $\nu = 4$  and higher modes (Allan, 1985) due to an effect of «vibration induced narrowing of the resonance» (Mündel *et al.*, 1985).

High vibronic levels are effectively excited in electronic transitions (see, *e.g.*, the experiment of Chan *et al.*, 1992 and the theory of Kołos *et al.*, 1982). On the other hand, separate processes, like the dissociative attachment, important for plasma modelling, strongly depend on the initial vibrational state of the  $H_2$  molecule (see, *e.g.*, Cacciatore and Capitelli, 1981; Bardsley and Wadehra, 1979).

*Rotational excitations.* Rotational-excitation energy transfer in  $H_2$  reveals to be more effective than the vibrational one. The swarm-derived CS (England *et al.*, 1988; Schmidt *et al.*, 1994) are in good agreement with the beam measurements performed by Linder and Schmidt (1971) up to 10 eV and by Wong and Schulz (1974) at 4.5 eV and Jung *et al.* (1987) at 0.2 eV and 0.6 eV. The rotational-excitation CS reaches a

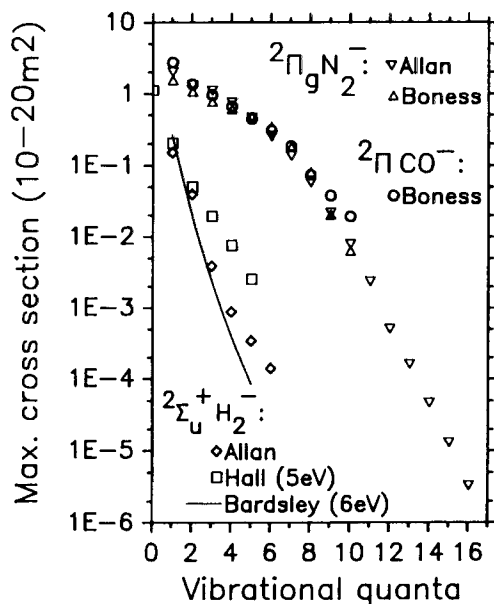


Fig. 19. – Magnitude of the first peak in the vibrational excitation to a  $\nu$  quantum state in diatomic molecules in the region of shape resonances.  $2\Sigma_u^+ H_2$ : squares and full line, Allan (1985) at 4 eV above relative thresholds for the  $\nu$  excitation, normalized to Ehrhardt and Willman (1967); Hall and Andrić (1984) at fixed 5 eV collision energy; theory of Bardsley and Wadehra (1979) at fixed 6 eV energy.  $2\Pi_g N_2$ : triangles, Allan (1985, see  $N_2$ ) normalized in this work to absolute  $\nu = 0 \rightarrow 1$  value from Brennan *et al.* (1992); Ehrhardt and Wilmann (1967) for low  $\nu$  and Boness and Schulz (1973) for high  $\nu$ , from the latter.  $2\Pi CO$ : full circles, Ehrhardt *et al.* (1968) and Boness and Schulz (1973) from the latter. References for CO and  $N_2$  are to be found in the respective subsections.

maximum at about 3.5 eV. In its maximum the CS for parahydrogen (excitation  $J = 0 \rightarrow 2$ ) exceeds that for orthohydrogen ( $J = 1 \rightarrow 3$ ) by a factor of 5/3 (England *et al.*, 1988). Averaging over the room temperature population (see Schmidt *et al.*, 1994), the contribution to the TCS coming from excitation of different rotational levels amounts to about 6% at 3.5 eV. At 40 eV the pure rotational excitation ( $J = 1 \rightarrow 3$ ) (Srivastava *et al.*, 1975b) still amounts to 4% of the TCS.

**Electronic excitation.** Overall electronic-excitation CS has been evaluated from early optical measurements by van Wingerden (1980). Energy loss studies were reviewed by Trajmar *et al.* (1983). More recently electronic excitation for dipole-allowed  $B^1\Sigma_u^+$ ,  $C^1\Pi_u$  and forbidden  $a^3\Sigma_g^+$ ,  $c^3\Pi_u$  states were measured by Khakoo and Trajmar (1986b) and excitation of the  $b^3\Sigma_u^+$  continuum (leading to dissociation of the molecule) by Hall and Andrić (1984), Mason and Newell (1986b), Nishimura and Danjo (1986), Khakoo and Trajmar (1986b) and Khakoo and Segura (1994). These data are in pretty good agreement with optical-emission measurements (Shemansky *et al.*, 1985; Ajello *et al.*, 1985; Ajello and Shemansky, 1993) as well as with distorted-wave calculations (Fliflet and McKoy, 1980; Mu-Tao *et al.*, 1982; Rescigno *et al.*, 1976), see fig. 20. One notices that the maximum cross-section values

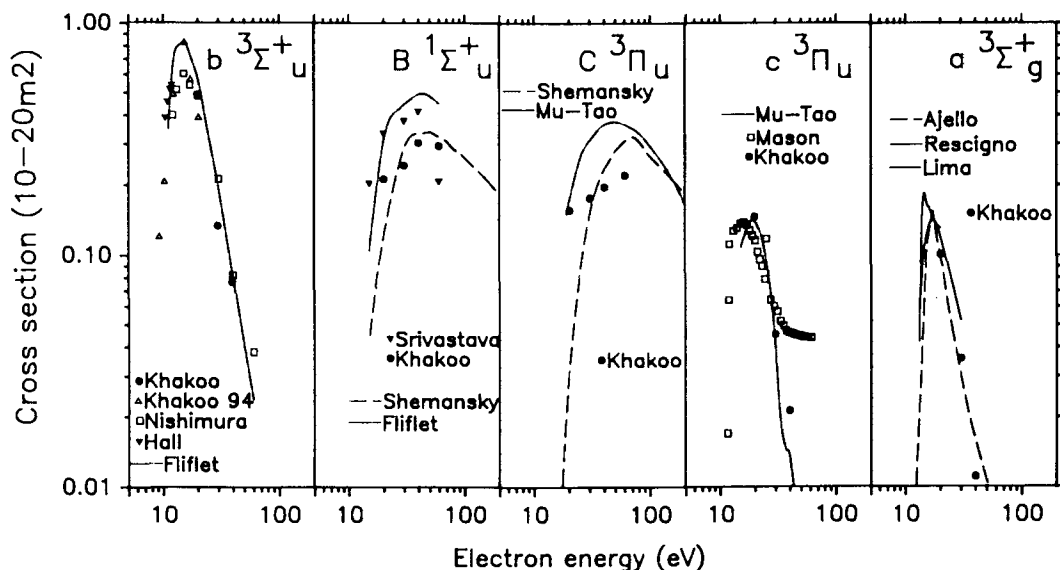


Fig. 20. – Summary of the electronic excitation cross-sections for  $H_2$ . *Experiment*: Khakoo and Trajmar (1986b) for  $B$ ,  $C$ ,  $c$ ,  $a$  states; Srivastava and Jensen (1977) renormalized to elastic cross-sections of Khakoo and Trajmar (1986a) for  $B$ -state; Khakoo *et al.* (1987), Khakoo and Segura (1994), Nishimura and Danjo (1986), Hall and Andrić (1984) for  $b$ -state; Mason and Newell (1986b) from metastables yield for  $c$ -state. *Optical measurements*: Shemansky *et al.* (1985); Ajello *et al.* (1985, 1993). *Theory*: distorted-wave calculations of Fliflet and McKoy (1980), Rescigno *et al.* (1976) and Mu-Tao *et al.* (1982); Schwinger-variational calculation of Lima *et al.* (1988).

for optically allowed transitions are about a factor of 2 higher than those for forbidden transitions. However, the two classes exhibit different energy dependencies, the optically forbidden CS falling rapidly with energy above about 20 eV. (A tail above 30 eV in the Mason and Newell's (1986b) measurements might be misleading, as they measured the metastables yield.)

At 100 eV, where the excitations into dipole-forbidden states are not important, the sum of the excitations from optical measurements (Shemansky *et al.*, 1985) amounts to  $0.79 \cdot 10^{-20} \text{ m}^2$ , in excellent agreement with the value of  $0.78 \cdot 10^{-20} \text{ m}^2$  used in the semiempirical analysis of van Wingerden *et al.* (1980). Optically allowed states other than those listed above, *i.e.*  $B' {}^1\Sigma_u$ ,  $B'' {}^1\Sigma_u^+$ ,  $D {}^1\Pi_u$  and  $D' {}^1\Pi_u$ , contribute at 100 eV to about 20% of the overall excitation CS (Mohlmann and de Heer, 1976; Shemansky *et al.*, 1985). Above 100 eV the electronic excitation that leads to emission in molecular bands (without molecular dissociation) exceeds the elastic CS (see van Wingerden *et al.*, 1980). This is a peculiar feature of the  $H_2$  partitioning which finds no analogy with other reported molecules.

*Ionization cross-section.* Integral gross ionization CS as measured by Rapp and Englander-Golden (1965) are in good agreement with the recent measurements of integral counting CS of Krishnakumar and Srivastava (1994) and somewhat higher than the gross integral measurements of Adamczyk *et al.* (1966). The measurements of gross integral ionization at high (0.6–20 keV) energies (Schram *et al.*, 1965) are at

1000 eV 20% lower than the data of Rapp and Englander-Golden (1965) and Krishnakumar and Srivastava (1994). As the measurements of Schram *et al.* (1965) have been already superseded in the semiempirical analysis of van Wingerden *et al.* (1980) we do not include them into the figure. Total and differential  $e^-$ -H<sub>2</sub> ionization CS have been successfully approximated with analytical formulae by Rudd (1991).

In several works (Adameczyk *et al.*, 1966; Edwards *et al.*, 1988; Kossmann *et al.* 1990; Jacobsen *et al.*, 1995) the ratio between the dissociative ( $H_2 + e^- \rightarrow 2H^+ + 3e^-$  plus  $H_2 + e^- \rightarrow H + H^+ + 2e^-$ ) and the non-dissociative ( $H_2 + e^- \rightarrow H_2^+ + 2e^-$ ) ionizations has been examined. As shown by Krishnakumar and Srivastava (1994), see also Van Zyl and Stephen (1994), this ratio reaches a maximum of about 11% at about 110 eV and decreases to about 6% at 1000 eV. It has been noticed that above its maximum the dissociative ionization ratio for electron collisions (Krishnakumar and Srivastava, 1994) merges with the analogous ratio obtained for antiprotons (Hvelplund *et al.*, 1994) and is approximately twice the ratio obtained for proton scattering (Edwards *et al.*, 1988).

*Dissociation into neutrals* was studied by Corrigan (1965) by a surface adsorption technique. The cross-section derived by him include both the dissociation into neutrals and the ionization. By subtracting the ionization part, one gets a pure dissociation-into-neutral CS, in good agreement with the CS for excitation of the autodissociating  $b^3\Sigma_u^+$  state (see the above subsection for references). An indirect evaluation of the dissociation comes also from measurement of the optical emission of the H fragments due to de-excitation of the  $2P$  state (Lyman- $\alpha$ ). An average value of  $7.5 \cdot 10^{-22} \text{ m}^2$  at 100 eV can be obtained from the recent measurements (Van Zyl *et al.*, 1985; Shemansky *et al.*, 1985; Woolsey *et al.*, 1986).

*Dissociative attachment.* Negative-ion formation cross-section does never exceed  $10^{-4}$  of the total one. A peak value of  $0.18 \cdot 10^{-24} \text{ m}^2$  at 3.7 eV (Schulz and Asundi, 1967) is attributed to a shape resonance. A strong isotope effect diminishes the probability of negative-ions production in D<sub>2</sub> by 500 times (Schulz and Asundi, 1967). Two other peaks, a wide one centred at 10 eV and a narrow one of  $2.05 \cdot 10^{-24} \text{ m}^2$  at 14 eV, were observed in the region of core-excited resonances (Rapp *et al.*, 1965; Tronc *et al.*, 1979).

*Resonances.* The maxima in the total and vibrational-excitation CS at about 3.5 eV are commonly attributed to a short-lived  $^2\Sigma_u^+$  shape resonance (see, *e.g.*, Geritschke and Domcke, 1993). Resonances due to several electronically excited parent states in the region of 11–15 eV, observed in different decay channels (Weingartshofer *et al.*, 1970, 1975; Elston *et al.*, 1974; Mason and Newell, 1986a; Furlong and Newell, 1995), have been extensively reviewed by Shimamura (1989) and Tawara *et al.* (1990). These resonances are barely visible in total cross-sections (see Dalba *et al.*, 1980) but significantly influence the negative-ions yield (Tronc *et al.*, 1979). Comparisons with D<sub>2</sub> resonances have been performed by Weingartshofer and Eyb (1975) and Furlong and Newell (1995).

*Sum check.* A sum check of partial cross-sections at selected energies is shown in table XII. At low energies the vibrationally elastic and rovibrational excitations are summed. At high energies the elastic CS is summed with the total ionization and with

TABLE XII. – *Integral cross-sections for electron scattering on molecular hydrogen (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Rotational <sub>E</sub>	Vibra- tional <sub>N</sub>	Electro- nic sum	b-state excit. <sub>ND</sub>	Neutral dissoc. <sub>C</sub>	Ioni- zation <sub>R</sub>	Sum	Total
1.0	12.3 <sub>L</sub>	0.30						12.6	12.8 <sub>F</sub>
2.0	14.6 <sub>B</sub>	(0.97)	0.33 <sub>B</sub>					14.9	15.6 <sub>J</sub>
3.0	15.4 <sub>B</sub>	(1.05)	0.48					15.9	16.5 <sub>J</sub>
4.0	15.1 <sub>F</sub>	(1.09)	0.46					15.6	16.1 <sub>J</sub>
5.0	13.9 <sub>B</sub>	(1.05)	0.41					14.3	15.2 <sub>J</sub>
6.0	13.3 <sub>F</sub>	(0.98)	0.37					13.6	14.2 <sub>J</sub>
10	10.2 <sub>F</sub>	(0.72)	0.15			0.28		10.6	10.6 <sub>J</sub>
15	7.04 <sub>K</sub>	(0.49)	0.06	—	(0.60)	0.88		7.98	8.10 <sub>NI</sub> *
20	5.55 <sub>K</sub>		0.03	0.62 <sub>KH</sub>	0.48	(0.76)	0.28	6.96	6.54 <sub>NI</sub>
30	3.63 <sub>K</sub>		0.02	0.50 <sub>KH</sub>	0.21	(0.51)	0.69	5.05	4.98 <sub>NI</sub>
40	2.52 <sub>K</sub>			0.53 <sub>KH</sub>	0.08	(0.35)	0.87	4.00	4.20 <sub>NI</sub>
60	1.27 <sub>SH</sub>			0.53 <sub>KH</sub> 0.70 <sub>W</sub>	0.04	(0.17)	0.97	2.81 2.98	3.34 <sub>NI</sub>
100	0.83 <sub>K</sub>			0.78 <sub>W</sub>	0.01 <sub>KT</sub>	(0.09)	0.92	2.54	2.53 <sub>NI</sub>
200	0.36 <sub>W</sub>			0.58 <sub>W</sub>			0.72	1.66	1.66 <sub>NI</sub>
500	0.12 <sub>W</sub>			0.31 <sub>W</sub>			0.41	0.84	0.83 <sub>W</sub>
1000	0.05 <sub>W</sub>			0.18 <sub>W</sub>			0.24	0.47	0.40 <sub>Z</sub>

( ) – Not used for summation.

\* – Interpolated value.

B – Brunger *et al.* (1991).

C – Corrigan (1965) total dissociation minus ionization of Rapp and Englander-Golden (1965).

E – England *et al.* (1988), averaged over relative populations at 298 K.

J – Jones (1985).

K – Khakoo and Trajmar (1986a).

KH – Khakoo and Trajmar (1986b) sum of the excitation into *B*, *C*, *c* and *a* electronic states.

KT – Khakoo *et al.* (1987).

L – Linder and Schmidt (1971).

N – Nishimura *et al.* (1985).

ND – Nishimura and Danjo (1986).

NI – Nickel *et al.* (1992).

R – Rapp and Englander-Golden (1965).

SH – Shyn and Sharp (1981).

W – van Wingerden *et al.* (1980), semiempirical.

Z – Zecca *et al.* (1995).

the electronic excitation, as measured by Khakoo and Trajmar (1986b). As these measurements do not include all the electronic states, the summed values are somewhat lower than the total ones.

The check indicates in particular that it is not possible to recommend a single set of experimental elastic CS in the entire energy range considered in the present paper. At 1 eV the elastic CS of Linder and Schmidt (1971) sums up with the rotational excitation to the total value within 2%. Between 2 eV and 5 eV the sum of rotationally elastic and rovibrational CS of Brunger *et al.* (1991) is only slightly (less than 7%) smaller than the TCS. Between 6 eV and 10 eV the most reliable elastic data are possibly those of Furst *et al.* (1984), while between 15 and 40 eV those of Khakoo and Trajmar (1986a) are in better coherence with other integral CS. It is worth noting that the elastic data of Srivastava *et al.* (1975a) from 3 eV to 75 eV, if multiplied by a constant factor of 1.23, as has been done by van Wingerden *et al.* (1980), sum up pretty well with solely electronic excitation and ionization to the total values. However, more measurements of elastic CS either absolute, or with well-established normalization procedures would be desirable.

*Particular features.* In molecular hydrogen the inelastic processes are dominating the scattering just above 50 eV. This also happens in He (see subsect. 2'1) but is not observed in other molecular gases. The elastic contribution to the TCS diminishes from 1/3 at 100 eV to about 1/10 at 1000 eV. On the other hand, the electronic excitation amounts to almost 40% of the total one at 1000 eV. Absorption effects (Fink *et al.*, 1975; Karwasz *et al.*, 1995) influence visibly the elastic CS between 50 eV and 1000 eV.

Merging of total positron and electron scattering CS was observed at 50 eV, much below the expected energy for the Born approximation to be valid (Hoffman *et al.*, 1982; Deuring *et al.*, 1983).

The present analysis indicates that further measurements of TCS with a good angular resolution and a good energy discrimination are needed for H<sub>2</sub> at high energies. Establishing of an elastic CS standard from a few eV up to a few keV would be desirable both from the theoretical as well the experimental point of view.

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4.2. *Molecular nitrogen* ( $N_2$ ). – The mutual agreement between cross-sections measured by different laboratories for specific processes in electron molecular nitrogen scattering is one of the best. The discovery of a structure in the vibrational excitation (Schulz, 1962) and the successive observation of a vibrational-like structure above 2 eV in transmission experiments (Golden and Nakano, 1966; Boness and Hasted, 1966) have triggered experimental research in the sixties and early seventies. Total and partial CS for electron and photon scattering on  $N_2$  have been reviewed extensively; among others by Itikawa *et al.* (1986) and Shimamura (1989). The integral CS for molecular nitrogen are summarized in fig. 21.

*Total cross-sections* have been measured probably in all the laboratories active in the field, covering by beam experiments an energy range from 0.05 eV to 5000 eV. At energies below 1 eV, three conference reports exist. The time-of-flight results of Ferch *et al.* (1991) are somewhat (10%) higher than the data of Buckman (1989)

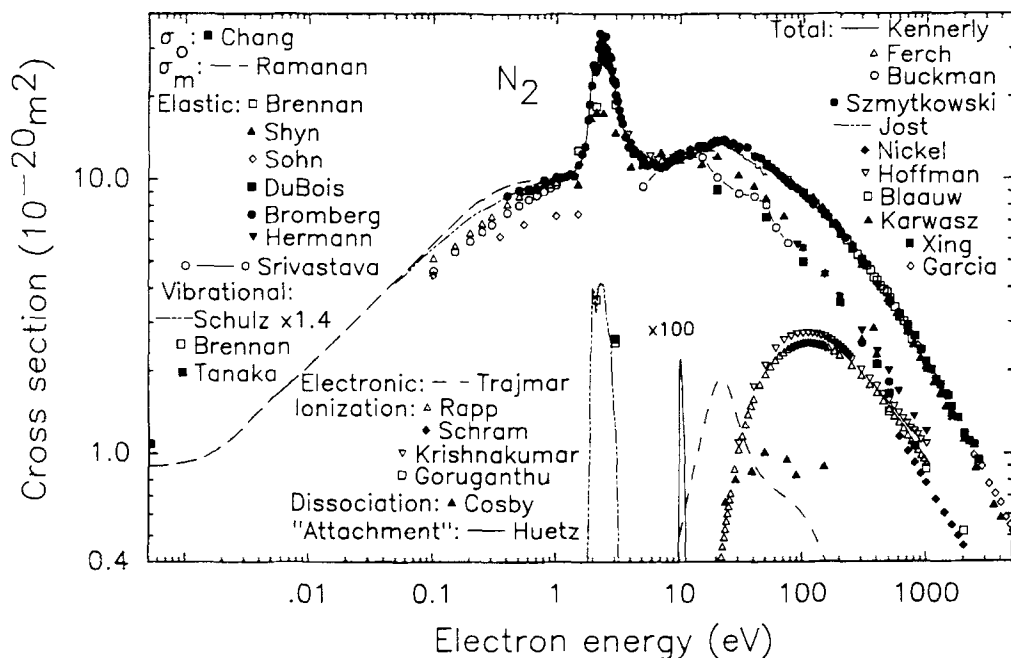


Fig. 21. – Integral cross-sections for electron scattering on  $N_2$ . *Total*: Jost *et al.* (1983) shown only up to 1 eV; Kennerly (1980); Ferch *et al.* (1991); Buckman (1989); Szmytkowski *et al.* (1995); Nickel *et al.* (1992); Hoffman *et al.* (1982); Blaauw *et al.* (1980) is shown only above 100 eV; Karwasz *et al.* (1993); Xing *et al.* (1994); García *et al.* (1988); Sueoka and Mori (1984) and Nishimura and Yano (1988) not presented for clarity. *Elastic*: Sohn *et al.* (1986); Brennan *et al.* (1992); Shyn and Carignan (1980); Srivastava *et al.* (1976); DuBois and Rudd (1976); Bromberg (1970); Herrmann *et al.* (1976) normalized to Shyn et Carignan at 100 eV; intermediate-energy elastic CS of Finn and Doering (1975) and low-energy elastic CS of Shi (1993) not presented for clarity. *Momentum transfer*: Ramanan and Freeman (1990). *Zero-energy cross-section*: Chang (1983), modified effective range extrapolation. *Vibrational* (rotationally summed): absolute sum of  $\nu = 0 \rightarrow 1$  to  $\nu = 0 \rightarrow 3$  from Brennan *et al.* (1992); sum of  $\nu = 0 \rightarrow 1$  to  $\nu = 0 \rightarrow 8$  from Schulz (1964) normalized (this work) by a factor 1.4 at 2.1 eV to the absolute value of Brennan *et al.* (1992) for  $\nu = 0 \rightarrow 1$  excitation;  $\nu = 0 \rightarrow 1$  excitation of Tanaka *et al.* (1981) multiplied by a factor of 2 (see table captions). *Electronic excitation*: summed from Trajmar *et al.* (1983) and extrapolated according to the Born-Bethe theory at higher energies. *Ionization*: Rapp and Englander-Golden (1965); Krishnakumar and Srivastava (1990); Goruganthu *et al.* (1987); Schram *et al.* (1965). *Dissociation into neutrals*: Cosby (1993). *Dissociative attachment*: differential cross-sections at  $90^\circ$  for production of  $N^-$  metastable ions, Huetz *et al.* (1980b) normalized to the total value of Spence and Burrow (1979).

obtained with a similar set-up. The measurements of Jost *et al.* (1983) are 10% higher than those of Ferch; however Jost *et al.* applied a «zero angular resolution» correction which raises the original experimental data. No comparison is possible with absolute «backward scattering» cross-sections measured by Randell *et al.* (1994) between 0.01 eV and 0.175 eV although these show to be underestimated.

The  $N_2$  TCS is characterized by the large resonant structure between 1.8 eV and 3.4 eV. This is attributed to the formation of a temporary negative ion with a  $^2\Pi_g$  configuration. The vibrational levels associated with this configuration are easily

resolved with a moderate-energy-resolution apparatus. The most detailed measurements of the vibrational-like structure in the TCS have been obtained in a time-of-flight experiment by Kennerly (1980) (see fig.22). However, at higher energies, the data of Kennerly are systematically (3% to 5%) lower than other sets of data (Blaauw *et al.*, 1977, 1980; Hoffman *et al.*, 1982; Nishimura and Yano, 1988; Nickel *et al.*, 1992; Szmytkowski *et al.*, 1995).

The normalized data of Sueoka and Mori (1984), not presented in fig. 21 for clarity reasons, deviate downwards from the set of other data starting above 100 eV. Between 1000 eV and 2000 eV the results of Xing *et al.* (1994), performed on an apparatus with a retarding field analyser, are 4–5% higher than the measurements without such an analyser published by Dalba *et al.* (1980, normalized by Karwasz *et al.*, 1993). Some difference (+ 12%) has also to be noticed at 4000 eV between the data of García *et al.* (1990) and those of Karwasz *et al.* (1993).

*Swarm measurements.* Recent measurements (Ramanan and Freeman, 1990) of electron mobility at temperatures above 66 K agree well with earlier swarm experiments (Lowke, 1963; Pack and Phelps, 1961). Derived momentum-transfer CS merge well with the TCS from beam experiments if truncated at 0.1 eV (see fig. 21).

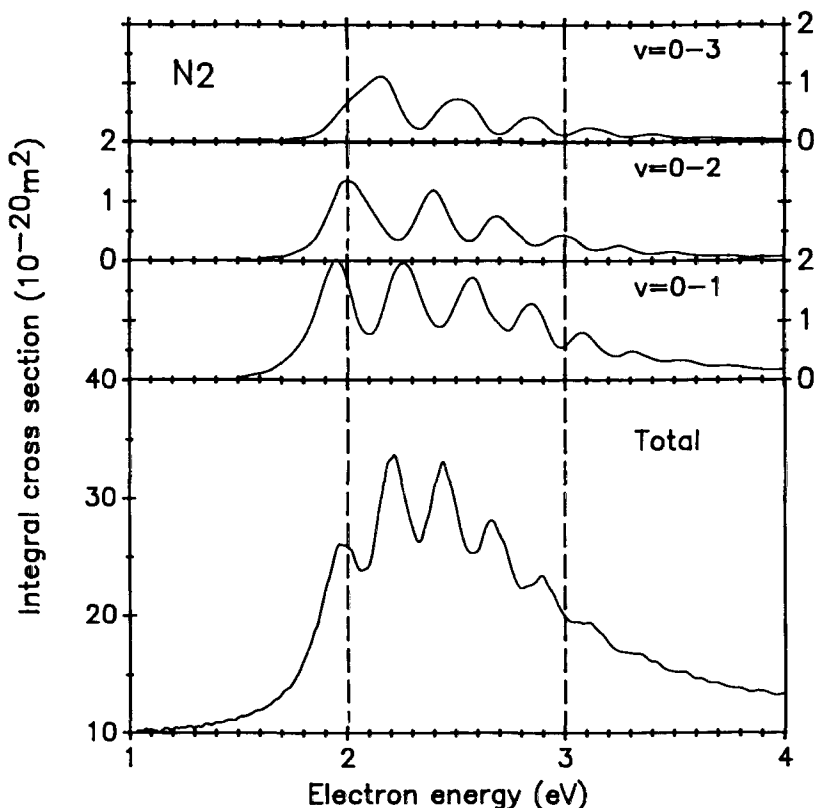


Fig. 22. - Total and vibrational excitation ( $\nu = 0 \rightarrow 1$ ,  $\nu = 0 \rightarrow 2$ ,  $\nu = 0 \rightarrow 3$ ) integral cross-sections for  $e^- + N_2$  scattering in the region of the  $^2\Pi_g$  shape resonance. *Total*: Kennerly (1980) absolute. *Vibrational*: relative measurements of Allan (1985); normalized at 2.1 eV to the absolute  $\nu = 0 \rightarrow 1$  value of Brennan (1992).

As stated by Ramanan and Freeman, «experimental data presently available do not rule out the existence of a Ramsauer-Townsend minimum at an electron energy of 0.4 meV or lower». Following this hypothesis, the zero-energy TCS would tend to about  $6 \cdot 10^{-20} \text{ m}^2$ . However, a semiempirical analysis (Chang, 1981) of swarm data (Engelhardt *et al.*, 1964, not reported in fig. 21) yielded a zero-energy  $\sigma_0 = 1.08 \cdot 10^{-20} \text{ m}^2$ , in rough agreement with the non-Ramsauer-like curve of Ramanan and Freeman (see fig. 21). A lower ( $0.68 \cdot 10^{-20} \text{ m}^2$ ) zero-energy CS has been derived from measurements of the pressure shift in the molecular absorption (Asaf *et al.*, 1992); this value is not marked in fig. 21.

Experiments with Rydberg atoms quenching (see reviews of Beigman and Lebedev, 1995 and Dunning, 1995) proved to be a successful tool in the determination of very-low-energy TCS (see for example  $\text{SF}_6$ ). However, in the case of  $\text{N}_2$  (Petitjean *et al.*, 1984) only a general relation between  $\text{N}_2$  and CO cross-sections, without defined energy dependencies, has been obtained.

*Elastic cross-section.* A generally good agreement exists between different sets of data. Jung *et al.* (1982) have measured pure elastic (*i.e.* without contributions from the rotational excitation) CS. At 2.47 eV a value of  $19.1 \cdot 10^{-20} \text{ m}^2$  has been obtained. Other «elastic» data in the literature include the rotational excitation.

Elastic CS of Sohn *et al.* (1986) agree well with the total values at 0.1 eV but are 30% lower at 1.5 eV. The authors do not state if the rotational excitation has been subtracted in their experiment. Rotationally summed vibrationally elastic CS of Brennan *et al.* (1992) and of Shi *et al.* (1993) agree at 1.5 eV with the total value (Kennerly, 1980; Szymkowski *et al.*, 1995). Also at higher energies (2 eV and 5 eV) the elastic and vibrational data of Brennan *et al.* (1992) add up, within experimental errors, to the total values.

Between 1.9 and 3.0 eV a 50% enhancement of the elastic CS with respect to out-of-resonance values has been observed in different measurements (Shyn and Carignan, 1980; Brennan *et al.*, 1992). Energy spectra of elastically scattered electrons (Shyn and Carignan, 1980) exhibit a vibrational-like structure, similar to the one seen in the TCS. Angular distributions vary rapidly with energy across the resonance (see fig. 23), from a symmetric shape with a maximum at  $90^\circ$  at 1.5 eV to a well-like form just above the resonance energy. Existing discrepancies between different data should be attributed to energy-calibration and normalization errors.

Two weaker maxima were observed in the integral elastic CS at higher energies (Shyn and Carignan, 1980). The first one at about 8 eV extends 7% above the «background» CS. In the TCS measurements of Hoffman *et al.* (1982) it remains just outside the statistical uncertainty and is visible as a shoulder in TCS of Kennerly (1980). A second maximum at about 20 eV has been seen both in the total as well as in the integral vibrational CS (Tanaka *et al.*, 1981).

The intermediate-energy range has been covered by numerous experiments and the consistency is better than in the case of  $\text{H}_2$ . At 20 eV the low-angle differential cross-sections of DuBois and Rudd (1976) and of Finn and Doering (1975) are lower than those of Shyn and Carignan (1980), Srivastava *et al.* (1976) and Nickel *et al.* (1988). All these data, including those of Jansen *et al.* (1976) but excluding those of Finn and Doering, are again in agreement at 100 eV. At high energies only DCS of Jansen *et al.* (1976), Bromberg (1970) and DuBois and Rudd (1976) have been obtained in absolute measurements. Renormalization of earlier results (Kambara and

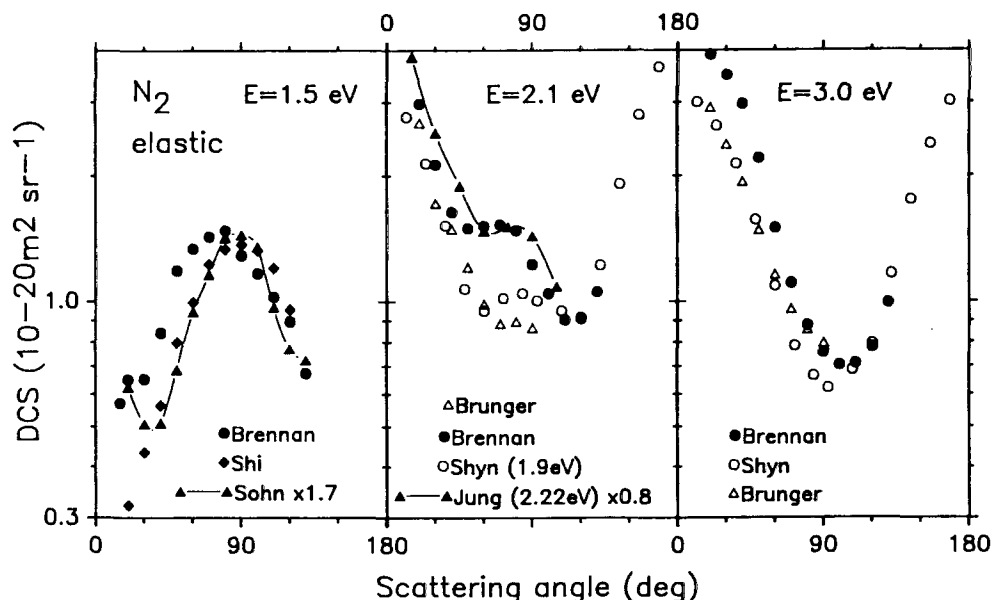


Fig. 23. – Differential elastic (rotationally unresolved) cross-sections for electron scattering on  $N_2$  in the region of the  $^2\Pi_g$  shape resonance. Points: Brennan *et al.* (1992); Brunger *et al.* (1989); Jung *et al.* (1982) normalized in this work; Sohn *et al.* (1986) normalized in this work; Shi *et al.* (1993); Shyn and Carignan (1980). Note that discrepancies at 2.1 eV can be caused by slight shifts in the energy determination.

Kuchitsu, 1972; Herrmann *et al.*, 1976), originally normalized to the independent-atoms model, also brings them in good agreement with the more recent data. At 300 eV the integral CS of Shyn and Carignan is in good agreement with the integral CS of Herrmann *et al.* (1976) if normalized to the absolute DCS of Jansen *et al.* (1976) at  $30^\circ$ . They are also in good agreement with the value obtained in the present work by integrating the absolute DCS of Bromberg (1970). At 500 eV DCS of Bromberg are higher than those of DuBois and Rudd (1976) and Goruganthu *et al.* (1986) but with a difference of merely 10% in the integral value. Note that between 400 and 800 eV the absolute integral CS of DuBois and Rudd exhibit an  $E^{-1}$  energy dependence, as the data of Herrmann *et al.* (1976), regardless of the normalization procedure. The DCS measurements of Jansen *et al.* (1976) extend up to 3000 eV but the limited angular range ( $5$ – $55^\circ$ ) does not allow to obtain integral values. At 2000 eV they are in good (within 6%) agreement with the DCS of Goruganthu *et al.* (1987).

At the high-energy limit (29 keV) the zero-angle elastic DCS amounts to  $17.4 \cdot 10^{-20} \text{ m}^2/\text{sr}$  (Zhang *et al.*, 1991) in agreement with the Born approximation (Bonham and Fink, 1986).

**Vibrational cross-section.** The most prominent structure in the energy dependence of the integral vibrational CS is the resonant maximum between 1.8 and 3.4 eV. As first observed by Schulz (1964) and successively confirmed in numerous experiments (Ehrhardt and Willmann, 1967; Boness and Schulz, 1973; Allan, 1985), the energy dependence of the CS for excitation to different levels  $\nu$  exhibits structures whose energy position depends on  $\nu$  (see fig. 22). Theoretical works (see

for instance: Domeke and Cederbaum, 1977; Dubé and Herzenberg, 1979) explained the observed structures in terms of a «boomerang» model of the resonant state.

A good accord can be obtained for the integral values summed over excitations to different vibrational levels. The sum of the  $\nu = 0 \rightarrow 1$  to  $\nu = 0 \rightarrow 8$  excitations from early experiments (Ehrhardt and Willmann, 1967; Schulz, 1964), normalized at 2.1 eV by a factor of 1.4 to the data of Brennan *et al.* (1992), are in agreement with the swarm analysis of Haddad (1984). Due to the above-mentioned shifting of the structure with  $\nu$ , the structure partially disappears in the summed cross-section (see Schulz in fig. 21).

At 2.1 eV the vibrational excitation (Brennan *et al.*, 1992) contributes to 15% of the TCS. The data of Jung *et al.* (1982) would indicate an even higher contribution; however, as follows from our sum check (see table XIII) and from a comparison with other results (Schulz, 1964; Ehrhardt and Willmann, 1967; Brennan *et al.*, 1992) the Jung *et al.*'s integral vibrational cross-sections for  $\nu = 0 \rightarrow 1$  excitation both at 2.2 eV and 2.47 eV seem to be overestimated by as much as 60%. At 3 eV the sum of the  $\nu = 0 \rightarrow 1$ ,  $\nu = 0 \rightarrow 2$ ,  $\nu = 0 \rightarrow 3$  excitations of Brennan *et al.* (1992) as well as the value of Tanaka *et al.* (1981) for  $\nu = 0 \rightarrow 1$ , normalized to account for all excitations (Allen, 1985), are somewhat higher (see fig. 21) than the normalized value of Schulz (1964).

The angular distributions in the  $^2\Pi_g$  resonance region (Brunger *et al.*, 1989; Brennan *et al.*, 1992; Tanaka *et al.*, 1981) for  $\nu = 0 \rightarrow 1$ ,  $\nu = 0 \rightarrow 2$ ,  $\nu = 0 \rightarrow 3$  transitions exhibit a *d*-wave-like shape, with a minimum at about  $55^\circ$  and a maximum at  $90^\circ$  (see fig. 24). In the resonance region, excitations of levels up to  $\nu = 17$  have been observed (Allan, 1985). In fig. 19 (see the hydrogen subsection) the dependence of maximum amplitude for the  $\nu$ -vibrational state function of  $\nu$  is shown. One notices a much slower fall of these maxima with rising  $\nu$  than has been observed for the shape resonance in  $\text{H}_2$ . Boness and Schulz (1973) argued that the observed fall reflects penetration of a *d*-wave through the centrifugal barrier of the scattering potential.

Vibrational excitation near to the threshold was studied both by beam techniques (Allan, 1985; Sohn *et al.*, 1986) as well as by analysis of swarm parameters (Engelhardt *et al.*, 1964; Haddad, 1984). At 1.0 eV the integral vibrational CS is more than two orders of magnitude lower than at the  $^2\Pi_g$  resonance and amounts to  $0.01 \cdot 10^{-20} \text{ m}^2$  (Sohn *et al.*, 1986). At 1.5 eV the direct excitation process is strongly masked by the vicinity of the resonant state.

Another enhancement of the vibrational CS has been observed (Pavlovic *et al.*, 1972; Tanaka *et al.*, 1981) between 15 eV and 25 eV, with a maximum of  $0.2 \cdot 10^{-20} \text{ m}^2$  at about 21 eV. Angular distributions around this energy indicate dominant *f*-partial-wave scattering (Tanaka *et al.*, 1981). These measurements merge well with other vibrational data between 5 eV and 75 eV (Truhlar *et al.*, 1976, 1977; Middleton *et al.*, 1992).

*Rotational cross-section.* Integral and differential CS for pure rotational ( $\nu = 0 \rightarrow 0$ ,  $\Delta J = \pm 2, \pm 4$ ) and ro-vibrational ( $\nu = 0 \rightarrow 1$ ,  $\Delta J = 4$ ) excitations have been measured between 1 and 4 eV by Wong and Dubé (1978) and around the 2.2 eV resonance for different  $\Delta J$  by Jung *et al.* (1982). The energy dependences of rotational excitations seen in the elastic ( $\nu = 0 \rightarrow 0$ ) or in the vibrational ( $\nu = 0 \rightarrow 1$ ) channels exhibit structures which follow the rotationally summed elastic or vibrational CS, respectively (consult fig. 22).

TABLE XIII. - *Integral cross-sections for electron scattering on molecular nitrogen (in  $10^{-20}$  m<sup>2</sup> units).*

Energy (eV)	Elastic <sup>+</sup>	Vibra- tional	Electronic	Disso- ciation <sub>C</sub>	Ioni- zation <sub>K</sub>	Sum	Total
0.1	4.44 <sub>S</sub>						
0.35	6.15 <sub>S</sub>						
0.55	9.24 <sub>SH</sub> 6.81 <sub>S</sub>	0.005 <sub>S</sub> *				9.24	8.91 <sub>K</sub>
1.0	7.30 <sub>S</sub>	0.009 <sub>S</sub>				7.30	9.91 <sub>K</sub>
1.5	11.6 <sub>SH</sub> 12.7 <sub>B</sub> 9.6 <sub>SC</sub> 7.43 <sub>S</sub>	0.09 <sub>B</sub>  0.05 <sub>S</sub>				11.7  7.48	11.2 <sub>K</sub>
2.1	18.4 <sub>B</sub> 17.6 <sub>SC</sub>	3.6 <sub>B</sub>				22.0	24.1 <sub>K</sub>
2.47	30.6 <sub>J</sub> 19.1 <sub>J</sub> <sup>+</sup>	6.0 <sub>J</sub> <sup>@</sup>				36.6	31.3 <sub>K</sub> *
3.0	18.7 <sub>B</sub> 14.8 <sub>SC</sub>	2.53 <sub>B</sub> 2.62 <sub>T</sub> <sup>@</sup>				21.2 17.4	19.7 <sub>K</sub>
5.0	11.3 <sub>B</sub> 11.2 <sub>SC</sub> 9.4 <sub>SR</sub>	0.06 <sub>T</sub> 0.08 <sub>B</sub> 0.06 <sub>TR</sub>				11.4 11.3 9.5	12.0 <sub>N</sub>
10	11.7 <sub>SC</sub> 12.0 <sub>SR</sub>	0.01 <sub>T</sub> 0.01 <sub>TR</sub>	0.5 <sub>TJ</sub>			12.2 12.5	12.1 <sub>N</sub>
20	12.1 <sub>SC</sub> 10.1 <sub>SR</sub>	0.20 <sub>T</sub>	1.8 <sub>CA</sub> *	(0.4)	0.27 0.25 <sub>KR</sub>	14.4 12.4	13.7 <sub>N</sub>
30	10.3 8.8 <sub>SR</sub>	0.03 <sub>T</sub> 0.025 <sub>TR</sub>	1.3 <sub>CA</sub>	(0.8)	1.03 1.08 <sub>KR</sub>	12.7	12.8 <sub>N</sub>
50	8.5 <sub>SC</sub> 8.0 <sub>SR</sub>	0.022 <sub>TR</sub>	(0.8 <sub>CA</sub> )	1.1	1.94 2.1 <sub>KR</sub>	11.5 11.2	11.3 <sub>N</sub>
100	5.6 <sub>SC</sub> 5.0 <sub>D</sub>		0.67 <sub>JA</sub>	(0.8)	2.53 2.73 <sub>KR</sub>	8.8 8.4	8.92 <sub>N</sub>
200	3.7 <sub>SC</sub> 3.53		0.3*		2.27 2.42 <sub>KR</sub>	6.3 6.25	6.43 <sub>N</sub>
300	2.6 <sub>SC</sub> 2.52 <sub>BR</sub>		0.2*		1.92 2.0 <sub>KR</sub>	4.72 4.72	5.11 <sub>N</sub> 4.85 <sub>KA</sub>
400	2.3 <sub>SC</sub> 2.11 <sub>BR</sub> 2.11 <sub>D</sub>		0.15*		1.66 1.75 <sub>KR</sub>	4.11 4.01	4.07 <sub>KA</sub> *

TABLE XIII (*continued*).

Energy	Elastic <sup>+</sup>	Vibra- tional	Electronic	Disso- ciation <sub>C</sub>	Ioni- zation	Sum	Total
500	2.0 <sub>H</sub> 1.82 <sub>BR</sub> 1.65 <sub>D</sub>		0.12*		1.45 1.56 <sub>KR</sub>	3.57 3.50	3.58 <sub>KA</sub>
600	1.68 <sub>H</sub>		0.06*		1.29 1.40 <sub>KR</sub>	3.03 3.14	3.15 <sub>KA</sub> *
800	1.36 <sub>H</sub> 1.06 <sub>D</sub>		0.08*		1.06 1.21 <sub>KR</sub>	2.50 2.35	2.46 <sub>KA</sub> *
1000	1.2 <sub>H</sub>		0.06*		0.92 1.08	2.18	2.08 <sub>KA</sub>

( ) - Not used for summation.

\* - From interpolation or a  $1/E$  extrapolation.

+ - Rotationally summed.

+ + - Rotationally elastic.

@ - Obtained by summing all excitations from Allen (1985b), computing the ratio to the  $\nu(0 \rightarrow 1)$  excitation and multiplying the values from Jung *et al.* (1982) and Tanaka *et al.* (1981) by this ratio.

BR - Bromberg (1970), integrated (5% error added).

C - Cosby (1993).

CA - Cartwright *et al.* (1977), renormalized by Trajmar *et al.* (1983).

D - DuBois and Rudd (1976).

H - Herrmann *et al.* (1976), digitized from the original figure.J - Jung *et al.* (1982).JR - James *et al.* (1990) and Ajello and Shemansky (1985), sum of optical-emission CS.

K - Kennerly (1980).

KA - Karwasz *et al.* (1993).S - Sohn *et al.* (1986).SH - Shi *et al.* (1993).

SC - Shyn and Carignan (1980).

SR - Srivastava *et al.* (1976).T - Tanaka *et al.* (1981), vibrational CS at 3.0 eV multiplied by a factor 2.1.TR - Truhlar *et al.* (1976, 1978).

The summed rotational excitation (vibrationally elastic) CS amounts to  $10.6 \cdot 10^{-20} \text{ m}^2$  at 2.47 eV (Jung *et al.*, 1982); this is as much as 30% of TCS. This value agrees roughly with  $13 \cdot 10^{-20} \text{ m}^2$  at 2.21 eV obtained from the partial excitation  $\Delta J = +4$  and branching ratios for different  $\Delta J$  given by Wong and Dubé (1978). The  $\Delta J = +2$  transition dominates, with a CS of  $4 \cdot 10^{-20} \text{ m}^2$  (Jung *et al.*, 1982). The branching ratios for the vibrational excitation ( $\nu = 0 \rightarrow 1$ ) at the  ${}^2\Pi_g$  resonance, measured at temperatures of 300 K (Wong and Dubé, 1978) and 500 K (Jung *et al.*, 1982), approximately agree and amount to 12:4:4:3:2 for the  $\Delta J = 0, +4, +2, -2, -4$  transitions, respectively. In other words, the rotational state changes roughly in half of the vibrational excitation events (see Jung *et al.*, 1982 for the absolute values), almost independently of the initial population of the  $J$  states. The direct non-resonant rotational excitation of the  $\text{N}_2$  molecule is two orders of magnitude smaller than at the resonance (Jung *et al.*, 1982).

*Electronic excitation.* Comprehensive measurements of electronic excitations in  $\text{N}_2$  were performed first by Cartwright *et al.* (1977a, b), Chutjian *et al.* (1977) and more recently by Brunger and Teubner (1990). Knowledge of these cross-sections is



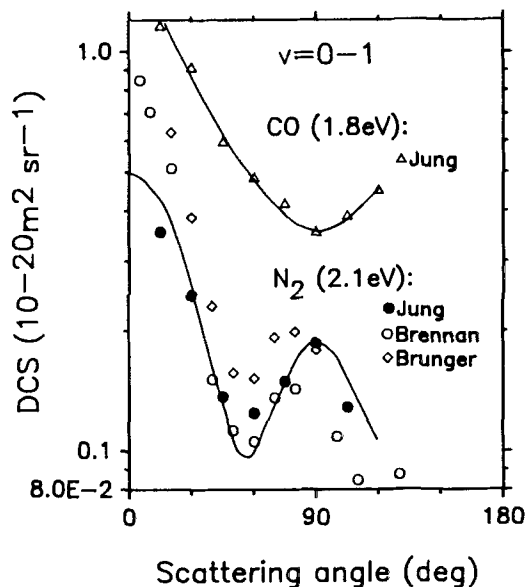


Fig. 24. – Differential cross-sections for  $\nu = 0 \rightarrow 1$  vibrational excitation in  $N_2$  and CO in the region of the  $^2\Pi$  shape resonance. Points: Jung *et al.* (1982); Brennan *et al.* (1992); Brunger *et al.* (1989). Lines, relative theoretical of Read and Andrick (1971) normalized by Jung *et al.* (1982).

important for plasma and swarm modelling (Taniguichi *et al.*, 1980). The subject has been revised, among others, by Register *et al.* (1983), Itikawa *et al.* (1986) and Shimamura (1989).

Cartwright *et al.* obtained differential 20–130° (1977a) and integral (1977b) CS for excitation from the ground  $X^1\Sigma_g^+$  state to the three lowest singlet ( $a'^1\Sigma_u^-$ ,  $a^1\Pi_g$ ,  $w^1\Delta_u$ ), five triplet ( $A^3\Sigma_u^+$ ,  $B^3\Pi_g$ ,  $W^3\Delta_u$ ,  $B'^3\Sigma_u^-$ ,  $C^3\Pi_u$ ) and two Rydberg ( $E^3\Sigma_g^+$ ,  $a''^1\Sigma_g^+$ ) levels. These CS have been subsequently normalized in the review of Trajmar *et al.* (1983); nevertheless, they are in several cases in a fairly serious (a factor of 2) disagreement with more recent measurements (Brunger and Teubner, 1990). These latter authors have not measured DCS above 90° and as a consequence they did not publish integral values.

Integral CS for transitions to the A, B, W and B' triplet states reach their maxima in the region 12–17 eV where they amount to  $(0.2\text{--}0.3) \cdot 10^{-20} \text{ m}^2$  each (see Trajmar *et al.*, 1983); for C state the maximum amounts to about  $0.5 \cdot 10^{-20} \text{ m}^2$  (Brunger and Teubner, 1990). Maxima for  $a'$  and  $w$  singlet excitations are equal to  $0.1 \cdot 10^{-20} \text{ m}^2$  (Trajmar *et al.*, 1983) and only the  $a^1\Pi_g$  metastable state reaches  $0.42 \cdot 10^{-20} \text{ m}^2$  at 15 eV (Brunger and Teubner, 1990). CS for all these singlet and triplet states, but  $a^1\Pi_g$ , fall down quickly with energy above their maxima, similarly to the optically forbidden states in  $H_2$ . (Please, note a probable transcription error in table XIV of Trajmar *et al.* (1983) for  $a^1\Pi_g$  excitation at 50 eV).

The dipole-forbidden quadrupole-allowed excitation to the  $a^1\Pi_g$  state amounts to  $0.06 \cdot 10^{-20} \text{ m}^2$  at 100 eV (Ajello and Shemansky, 1985; Finn and Doering, 1976) and descends at higher energies approximately as  $E^{-1}$  (compare electron excitation

measurements of Finn and Doering, 1976; Oda and Osawa, 1981 with optical measurements of Holland, 1969; Ajello, 1970; Ajello and Shemansky, 1985).

At 100 eV the integral cross-sections for different optically allowed  $b^1\Pi_u$ ,  $c^1\Pi_u$ ,  $o^1\Pi_u$ ,  $b'\Sigma_u^+$ ,  $c'\Sigma_u^+$  transitions are of the same order of magnitude, amounting to about  $0.15 \cdot 10^{-20} \text{ m}^2$  each (Ratliff *et al.*, 1991; James *et al.*, 1990). An  $E^{-1}$  behaviour of the optically allowed CS was observed just between 40 eV and 60 eV (Chutjian *et al.*, 1977). We have used this observation to extrapolate optically allowed excitations down to 20 eV; this allows to derive the overall excitation CS presented in fig. 21. The sum of all electronic transitions as measured by Cartwright *et al.* (1977b) and Chutjian *et al.* (1977) amounts to 7% of TCS at 50 eV. More recent measurements of electronic excitation to  $C^3\Pi_u$ ,  $E^3\Sigma_g^+$ ,  $a''^1\Sigma_g^+$  optically forbidden states include works of Furlan *et al.* (1990), Zubek (1994) and Zubek and King (1994).

*Ionization cross-section* reaches its maximum of  $2.7 \cdot 10^{-20} \text{ m}^2$  at 80 eV (Krishnakumar and Srivastava, 1990). In the whole energy range from the threshold up to 1000 eV, the counting integral CS of Krishnakumar and Srivastava is higher than the gross integral ionization of Rapp and Englander-Golden (1965). At 1000 eV, the integral ionization CS obtained from differential measurements (Goruganthu *et al.*, 1987) agrees well with the gross integral value of Rapp and Englander-Golden (1965) and lies between the results of Schram *et al.* (1965) and Krishnakumar and Srivastava.

The dissociative ionization fraction ( $N^+/N_2^+$ ) varies little with energy between 100 eV and 1000 eV and amounts to 0.25–0.22 (Rapp *et al.*, 1965; Crowe and McConkey, 1975; Krishnakumar and Srivastava, 1990; Van Zyl and Stephen, 1994). Doubly charged ions  $N_2^{2+}$  are produced approximately in 1% of the total yield (Märk, 1975; Halas and Adameczyk, 1972). Comparative studies of  $N_2$  ionization by anti-particles (Knudsen *et al.*, 1995) showed that the  $N_2^+$  yields for  $e^-$ ,  $p^+$  and  $p^-$  projectiles, plotted as a function of the collision velocity, merge in the limit of high energies.

*Dissociation into neutrals.* Recent measurements of electron impact dissociation into neutrals by a crossed-beam technique (Cosby, 1993) yielded CS on the average 40% lower than the surface adsorption measurements of Winters (1966). Despite the large bond dissociation energy (9.75 eV), the CS in its maximum (at about 50 eV) amounts to 10% of the TCS. Numerous electronically excited states contribute to the dissociation CS (James *et al.*, 1990).

*Dissociative attachment.* No stable negative ions of the  $N_2$  molecule are known. However, evidence of formation of unstable  $N_2^-(A^2\Pi_u)$  excited complex, decaying to excited  $N^-(^3P)$  and  $N(^4S)$  was observed just above the threshold for dissociation (Spence and Burrow, 1979; Huetz *et al.*, 1980b). Spence and Burrow evaluated the maximum in the integral CS as  $2.4 \cdot 10^{-20} \text{ m}^2$ . In fig. 21 we present the DCS at  $90^\circ$  for detection of electrons from decaying  $N^-$  ions (Huetz *et al.*, 1980b), normalized to the value of Spence and Burrow.

*Metastables.* Cross-sections for metastable yield were studied by Borst and Zipf (1971), Borst (1972) and more recently by Mason and Newell (1987).  $A^3\Sigma_u^+$ ,  $a^1\Pi_g$  and  $E^3\Sigma_g^+$  states lie, respectively, 6.17, 8.55, and 11.87 eV above the ground state. Lifetimes for the two latter are of 115  $\mu\text{s}$  and 190  $\mu\text{s}$ , respectively (Borst and Zipf,

1971). Integral CS for production of the  $a^1\Pi_g$  state amounts to 3% of the TCS at the maximum (17 eV), while that for  $E^3\Sigma_g^+$  is one order of magnitude smaller (Borst, 1972; Mason and Newell, 1987). Yield of the  $A^3\Sigma_u^+$  state (maximum at 10.5 eV) is even higher than for the  $a$  state. This CS determination is subject to a large error bar (Borst, 1972).

*Resonances.* The nitrogen molecule provides textbook examples of resonance phenomena. Both extremely short and long-lived resonances have been observed (see for example the review of Schulz, 1973). The  $^2\Pi_g$  shape resonance shows up as one of the most prominent structures in the known molecular total cross-sections. As already mentioned, another  $^2\Pi_u$  (Huetz *et al.*, 1980a) shape resonance is barely visible in the total and elastic CS at about 8 eV. A long-lived  $^2\Sigma_u$  (Dehmer, 1980; Burke *et al.* 1983; Chang, 1983; Malegat and Dourneuf, 1988) shape resonance is observed as a wide maximum in the elastic (and in the vibrational) CS at about 20 eV.

A number of Feshbach resonances between 11.5 and 14.5 eV were observed in transmission experiments (Sanche and Schulz, 1972), electron excitation spectra (Mazeau *et al.*, 1973; Lawton and Pichanick, 1973), ultraviolet emission (Brunt *et al.*, 1978), and metastables excitation (Brunt *et al.*, 1978; Newman *et al.*, 1983).

*Sum check* indicates a very good coherence between total and partial cross-sections measurements almost in the whole energy range. Elastic CS of Brennan *et al.* (1992) and Shi *et al.* (1993) at low energies, Shyn and Carignan (1980) between 5 eV and 50 eV and those of Herrmann *et al.* (1976) at high energies sum up in the best way with inelastic CS and in particular with the ionization measurements due to Rapp and Englander-Golden (1965) to the total values. However, the sum check cannot rule out the validity of a different set of data, lower in the elastic part (Bromberg, 1970; DuBois and Rudd, 1976) and higher in the ionization contribution (Krishnakumar and Srivastava, 1990). Typical for  $N_2$ , in analogy to heavier noble gases, is the dominance of the elastic scattering, up to the highest energy considered (1000 eV).

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4.3. *Carbon monoxide* (CO). – Interest in electron-carbon monoxide scattering has been partially triggered by its similarity to the isoelectronic nitrogen molecule. The CO cross-section shows several features which have a correspondence in N<sub>2</sub>. Differently than N<sub>2</sub>, carbon monoxide possesses a weak (0.11D) permanent dipole moment. The occurrence of CO as an atmospheric pollutant has been a further reason for its investigations. Figure 25 shows the total and partial cross-sections for CO molecule.

*Total cross-sections* of Buckman and Lohmann (1986), Kanik *et al.* (1992) and Szymtkowski *et al.* (1995) at low and intermediate energies agree within 3% and merge well with the measurements of Karwasz *et al.* (1993), García *et al.* (1990) and Xing *et al.* (1995) at intermediate and high energies. The data of Kwan *et al.* (1983) agree in shape at low energies with other measurements but seem to be shifted by 0.15 eV, probably due to some contact potentials. The normalized CS of Sueoka and Mori (1984), not shown in the figure, are significantly (15–20%) lower than the remaining sets of data. At low energies TCS is dominated by a broad maximum between 1 eV and 4 eV, with a peak of  $43.4 \cdot 10^{-20} \text{ m}^2$  at 1.94 eV (Buckman and Lohmann, 1986) attributed to a  $^2\Pi$  shape resonance. A broad maximum follows at about 20 eV. A small hump at about 8 eV, in between these two maxima, is visible in all measurements. The logarithmic scale in fig. 25 and the superposition of the data symbols hide partially its presence. The magnitude of this hump is of the order of 2% (Kanik *et al.*, 1992).

In the high-energy limit (2000 eV) the measurements of Karwasz *et al.* (1993) are substantially (about 15%) lower than the data of García *et al.* (1990) and Xing *et al.* (1995). One possible reason for this discrepancy could be a rather coarse resolution of the energy analysis at the exit of the scattering cell in the apparatus used by Karwasz *et al.* (1993); however, this could hardly explain such a big difference. A different argument throws the suspicion of a possible error in the measurements of both García *et al.* (1990) and Xing *et al.* (1995). If CO and N<sub>2</sub> are compared, all authors agree that the CO total cross-section is not more than 5% higher than that of N<sub>2</sub>, in the entire 20 eV to 500 eV range. This percentage difference remains constant up to 2000 eV in the measurements of Karwasz *et al.* (1993), while it increases to 20% in the experiment of García *et al.* (1988, 1990).

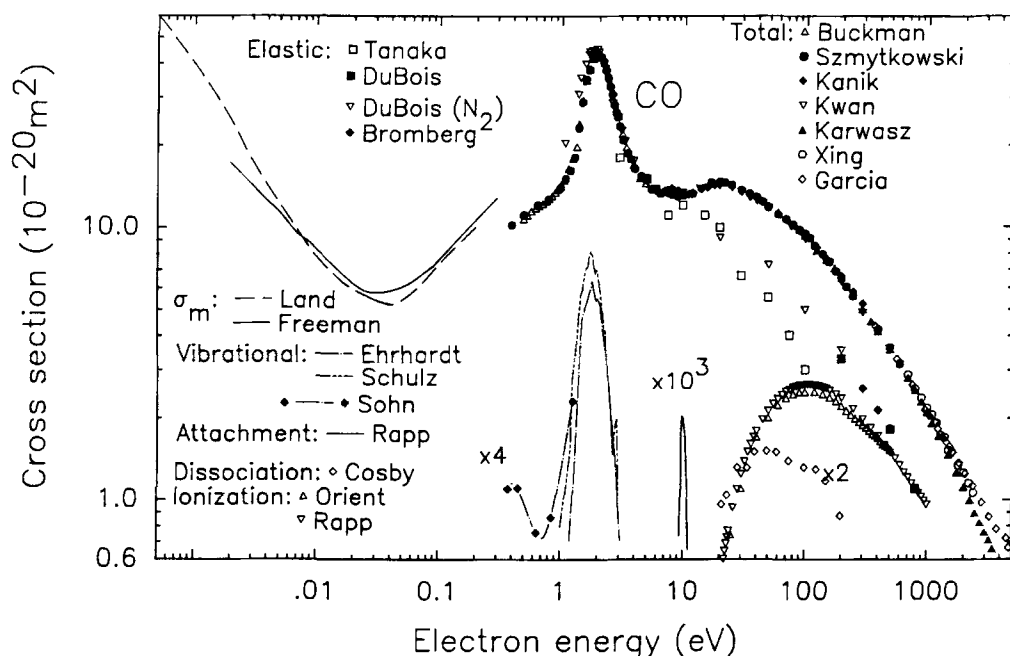


Fig. 25. – Integral cross-sections for electron scattering on CO. *Total*: Buckman and Lohmann (1986); Szmytkowski *et al.* (1995); Kanik *et al.* (1992); Kwan *et al.* (1983); Karwasz *et al.* (1993); Xing *et al.* (1995); García *et al.* (1990); data of Sueoka and Mori (1984) not shown. *Elastic*: Tanaka *et al.* (1978); DuBois and Rudd (1976) at 200, 500, 800 eV, integrated in this work; total of DuBois and Rudd (1976) for N<sub>2</sub> at low energies; Bromberg (1970) at 300, 400, 500 eV, integrated in this work. *Momentum transfer*: Land (1978); Ramanan and Freeman (1991). *Vibrational excitation*: Ehrhardt *et al.* (1968) ( $\nu = 0 \rightarrow 1-7$ ), summed in this work; sum ( $\nu = 0 \rightarrow 1-8$ ) of Schulz (1964); absolute integral of Sohn *et al.* (1985); Chutjian and Tanaka (1980), not shown (out of scale). *Dissociative attachment*: Rapp and Briglia (1965). *Dissociation into neutrals*: Cosby, 1993. *Ionization*: Orient and Srivastava (1987); Rapp and Englander-Golden (1965).

*Swarm experiments.* A good agreement exists between numerous swarm measurements in a wide range of temperatures (we quote Lakshminarasimha *et al.*, 1974; Roznerski and Mechlińska-Drewko, 1979; Roznerski and Leja, 1984; Nakamura, 1987; Petrović and Crompton, 1989). At energies below 0.1 eV, the TCS as obtained in beam experiments matches satisfactorily with the swarm-derived momentum transfer CS (Pack *et al.*, 1962; Hake and Phelps, 1967; Haddad and Milloy, 1983; Ramanan and Freeman, 1991). The rise of the momentum transfer CS in the zero-energy limit should be attributed to the permanent dipole moment of the CO molecule. This rise was also observed in Rydberg-atoms quenching experiment (Petitjean *et al.*, 1984) and in the cyclotron resonance (Tice and Kivelson, 1967) but the derived CS differ significantly from the swarm data and are not reported in fig. 25.

*Elastic cross-sections* have been measured between 3 eV and 70 eV by Tanaka *et al.* (1978), at 200, 500 and 800 eV by DuBois and Rudd (1976), at 300, 400, 500 eV by Bromberg (1970). Nickel *et al.* (1988) carefully examined the ratios between N<sub>2</sub> and CO differential CS at 20–120° and 20–100 eV. Generally, between 20 eV and 100 eV the

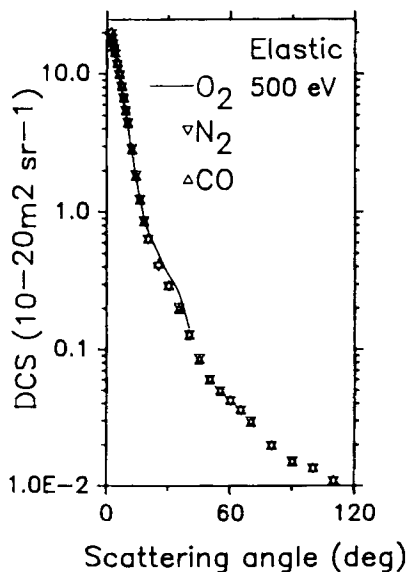


Fig. 26. – Differential elastic cross-sections for electron scattering on  $N_2$ , CO (Bromberg, 1970) and  $O_2$  (Bromberg, 1974) at 500 eV.

CO differential CS at their minimum (about  $90^\circ$ ) are slightly higher (by a few per cent) than those in  $N_2$ . However, the data of Nickel *et al.* (1988) did not report integral CS either for CO or  $N_2$ . We note that at 500 eV the DCS at  $2-5^\circ$  is about 4% higher in CO than in  $N_2$  (Bromberg, 1970; DuBois and Rudd, 1976, see fig. 26). For these reasons, in fig. 25 we have decided to present in the 20–100 eV range the  $N_2$  cross-sections of DuBois and Rudd (1976) as a possible lower-bound approximation of the CO elastic data. This is conflicting with the data of Tanaka *et al.* (1978), and could be an indication that these measurements are too low. Further, the elastic integral CS of Tanaka *et al.* are lower than the rough estimates obtained by us from integration of the differential measurements of Nickel *et al.* (1988) and of Middleton *et al.* (1993). At very low energies (0.165 eV) the elastic scattering in CO (Sohn *et al.*, 1985) is strongly forward-peaked, due to the influence of the permanent dipole moment. No integral CS have been given in the measurements of Sohn *et al.* (1985) nor in those of Ehrhardt *et al.* (1968) between 1.0 and 3.5 eV. A limited angular range (less than  $120^\circ$ ) of these measurements does not allow to perform the integration.

*Vibrational excitation* at energies below 1 eV and at small scattering angles agrees well with values calculated from the Born approximation but exceeds them slightly at higher scattering angles (Sohn *et al.*, 1985). Above 1 eV the vibrational excitation is enhanced by resonant scattering (see fig. 25). Schulz (1964), Ehrhardt *et al.* (1968) and Allan (1989) have seen structures in the excitation functions for separate vibrational channels similar to those in  $N_2$  (see fig. 22). However, the structures in the first  $v = 0 \rightarrow 1, 2, 3$  channels for CO are not so well pronounced as in  $N_2$ . A boomerang model (Zubek and Szmytkowski, 1977) as well as *ab initio* calculations (Morgan, 1991) for electron capture into a  $\pi$  molecular orbital and for a  $p$ -partial-wave scattering predict well the observed



dependencies. The influence of the permanent dipole moment on the CO resonance has not been explicitly discussed (Morgan, 1991).

In fig. 25 we present the sum of excitations up to  $\nu = 7$  from Ehrhardt *et al.* (1968) and up to  $\nu = 8$  from Schulz (1964): these data are in good mutual congruence, but somewhat lower than the values adopted in the swarm analysis of Land (1978). Structures visible in the excitation functions of separate channels disappear in the overall vibration excitation CS. At 1.9 eV the vibrational excitation CS (Ehrhardt *et al.*, 1968), as summed by us, amounts to about 15% of the TCS values given by Szmytkowski *et al.* (1995). Within the experimental uncertainty this is the same relative contribution as in  $N_2$ . Angular distributions for electrons vibrationally scattered in the region of the shape resonance in  $N_2$  and CO have been compared in fig. 24. DCS for vibrational excitation in CO exhibit a dominant  $p$ -wave scattering character. The vibrational excitation was studied by Chutjian and Tanaka (1980) at selected energies between 3 eV and 100 eV and by Middleton *et al.* (1992) between 20 and 50 eV. DCS in this energy range are similar to those in  $N_2$  (Tanaka *et al.*, 1981), indicating no influence of the permanent dipole moment. At 3 eV the integrated CS for the  $\nu = 0 \rightarrow 1$  excitation is equal to  $0.3 \cdot 10^{-20} \text{ m}^2$ . A further rise of the vibrational CS above the background, descending monotonically with energy, was observed at about 20 eV (Chutjian and Tanaka, 1980). The presence of a  $\Sigma$  shape resonant state at this energy has been deduced (Tronc *et al.*, 1980).

*Rotational excitation.* The rotational  $\Delta J = \pm 1$  transitions at low energies are induced by the permanent dipole moment of the molecule. At 0.5 eV the pure  $\Delta J = \pm 1$  rotational CS amounts to  $0.17 \cdot 10^{-20} \text{ m}^2$  (Jung *et al.*, 1982). The CS for rotational transitions  $\Delta J = \pm 1$  in the vibrational excitation events  $\nu = 0 \rightarrow 1$  is approximately the same. However, the elastic ( $\Delta J = 0$ ) scattering dominates at 0.5 eV. The  $\Delta J = \pm 2$  rotational excitations, induced by the molecular polarizability, are, similarly as for  $N_2$ , of the order of  $10^{-22} \text{ m}^2$  (Jung *et al.*, 1982). In the region of the  $^2\Pi$  shape resonance (1.8 eV) the sum of the rovibrational (all  $\Delta J$ ,  $\nu = 0 \rightarrow 1$ ) transitions is of the order of  $10^{-20} \text{ m}^2$  (Jung *et al.*, 1982); odd  $\Delta J = \pm 1, \pm 3$  transitions prevail over even ones (Chang *et al.*, 1984).

*Electronic excitations.* Electronic excitation CS have been extensively studied for scattering angles between  $10^\circ$  and  $90^\circ$  and energies from 20 to 50 eV by Middleton *et al.* (1993). DCS for  $X^1\Sigma^+$  into-singlet  $A^1\Pi$ ,  $B^1\Sigma^+$ ,  $C^1\Sigma^+$ ,  $E^1\Pi$  transitions are forward-peaked in the whole 20–50 eV energy range while angular distributions for transitions to the triplet states ( $a^3\Pi$ ,  $a'^3\Sigma^+$ ,  $b^3\Sigma^+$  and  $d^3\Delta_i$ ) are more uniform. At 30 eV the CS for the  $A^1\Pi$  excitation (Middleton *et al.*, 1993) as integrated by us is of the order of  $0.6 \cdot 10^{-20} \text{ m}^2$  (*i.e.* 5% of TCS), while the other most significant singlet states  $B$ ,  $C$  and  $E$  as well as the  $a^3\Pi$  and  $a'^3\Sigma^+$  triplet states are excited with a probability roughly one order of magnitude smaller. The limited energy span of Middleton *et al.*'s (1993) measurements does not allow to judge on the energy dependencies of integral CS for the particular transitions. At 100 eV the integral CS for excitation into the  $C$  state amounts to  $0.12 \cdot 10^{-20} \text{ m}^2$  and for the  $B$  and  $E$  states to  $0.04 \cdot 10^{-20} \text{ m}^2$  each (Kanik *et al.*, 1993). Theoretical calculations (see Middleton *et al.*, 1993 for references) approximate pretty well the shapes (but not the absolute values) of the experimentally observed DCS (Middleton *et al.*, 1993).

*Optical emission.* Emission CS from molecular bands of CO were studied by Aarts and de Heer (1970) who measured integral CS (normalized to Lassettre and Silverman, 1964) for  $A \rightarrow X$ ,  $B \rightarrow X$  and  $C \rightarrow X$  transitions; by Ajello (1971) who covered  $A \rightarrow X$  transitions; and more recently in a detailed way by James *et al.* (1992) who gave integral CS for  $C \rightarrow X$ ,  $E \rightarrow X$  transitions and parts of the  $B \rightarrow X$  and  $A \rightarrow X$  bands. Some discrepancies between existing measurements were stressed in the review of van der Burgt *et al.* (1989). We notice a rough agreement between the excitation CS for the  $A \rightarrow X$  transition at 30 eV as obtained from emission measurements ( $0.4 \cdot 10^{-20} \text{ m}^2$ , Ajello, 1971) and electron data ( $0.6 \cdot 10^{-20} \text{ m}^2$ , Middleton *et al.*, 1993, integrated in this work). Emission measurements (Aarts and de Heer, 1970; James *et al.*, 1992) show that at 200 eV the  $C \rightarrow X$  transition becomes dominant over other ( $A \rightarrow X$ ,  $B \rightarrow X$ ) bands, which are important at low energies. Vibronic ( $v = 0 \rightarrow 0$ ) cross-sections for the  $E$ ,  $C$ ,  $B$  and  $D$  terms at 20, 100 and 200 eV were given by Kanik *et al.* (1995). The sum of these latter CS amounts to 1/4 of the overall excitation at 200 eV.

*Metastables.* Excitation to metastable states was studied among others by Borst and Zipf (1971), Wells *et al.* (1973), Brunt *et al.* (1978), Newman *et al.* (1983), Mason and Newell (1988), Barnett *et al.* (1992). Integral CS for total yield of metastables in CO can be separated into two components (Borst and Zipf, 1971): 1) the first one coming from excitation of a long-lived ( $> 1 \text{ ms}$ )  $a^3\Pi$  state, reaching its maximum at about 10 eV; 2) the second one, higher-lying state (or states) with formation threshold at 9.45 eV (Mason and Newell, 1988). No accord exists on absolute CS for these two channels. Wells *et al.* (1973) reported a maximum of  $0.03 \cdot 10^{-20} \text{ m}^2$  for the second channel. This would normalize the maximum for the  $a^3\Pi$  state (Borst and Zipf, 1971) to  $0.045 \cdot 10^{-20} \text{ m}^2$ . However, the energy loss investigations (Middleton *et al.*, 1993) of the  $a^3\Pi$  electronic excitation would indicate a much higher maximum ( $0.4 \cdot 10^{-20} \text{ m}^2$ ) of this CS, comparable to the magnitude of the bump observed in TCS at 8–10 eV.

*Ionization.* Ionization CS of Orient and Srivastava (1987) are slightly lower than the values of Rapp and Englander-Golden (1965). At 800 eV the integral ionization CS of  $1.1 \cdot 10^{-20} \text{ m}^2$  obtained from measurements of doubly differential CS (Ma and Bonham, 1988) agrees well with the Rapp and Englander-Golden's value. At 200 eV the  $\text{CO}^+$  ions constitute about 85% of the total ion yield, followed by  $\text{C}^+$  (10%) (Orient and Srivastava, 1987). The ratio between the single and double parent ionization ( $\text{CO}^+/\text{CO}^{2+}$ ) amounts to about 1:100 (Hille and Märk, 1978). At high energies (above 500 eV) the ionization CS (Rapp and Englander-Golden, 1965) constitutes about 45% of the TCS.

*Dissociation.* The dissociation CS reaches a maximum of  $0.75 \cdot 10^{-20} \text{ m}^2$  at about 40 eV (Cosby, 1993). Cosby also gave partial CS for dissociation resulting from different electronically excited states. Dissociation into metastable fragments was studied by Barnett *et al.* (1992).

*Dissociative attachment.* A single peak at 10.0 eV was observed in the integral CS for  $\text{O}^-$  ions production (Rapp and Briglia, 1965; Harland *et al.*, 1973). At the peak, the dissociative attachment CS amounts to  $1.3 \cdot 10^{-4}$  of the TCS.

TABLE XIV. – *Integral cross-sections for electron scattering on carbon monoxide (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Vibra- tional	Electronic	Ioni- zation <sub>RE</sub>	Disso- ciation <sub>C</sub>	Sum	Total
0.05	6.0 <sub>R</sub>						
0.1	7.6 <sub>R</sub>						
0.5		0.28 <sub>S</sub>					10.7 <sub>B</sub>
1.26		0.58 <sub>S</sub>					18.0 <sub>B</sub> *
1.50		4.6 <sub>E</sub>					29.2 <sub>B</sub>
2.0		5.5 <sub>E</sub>					43.2 <sub>B</sub>
3.0	18.0 <sub>T</sub>	0.9 <sub>E</sub>				18.9	23.6 <sub>SZ</sub>
5.0	15.0 <sub>T</sub>	0.1 <sub>CH</sub>				15.1	15.1 <sub>SZ</sub>
7.5	11.0 <sub>T</sub>	0.02 <sub>CH</sub> *				11.0	13.4 <sub>SZ</sub>
9.9	12.0 <sub>T</sub>	0.03 <sub>CH</sub> *				12.0	13.0 <sub>K</sub>
20.0	9.9 <sub>T</sub>	0.1 <sub>CH</sub>	1.2 <sub>M</sub>		0.36*	11.6	14.5 <sub>K</sub>
30.0	8.5 <sub>DN</sub> (6.6 <sub>T</sub> )		1.0 <sub>M</sub>	1.24	0.66*	11.4	13.5 <sub>K</sub>
50.0	7.2 <sub>DN</sub> (5.5 <sub>T</sub> )		0.9 <sub>M</sub>	2.12	0.75	11.0	11.9 <sub>K</sub>
100	5.0 <sub>DN</sub> (3.0 <sub>T</sub> )		0.5**	2.65	0.65	8.8	9.29 <sub>K</sub>
200	3.29 <sub>D</sub>		0.25**	2.37	0.4	6.31	6.60 <sub>K</sub>
300	2.57 <sub>BR</sub>		0.17**	1.99		4.73	5.23 <sub>K</sub>
400	2.14 <sub>BR</sub>		0.12**	1.72		3.98	4.14 <sub>KA</sub>
500	1.84 <sub>BR</sub> 1.82 <sub>D</sub>		0.1**	1.50		3.44 3.42	3.56 <sub>KA</sub>
800	1.1 <sub>D</sub>		0.06**	1.11		2.27	2.52 <sub>KA</sub>
1000				0.96			2.10 <sub>KA</sub>

( ) – Not used for summation.

\* – Interpolated value.

\*\* – Extrapolated, assuming a  $1/E$  behaviour of the excitation cross-section.

B – Buckman and Lohmann (1986).

BR – Bromberg (1970), integrated in this work.

C – Cosby (1993).

CH – Chutjian and Tanaka (1980).

D – DuBois and Rudd (1976), integrated in this work.

DN – DuBois and Rudd (1976), integral for  $\text{N}_2$ .E – Ehrhardt *et al.* (1968), summed in this work.K – Kanik *et al.* (1992).KA – Karwasz *et al.* (1993).M – Middleton *et al.* (1993), rough estimate ( $\pm 20\%$ , this work).

R – Ramanan and Freeman (1991), momentum transfer.

RE – Rapp and Englander-Golden (1965).

S – Sohn *et al.* (1985).SZ – Szymkowski *et al.* (1995).T – Tanaka *et al.* (1978), vibrationally elastic.

*Resonances.* The prominent maximum both in the total and in the elastic CS at 1.9 eV (see fig. 25) has been assigned to a  $^2\Pi$  shape resonance. Boness and Schulz (1973), from amplitude studies of the high ( $v = 6$  to 10) vibrational excitations, have attributed a  $p$ -wave character to the resonance at 2–4 eV. The analogous resonance in  $N_2$  has, on the contrary, a  $d$ -wave character. A comparison among low-energy resonances in  $H_2$ ,  $N_2$  and CO, as observed in high vibrational channels, has been illustrated in fig. 19.

A core excited resonance at 10.04 eV well visible in the dissociation attachment channel, and numerous weaker, higher-lying resonances were evidenced among others by Sanche and Schulz (1971), Comer and Read (1971), Mazeau *et al.* (1972) and Swanson *et al.* (1975) in spectra of scattered electrons and by Newell *et al.* (1983), Mason and Newell (1988) in the metastables' yield. Resonant structures in the electronic excitation near the thresholds were studied in surface absorbed layers by Marsolais *et al.* (1987).

The existence of a  $\Sigma$  shape resonance at 19.5 eV with dominant contribution from an  $f$  partial wave was evidenced in vibrational-excitation measurements (Tronc *et al.*, 1980).

*Sum check.* The lack of absolute elastic integral CS data below 3 eV does not allow to perform the sum check in the region of the low-energy shape resonance. At intermediate energies the summed values are generally somewhat smaller (10% at 100 eV) than the TCS. This can result mainly from underestimation of the elastic part (for example by using  $N_2$  values) and from a lack of integral electronic excitation CS. Table XIV reports possible patterns for partial CS summing at selected energies.

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4.4. *Molecular oxygen* ( $O_2$ ). – The knowledge of electron collision CS on molecular oxygen is of basic importance in understanding atmospheric processes, in modelling electrical discharges (Gousset *et al.*, 1991) and in technological applications, like plasma passivation and etching (Ricard *et al.*, 1983). Oxygen has been studied in numerous experiments and we have a good knowledge of partial and total CS. However some discrepancies still existed until recently, as far as total and vibrational excitations are concerned. The  $O_2$  molecule has a positive electron affinity of 0.44 eV (Celotta *et al.*, 1972; Land and Raith, 1974); therefore the first temporary compound state has a negative formation energy. A recent extensive review of photon and electron scattering CS has been presented by Itikawa *et al.* (1989). Integral CS for  $O_2$  are presented in fig. 27.

*Total cross-section.* Zecca *et al.* (1986) published absolute CS in the 0.2 eV to 100 eV energy range from independent experiments performed in Trento and Gdańsk. A resonant vibrational structure superimposed on a slow rise of the CS was evidenced below 1 eV in the absolute data from Trento. This structure, resolved into doublets corresponding to the  $\Pi_{1/2}$  and  $\Pi_{3/2}$  states of  $O^-$  temporary negative ion, has been observed in high-energy resolution time-of-flight experiments by Land and Raith (1974), Ferch *et al.* (1980) and recently by Ziesel *et al.* (1993), see also Field *et al.* (1984). However, the oscillatory structure observed by Ziesel *et al.* is somewhat deeper (25% modulation in the TCS) as seen in other measurements. This discrepancy can hardly be attributed to a difference of the energy resolution of the apparatuses. A 25% contribution to the TCS is also inconsistent with the vibrational excitation CS measured by Linder and Schmidt (1971) which suggest a share of 10% at most (see the discussion in the «vibrational excitation» subsection). The «backwards» TCS of Randell *et al.* (1994) cannot be compared directly with other data. Large discrepancies in the very-low-energy trends has to be noticed between the absolute measurements of Zecca *et al.* (1986) for which no reliability was claimed below 0.2 eV, absolute data of Subramanian and Kumar (1990) extending down to 0.15 eV and the relative data of Ziesel *et al.* (1993) reaching 0.1 eV. The values from the last paper have been normalized by us to the absolute value of Szmytkowski *et al.* (1995) at 0.6 eV. The old absolute measurements of Ramsauer and Kollath (1930) below 1 eV are slightly higher than the latest ones (Zecca *et al.*, 1986; Szmytkowski *et al.*, 1995) and indicate a rise of TCS towards zero energy. However, due to the lack of established energy scale calibration standards, a systematic energy shift in those measurements cannot be ruled out. In fig. 27 we present the absolute TCS of Ramsauer and Kollath shifted by an (arbitrary) value of  $-0.15$  eV.

Somewhat smaller (10%) discrepancies exist in the 1–5 eV range, where recent measurements from Gdańsk laboratory (Szmytkowski *et al.*, 1995) in an improved scattering geometry are lower than the previous data (Zecca *et al.*, 1986) but agree well with the measurement of Kanik *et al.* (1993), not presented in the figure. Measurements of Subramanian and Kumar (1990), who used a gas-photoionization electron source, show the lowest CS values in this region. Absolute TCS of Salop and Nakano (1970) from a Ramsauer-like set-up agree well with the results of Szmytkowski *et al.* (1995) between 2 and 5 eV but tend to be underestimated above 10 eV. Different sets of absolute data (Zecca *et al.*, 1986; Dababneh *et al.*, 1988; Kanik *et al.*, 1992; Szmytkowski *et al.*, 1995) agree at 10 eV. Between 10 and 100 eV the most reliable set of data consists probably in the measurements of Kanik *et al.* (1992), the Trento data in Zecca *et al.* (1986) and the recent results of Szmytkowski *et al.* (1995).

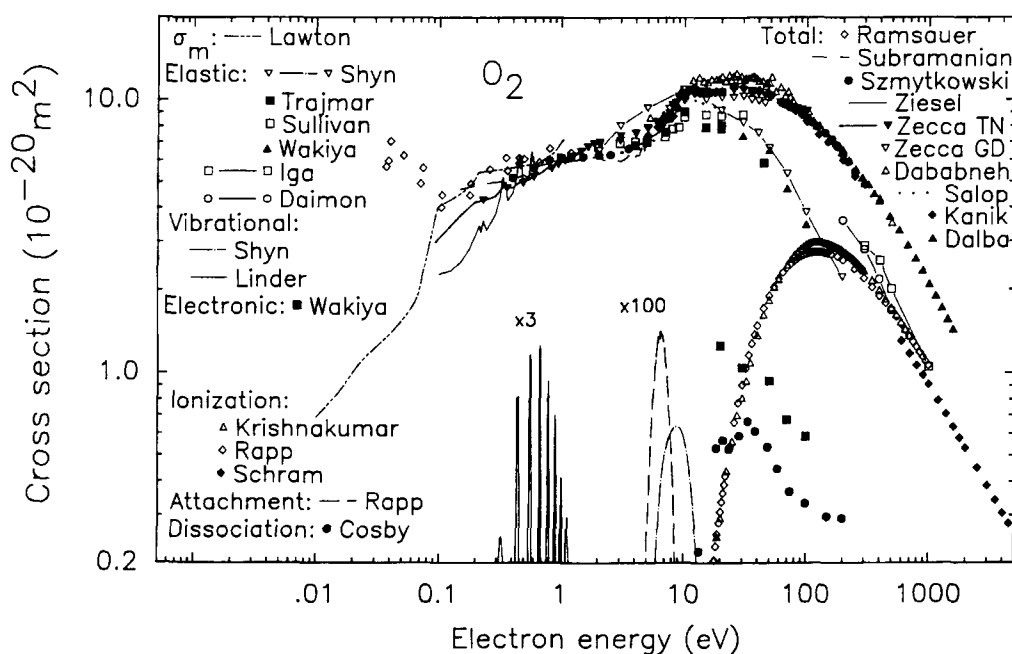


Fig. 27. – Integral cross-sections for electron scattering on  $O_2$ . *Total*: Ramsauer and Kollath (1930) absolute, – 0.15 eV energy correction applied (this work); Subramanian and Kumar (1990); Szmytkowski *et al.* (1995); Ziesel *et al.* (1993) relative, normalized (present work) to Szmytkowski *et al.* (1995) at 0.6 eV; Zecca *et al.* (1986); Gdańsk measurements from Zecca *et al.* (1986); Dababneh *et al.* (1988); Salop and Nakano (1979); Kanik *et al.* (1992); Dalba *et al.* (1980); absolute data of Kanik *et al.* (1993), normalized data of Katayama *et al.* (1985) and recoil-beam of Sunshine *et al.* (1967) not presented for clarity. *Elastic*: absolute of Shyn and Sharp (1982); Trajmar *et al.* (1971) and Wakiya (1978a) normalized to total; absolute of Sullivan *et al.* (1995); Iga *et al.* (1987) normalized to independent-atoms model; Daimon *et al.* (1982) normalized to Bromberg (1974) and integrated in this work; absolute of Wöste *et al.* (1995) at 5–20 eV not presented for clarity. *Momentum transfer*: Lawton and Phelps (1978). *Vibrational*: Shyn and Sweeney (1993b); Linder and Schmidt (1971) normalized in this work for 30 meV peaks FWHM, see text. *Electronic excitations (sum)*: Wakiya (1978a). *Ionization*: Krishnakumar and Srivastava (1992); Rapp and Englander-Golden (1965); Schram *et al.* (1965). *Dissociative attachment*: Rapp and Briglia (1965). *Dissociation*: Cosby (1993).

The data of Dababneh *et al.* (1988), similarly to the  $CO_2$  measurements from the same laboratory, seem to be overestimated over the 15–80 eV energy range. All the measurements, including those of Dababneh *et al.* (1988) and the high-energy data of Dalba *et al.* (1980), merge at 100 eV. The normalized measurements of Katayama (1985), not presented in fig. 27, agree well with the absolute data of Salop and Nakano (1970) and Szmytkowski *et al.* (1995) between 1 eV and 10 eV but fall 20% below the above «recommended» set at 100 eV. Also the recoil-beam measurements of Sunshine *et al.* (1967), deviating from other data by more than 10% in the whole 0.5–100 eV range, are not presented in this figure. In spite of differences in absolute values, different measurements indicate the existence of two maxima in TCS: at about 12 eV and a broad one at 25 eV. Note that both of them have analogies with other diatomic gases like  $N_2$  or CO.

*Swarm experiments.* Generally, fewer swarm experiments have been performed for  $O_2$  than for other simple gases. This reflects the experimental difficulty of quick depletion of the electron swarm due to attachment processes (Crompton and Elford, 1973). An early analysis of swarm coefficients indicated a constant  $3.0 \cdot 10^{-20} \text{ m}^2$  CS in the 0.01–0.1 eV energy range while microwave results pointed out for a descending CS towards zero energy (see Hake and Phelps, 1967). A more recent analysis (Lawton and Phelps, 1978, see also Reid and Crompton, 1980) gives a zero-energy CS in the  $10^{-21} \text{ m}^2$  range. Following this analysis (and also Shimamura, 1989) the zero-energy TCS in molecular oxygen ( $0.35 \cdot 10^{-20} \text{ m}^2$ ) is somewhat higher than the value for Ne ( $0.16 \cdot 10^{-20} \text{ m}^2$ ) but lower than the one for  $N_2$  (about  $1.0 \cdot 10^{-20} \text{ m}^2$ ).

*Elastic cross-section.* Only few experimental data exist for elastic scattering on  $O_2$ . The very-low-energy range (from 0.1 eV to 4.0 V) has been examined by Linder and Schmidt (1971). Energy spectra of elastically scattered electrons at  $60^\circ$  are slowly rising functions of the energy between 0.1 and 1.0 eV and exhibit an oscillatory structure with an energy distance corresponding to vibrational levels of the  $O^-$  temporary negative ion and a modulation of about 15%. Elastic scattering at low energies is almost isotropic, varying at 0.74 eV from  $0.2 \cdot 10^{-20} \text{ m}^2$  at  $20^\circ$  to  $0.45 \cdot 10^{-20} \text{ m}^2$  at  $110^\circ$  (Linder and Schmidt, 1971). A rough ( $\pm 20\%$ ) estimate of the integrated value (this work) gives  $5.0 \cdot 10^{-20} \text{ m}^2$  at 0.74 eV; this is congruent with the total value of  $5.8 \cdot 10^{-20} \text{ m}^2$  (Szymkowski *et al.*, 1995).

Absolute differential and integral CS have been recently obtained by Sullivan *et al.* (1995) at 1–30 eV and by Wöste *et al.* (1995) at 5 eV to 20 eV. DCS at the lowest studied energies (Sullivan *et al.*) agree pretty well with the data of Linder and Schmidt (1971); also their integral CS between 1 eV and 5 eV follow very well the recent (Kanik *et al.*, 1993; Szymkowski *et al.*, 1995) total cross-sections. Similarly good accord exists among different (Shyn and Sharp, 1982; Wöste *et al.*, 1995; Sullivan *et al.*, 1995) integral elastic CS between 5 eV and 20 eV.

Integral, normalized to He, elastic CS of Shyn and Sharp (1982) agree with TCS values at 2 eV and 10 eV but overestimate them at 3 eV and 5 eV. At intermediate energies Shyn and Sharp's data are somewhat higher than the measurements of Wakiya (1978a) and Trajmar *et al.* (1971) normalized to TCS. At high energies good agreement exists between absolute elastic DCS of Bromberg (1974), data of Iga *et al.* (1987) normalized to the independent-atoms model and the results of Daimon *et al.* (1982). At 300–500 eV the DCS for  $O_2$  between  $2^\circ$  and  $10^\circ$  are equal, within experimental uncertainties, to those for  $N_2$  but are higher at  $20$ – $40^\circ$  (Bromberg, 1974), see fig. 26. As follows from independent-atom calculations (Iga *et al.*, 1987; Khare and Raj, 1991) this is to be attributed to interference effects in the intermolecular multiple scattering. The zero-angle elastic DCS at 29 keV for  $O_2$  is slightly (but outside the experimental errors) lower than for  $N_2$  and amounts to  $17.1 \cdot 10^{-20} \text{ m}^2/\text{sr}$  (Zhang *et al.*, 1991), in agreement with the Born approximation (Bonham and Fink, 1986).

*Vibrational excitations.* Schulz and Dowell (1962) during trapped-electron measurements noticed a resonant structure in the vibrational excitation CS at very low energies. Differently than in the case of  $N_2$ , the peaks for excitations of the oxygen molecule into particular states do not shift with energy (Linder and Schmidt, 1971), so the resonant structure is visible also in the integral CS for the vibrational excitation. Due to the long lifetime of the compound  $O_2^-$  state, the resonant peaks in



the vibrational excitation are narrow: TCS measurements with a 5 meV energy resolution (Land and Raith, 1974) indicate that the FWHM of the convoluted  $\Pi_{1/2}$ - $\Pi_{3/2}$  doublets is of the order of 30 meV. The energy resolution in Linder and Schmidt's (1971) experiment was about 50 meV, therefore they gave only energy-integrated absolute values for excitations of separate  $\nu$  states. Assuming a 30 meV width of the resonant peaks, a maximum of  $0.4 \cdot 10^{-20} \text{ m}^2$  (i.e. roughly 10% of the TCS) in the integral CS for vibrational excitation at 0.69 eV can be deduced. We stress, however, the approximate character of this value and of the vibrational structure as presented in fig. 27. The trapped-electrons result (Schulz and Dowell, 1962) is one order of magnitude lower but the excitation functions at 60° (Linder and Schmidt, 1971) indicate a similar contributions from elastic and vibrational channels. Renewed measurements are needed for  $\text{O}_2$  vibrational excitations at very low energies (see also Allan, 1995).

An enhancement of the vibrational CS has been observed between 5 eV and 15 eV (Wong *et al.*, 1973; Shyn and Sweeney, 1993b) and has been attributed to a  $^4\Sigma_u^-$  shape resonance on  $\sigma^*$  orbital (Wong *et al.*, 1973). At 10 eV the integral vibrational CS amounts to about 6% of the total one. Only a few levels up to  $\nu = 4$  were observed and angular distributions exhibit minima at 90° (Shyn and Sweeney, 1993b).

*Electronic excitation.* Excitations of low-lying  $a^1\Delta_g$  (threshold at 0.98 eV) and  $b^1\Sigma_g^+$  (1.63 eV) electronic states exhibit some essential differences with respect to typical electronic excitations, with higher thresholds. Different measurements (Schulz and Dowell, 1962; Konishi *et al.*, 1970; Linder and Schmidt, 1971; Trajmar *et al.*, 1971; Hall and Trajmar, 1975; Wong *et al.*, 1973; Wakiya, 1978b; Shyn and Sweeney, 1993a; Middleton *et al.*, 1992, 1994) indicate that integral CS for both  $a^1\Delta_g$  and  $b^1\Sigma_g^+$  states reach maxima at about 7 eV, but with amplitudes of merely 0.1 and  $0.03 \cdot 10^{-20} \text{ m}^2$ , respectively. These values are well reproduced by resonant-like (Teillet-Billy, 1987) and *R*-matrix (Middleton *et al.*, 1994; Higgins *et al.*, 1994) treatments. A resonant-like spike has recently been observed experimentally at about 10 eV in the integral CS for the excitation of both  $a^1\Delta_g$  and  $b^1\Sigma_g^+$  states (Middleton *et al.*, 1992; Allan, 1995, visible also in measurements of Shyn and Sweeney, 1993a). A good agreement has to be acknowledged with *R*-matrix calculations (Noble and Burke, 1992). Integral CS for the  $a^1\Delta_g$  excitation is presented in fig. 28.

Angular distributions for the  $X^3\Sigma_g^- \rightarrow a^1\Delta_g$  transition are pretty isotropic (Trajmar *et al.*, 1971; Wong *et al.*, 1973; Shyn and Sweeney, 1993a; Middleton *et al.*, 1994). On the other hand, for  $X^3\Sigma_g^- \rightarrow b^1\Sigma_g^+$  the experiments indicate a zero scattering probability into 0° and 180° angles, in agreement with selection rules (Cartwright *et al.*, 1971) for the transitions between  $\Sigma^-$ - $\Sigma^+$  symmetries. The drop to the null value at 0° and 180° can be partially masked in the experiment by superposition of the vibrational excitations.

The excitation energies to the  $a^1\Delta_g$  and  $b^1\Sigma_g^+$  electronic states coincide with  $\nu = 5$  and  $\nu = 8$  vibrational excitations, respectively. It is peculiar that the electron energy loss spectra both at 2 eV (Schulz and Dowell, 1962) as well at 10 eV (Shyn and Sweeney, 1993b) indicate the same order of magnitude coming from corresponding ( $a^1\Delta_g$  and  $\nu = 5$ ,  $b^1\Sigma_g^+$  and  $\nu = 8$ ) electronic and vibrational channels. At energies above 50 eV the integral CS for both *a* and *b* states decreases with energy approximately like  $E^{-3}$  (Wakiya, 1978b).

CS for optically allowed electronic excitation, i.e. the Schuman-Runge continuum

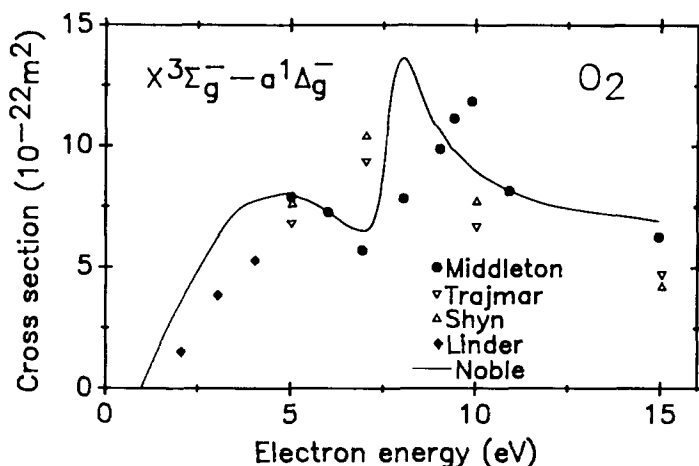


Fig. 28. – Integral cross-section for the excitation to the  $a^1\Delta_g^-$  electronic state in  $O_2$ : Middleton *et al.* (1992), Trajmar *et al.* (1971), Shyn and Sweeney (1993a), Linder and Schmidt (1971), Noble and Burke (1992).

and the excited states in the 9.7–12.1 eV range, were studied by Trajmar *et al.* (1972), Wakiya (1978a) and Newell *et al.* (1980). At 20 eV the optically allowed transitions contribute to 75% of the overall electronic excitation. Above 20 eV the integral CS for optically allowed transitions follows the Born-Bethe formula (Wakiya *et al.*, 1978a). Other optically forbidden states,  $A^3\Sigma_u^+$ ,  $C^3\Delta_u$ ,  $c^1\Sigma_u$ , all of them with excitation energy around 6 eV, reach a maximum of the integral CS of about  $0.12 \cdot 10^{-20} \text{ m}^2$  (Wakiya, 1978b). At 20 eV the sum of all electronic excitations contributes to 13% of the TCS (Wakiya *et al.*, 1978a).

Ajello and Franklin (1985) reviewed earlier optical-emission measurements in  $O_2$  and completed the spectrum for the extreme ultraviolet range. Emission from atomic states was also studied by Schulman *et al.* (1985), Zipf *et al.* (1985) and Zipf (1986). High-resolution optical-absorption spectra have been obtained recently by Chan *et al.* (1993).

*Ionization cross-section.* The total ionization cross-section in  $O_2$  (Rapp and Englander-Golden, 1965; Märk, 1975; Evans *et al.*, 1988) reaches a maximum of  $2.98 \cdot 10^{-20} \text{ m}^2$  at 120 eV (Krishnakumar and Srivastava, 1992), compared with  $2.73 \cdot 10^{-20} \text{ m}^2$  for  $N_2$  (see Krishnakumar and Srivastava in subsect. 4'2). The contribution from dissociative ionization is higher than in  $N_2$  (Rapp *et al.*, 1965; Krishnakumar and Srivastava, 1992). It reaches 40% of the total ionization at 120 eV (Van Zyl and Stephen, 1994). The data of Schram *et al.* (1965) at 1000 eV are 10% lower than other data at this energy. DCS for dissociative ionization were studied by Zhukov *et al.* (1990).

*Metastables.* Electron scattering from metastable states of  $O_2$  is important in plasma and aurora processes. Elastic (Hall and Trajmar, 1975) and electronic excitations (Khakoo *et al.*, 1983) have been studied for the long-lived ( $\tau = 2.7 \cdot 10^3 \text{ s}$ )  $a^1\Delta_g$  metastable state of  $O_2$ . Collisional de-excitation of this state has been studied by Yamabe and Phelps (1983).

TABLE XV. – *Integral cross-sections for electron scattering on molecular oxygen (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Vibra- tional <sub>SS</sub>	Electronic <sub>W</sub>	Disso- ciation <sub>C</sub>	Ioni- zation <sub>K</sub>	Sum	Total
0.74	5.0 <sub>L</sub>	0.4 <sub>L</sub>				5.4	5.8 <sub>SZ</sub> *
2.0	6.5 <sub>S</sub>						6.27 <sub>SZ</sub>
3.0	8.0 <sub>S</sub>						6.45 <sub>SZ</sub> *
5.0	9.3 <sub>S</sub>	0.13				9.4	7.40 <sub>KA</sub> 7.18 <sub>SZ</sub>
7.0	8.9 <sub>S</sub>	0.53				9.4	8.37 <sub>SZ</sub> *
10.0	10.9 <sub>S</sub> 9.0 <sub>T</sub>	0.59				11.5 9.6	10.14 <sub>KA</sub> 10.4 <sub>SZ</sub>
15.0	10.0 <sub>S</sub> 7.9 <sub>T</sub>	0.08	0.6**	(0.31)		10.7 8.6	10.75 <sub>KA</sub> 10.8 <sub>SZ</sub>
20	9.1 <sub>S</sub> 7.8 <sub>W</sub> 8.0 <sub>T</sub>		1.25	(0.55)	0.29	10.6 9.3 9.5	10.79 <sub>KA</sub> 10.7 <sub>SZ</sub>
30	8.2 <sub>S</sub> 7.3 <sub>W</sub>		1.04	(0.61)	0.81	10.1	11.12 <sub>KA</sub>
50	6.6 <sub>S</sub> 6.5 <sub>W</sub>		0.93	(0.52)	1.82	9.4	10.36 <sub>KA</sub>
70	5.3 <sub>S</sub> 4.7 <sub>W</sub>		0.67	(0.38)	2.45	8.42	9.41 <sub>KA</sub>
100	3.8 <sub>S</sub>		0.58	(0.33)	2.91	7.29	8.26 <sub>KA</sub>
150	2.7 <sub>S</sub>		0.39**	(0.29)	2.95	6.04	6.97 <sub>KA</sub>
200	2.2 <sub>S</sub> 3.6 <sub>DA</sub>		0.29**		2.75	5.24 6.64	5.97 <sub>KA</sub>
300	2.88 <sub>I</sub> 2.7 <sub>DA</sub>		0.19**		2.33	5.40 5.22	4.88 <sub>KA</sub> 5.05 <sub>D</sub> *
400	2.54 <sub>I</sub> 2.2 <sub>DA</sub>		0.14**		1.98	4.66 4.32	4.21 <sub>D</sub>
500	2.00 <sub>I</sub> 1.7 <sub>DA</sub>		0.11**		1.71	3.82 3.52	3.61 <sub>D</sub> *
1000	1.05 <sub>I</sub>		0.05**		1.05	2.15	2.13 <sub>D</sub>

( ) – Not used for summation.

\* – Interpolated data.

\*\* – Extrapolated data.

C – Cosby (1993).

DA – Daimon *et al.* (1982) normalized to Bromberg (1974) and integrated in this work ( $\pm 10\%$  error).D – Dalba *et al.* (1980).I – Iga *et al.* (1987).

K – Krishnakumar and Srivastava (1992).

KA – Kanik *et al.* (1992).

L – Linder and Schmidt (1971), rough estimates.

S – Shyn and Sharp (1982).

SS – Shyn and Sweeney (1993b).

SZ – Szmytkowski *et al.* (1995).T – Trajmar *et al.* (1971), normalized to total.

W – Wakiya (1978a).

Molecular dissociation into the metastable  $O(^5S_0)$  atoms was studied by Borst and Zipf (1971), Freund (1971), Erdman and Zipf (1987) and Mason and Newell (1990). Erdman and Zipf (1987) argued that the previously accepted maximum CS of  $0.11 \cdot 10^{-20} \text{ m}^2$  at 90 eV for this state (Wells *et al.*, 1971) can be overestimated by a factor larger than 2. Dissociation into the  $^1S_0$  metastable state of atomic oxygen reaches a maximum of  $0.02 \cdot 10^{-20} \text{ m}^2$  at 80 eV (LeClair and McConkey, 1993).

*Dissociation into neutrals.* Dissociation integral CS in the 13.5–200 eV energy range has been obtained in a crossed-beam experiment by Cosby (1993). It reaches a maximum of about  $0.66 \cdot 10^{-20} \text{ m}^2$  at 33 eV. In the 15–150 eV range the total dissociation cross-section amounts roughly to half of that for the overall electronic excitation (see table XV).

*Dissociative attachment.* Dissociative attachment CS exhibits a single, broad peak centred around 7 eV, where it amounts to 0.1% of the TCS (Schulz, 1962; Rapp *et al.*, 1965).

*Resonances.* The existence of a  $^2\Pi_g O_2^-$  resonant state below 1 eV was observed in transmitted-current experiments (Boness and Hasted, 1966; Spence and Schulz, 1970; Boness and Schulz, 1970), in vibrational excitation (Schulz and Dowell, 1962; Linder and Schmidt, 1971) and in TCS measurements (Land and Raith, 1974; Ferch *et al.*, 1980; Zecca *et al.*, 1986). Recent measurements (Allan, 1995) of the excitation to the  $a^1\Delta_g$  and  $b^1\Sigma_g^+$  states showed three resonant peaks centred at 4 eV, 6.5 eV and 8 eV but their assignment is not clear.

The  $^4\Sigma_u^-$  shape resonance at about 9.5 eV (Wong *et al.*, 1973) shifts to lower energies when scattering takes place on  $O_2$  molecules adsorbed on surfaces (Šiller *et al.*, 1993).

Resonances in the 8–13 eV region were studied by Sanche and Schulz (1971, 1972), Trajmar *et al.* (1976) and reviewed in numerous works, starting from Schulz (1973).

*Sum check.* Sum check indicates a rather poor agreement between partial CS and TCS for  $O_2$ . Elastic CS in particular show to have a large scatter, being sometimes larger than the TCS. At 20 eV, the sum obtained using the elastic CS of Shyn and Sharp (1982) agrees better with the TCS than the sum obtained when Wakiya's (1978a) or Trajmar *et al.*'s (1971) data are used. At 200 eV, *i.e.* at the only point of overlap between elastic CS of Shyn and Sharp and those of Daimon *et al.* (1982), neither of these results is compatible with the total value. At 500 eV the value of Daimon *et al.*, normalized to Bromberg (1974) and integrated by us, is in closer agreement with the TCS of Dalba *et al.* (1980) than the integral CS of Iga *et al.* (1987), normalized to the independent-atoms model. At 1000 eV the value of Iga *et al.* is coherent with the TCS, due to the better reliability of the independent-atoms model at high energies.

*Note added in proofs.* Elastic and vibrational cross-sections from 0.15 eV to 16 eV have been measured with a high resolution by Allan (*J. Phys. B*, 28 (1995) 5163).

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**4.5. Nitric oxide (NO).** – Nitrogen monoxide is of basic importance for atmospheric processes. Its role in aurora phenomena has been recognized (Rusch and Barth, 1975). The growing interest for anthropogenic pollutants has triggered new research in the last years. Existing measurements concentrated mainly on resonance and ionization phenomena. TCS data, apart from the pioneering measurements of Brüche (1927), come exclusively from two laboratories (Zecca *et al.*, 1974; Dalba *et al.*, 1980; Szmytkowski and Maciąg, 1991; Szmytkowski *et al.*, 1995). Only recently, elastic measurements of Mojarrabi (1995) have superseded earlier fragmentary data of Kubo *et al.* (1981). Integral cross-sections for NO are shown in fig. 29.

*Total cross-sections* have been measured by Brüche (1927) between 1.0 eV and 50 eV, Zecca *et al.* (1974) between 0.03 eV and 10 eV, by Szmytkowski and Maciąg (1991) between 0.5 and 150 eV, Szmytkowski *et al.* (1995) at 0.4–200 eV and Dalba *et al.* (1980) at 100–1400 eV. All the low-energy measurements evidenced a resonant structure between 0.3 and 1.5 eV. The data of Zecca *et al.* (1974) are approximately 10% lower than those of Szmytkowski and collaborators (1991, 1995). This might be attributed to the normalization procedure adopted by Zecca *et al.* (1974). At 100 eV the data of Szmytkowski and co-workers match well with the absolute measurements of Dalba *et al.* (1980).

Experimental TCS (Szmytkowski and Maciąg, 1991) exhibit a large maximum at

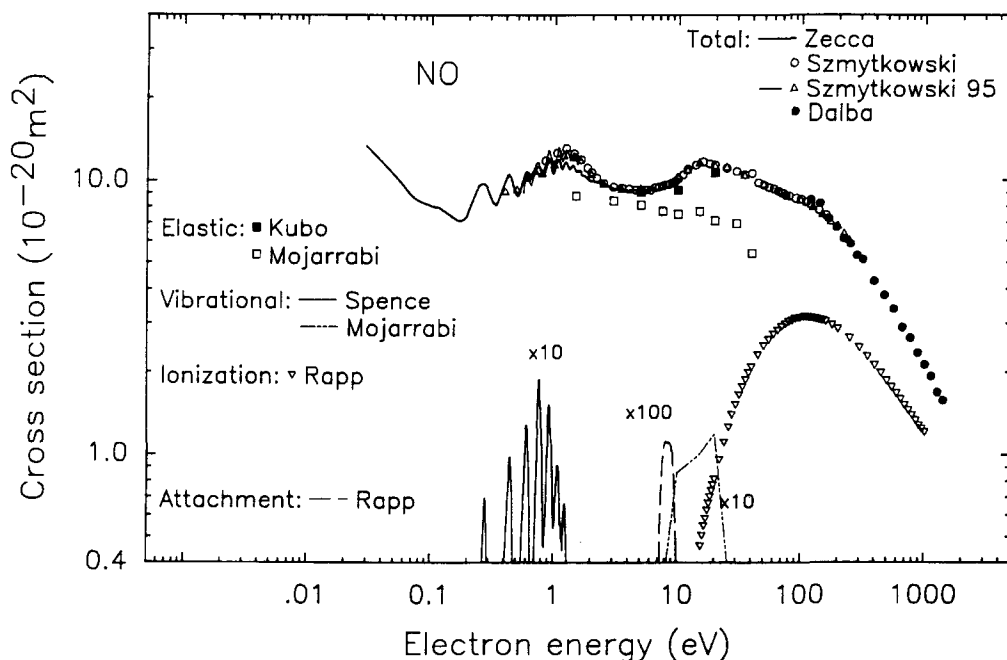


Fig. 29. – Integral cross-sections for electron scattering on NO. *Total:* Zecca *et al.* (1974); Szmytkowski and Maciąg (1991); Szmytkowski *et al.* (1995); Dalba *et al.* (1980). *Elastic:* Kubo *et al.* (1981) digitized from their figures and integrated in this work ( $\pm 20\%$  extrapolation error); Mojarrabi *et al.* (1995) absolute. *Vibrational:* Mojarrabi *et al.* (1995) absolute for  $\nu = 0 \rightarrow 1$  and  $\nu = 0 \rightarrow 2$  excitations; visualization of overall vibrational cross-section from trapped-electrons studies (Spence and Schulz, 1971). *Dissociative attachment:* Rapp and Briglia (1965). *Ionization:* Rapp and Englander-Golden (1965).

about 16 eV. A weak shoulder structure at 8 eV is present in fig. 1 of Szmytkowski and Maciąg (1991). The fixed-nuclei optical model (Jain *et al.*, 1995), not presented in our fig. 29, predicts a well-pronounced maximum at the same energy. As can be noticed for example for OCS, the discrepancy regarding the magnitude of this feature could derive from neglecting the nuclear motion in the calculation. Jain *et al.*'s total (elastic + absorption) cross-section above 100 eV agrees well (within 10%) with the experiment of Dalba *et al.* (1980).

A vibrational structure has been observed between 0.3 eV and 1.5 eV in all (Zecca *et al.*, 1974; Szmytkowski and Maciąg, 1991; Szmytkowski *et al.*, 1995) TCS measurements. Brüche (1927) has not observed any structures; this is explainable by the poor energy resolution of his set-up. On average, Brüche's absolute values (with a maximum of  $12.4 \cdot 10^{-20} \text{ m}^2$  at 1.5 eV) are in a good agreement with the recent measurements (Szmytkowski *et al.*, 1995).

*Elastic cross-sections* have been reported by Kubo *et al.* (1981) at 5 eV, 10 eV and 20 eV and recently by Mojarrabi *et al.* (1995) from two independent determinations (relative measurements from Flinders University and absolute from Australian National University at Canberra) between 1.5 eV and 40 eV. The data of Kubo *et al.* agree with the more recent results except for the point at 20 eV where they seem to be overestimated at intermediate and high scattering angles.

Born-closure Schwinger variational calculations (Lee *et al.*, 1992) reproduce well the experimental DCS of Kubo *et al.*, and, to a less extent, the data of Mojarrabi *et al.*; unfortunately no integral CS are given by the theory. The calculation of Jain *et al.* (1995) does not reproduce correctly the shape of the experimental DCS. Integral experimental CS (Mojarrabi *et al.*, 1995) are at 3 eV and 5 eV slightly (15%) lower than the TCS (Szmytkowski *et al.*, 1995). Integral CS of Mojarrabi descend slowly with energy between 1.5 eV and 40 eV and exhibit a weak maximum at 15 eV. The integral cross-sections evaluated in this work by a rough integration of Kubo *et al.*'s data are in disagreement with the data of Mojarrabi *et al.* (1995).

Elastic scattering in the 0.1–1.5 eV energy range has been studied by Tronc *et al.* (1975). A vibrational structure, similar to the one occurring in  $\text{N}_2$ , has been observed at different scattering angles (see also Field *et al.*, 1989). However, the intensity of the modulation, when viewed in TCS, is smaller for NO than for  $\text{N}_2$ . DCS between 0.43 eV and 0.91 eV vary quickly with energy, indicating the presence of resonant states.

In fig. 30 we compare the NO elastic differential cross-sections with those of  $\text{N}_2$ ,  $\text{O}_2$  and CO at 5 eV, 10 eV and 30 eV. An essential similarity of these CS at each considered energy can be noticed immediately. At 30 eV the four DCS coincide within the experimental error (note that no single-laboratory set of data can be chosen for these gases). At 10 eV the  $\text{O}_2$  and NO data almost coincide, with CO being higher due to the influence of the nearby resonance.

*Vibrational excitation* functions (Ehrhardt and Willmann, 1967; Spence and Schulz, 1971; Tronc *et al.*, 1975) below 2 eV are strongly influenced by the existence of a resonant state. Overtones up to  $\nu = 7$  have been detected in the energy loss spectra (Tronc *et al.*, 1975). Excitation functions to specific levels exhibit resonant peaks at energies corresponding to vibrational levels of the compound  $\text{NO}^-$  state (Spence and Schulz, 1971). The peaks in the summed vibrational CS correspond to those observed in TCS. A rough estimate ( $\pm 50\%$ ) of the absolute value of the summed vibrational



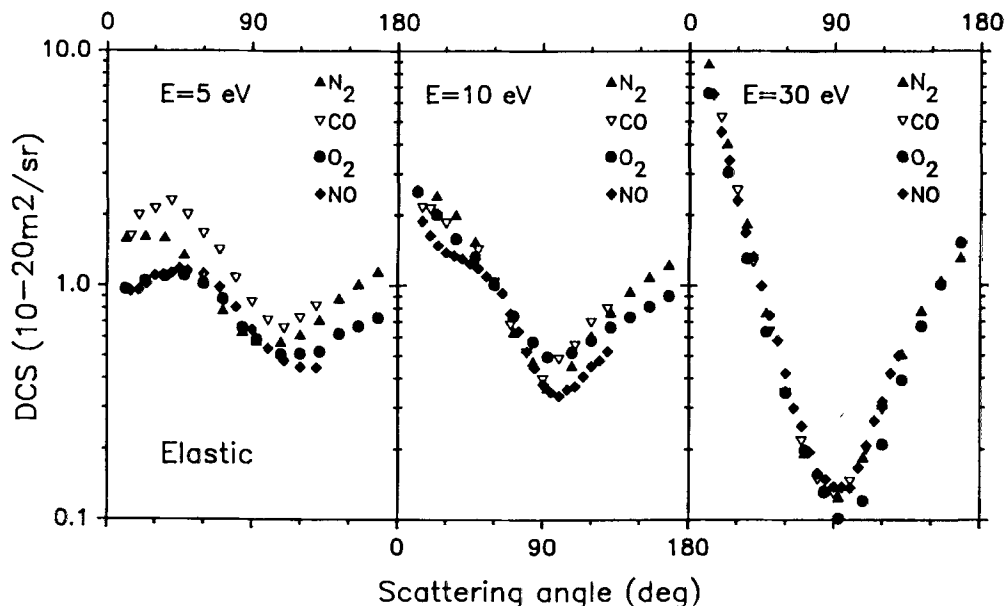


Fig. 30. – Comparison of elastic differential cross-sections for  $\text{N}_2$ ,  $\text{CO}$ ,  $\text{O}_2$  and  $\text{NO}$  at 5, 10 and 30 eV.  $\text{N}_2$  data, Shyn and Carignan (1980);  $\text{O}_2$  data, Shyn and Sharp (1982);  $\text{NO}$  data, Mojarrabi *et al.* (1995), 5 eV;  $\text{CO}$  data, Tanaka *et al.* (1978) at 5 eV and 10 eV, Nickel *et al.* (1988) at 30 eV.

excitation (Spence and Schulz, 1971) has been made by the authors of this review. It gives a value of  $0.2 \cdot 10^{-20} \text{ m}^2$  at 0.75 eV. The probabilities of excitation to the overtones  $\nu = 1$  to  $\nu = 5$  diminish by a factor of 2 for each successive  $\nu$  (Tronc *et al.*, 1975). These branching ratios are somewhat lower than for  $\text{O}_2$  and indicate a smaller barrier penetration effect, due to allowance for a  $p$ -wave contribution in  $\text{NO}$  (a similar difference holds for  $\text{N}_2$  and  $\text{CO}$ , as described previously). No unique partial-wave classification, as has been done for  $\text{N}_2$  and  $\text{CO}$  (compare fig. 24), can be attributed to the observed DCS for vibrational excitations in  $\text{NO}$  at low energies (Tronc *et al.*, 1975).

Absolute measurements of vibrational excitation in  $\text{NO}$  between 1.5 and 40 eV have been performed by Mojarrabi *et al.* (1995). Between 7.5 eV and 40 eV the vibrational excitation amounts to about 3% of the elastic part. A maximum in the integral vibrational CS has been observed at 15 eV, in analogy with  $\text{N}_2$  and  $\text{CO}$ . This enhancement as well as a change in the shape of the differential CS for  $\nu = 0 \rightarrow 1$  and  $\nu = 0 \rightarrow 2$  excitations (from a forward-peaked one at 7.5 eV to a flatter one at 15 eV) indicate the presence of a further resonant process.

*Electronic excitation and optical emission.* We are unaware of electronic excitation CS obtained by the energy loss technique. Optical-emission CS have been measured by Lawrence (1970), Mentall and Morgan (1972), Stone and Zipf (1972), Imami and Borst (1975), Van Sprang *et al.* (1979), Ajello *et al.* (1989a, b) and reviewed by van der Burgt *et al.* (1989). The extreme ultraviolet spectrum (40–120 nm) consists entirely of emission from excited O and N atoms and ions (Ajello *et al.*, 1989a), with the 120.0 nm feature from the  $\text{N}^+ g^4S^0 \rightarrow P$  transition dominating over the  $\text{O}^+ g^3P \rightarrow$

$\rightarrow {}^3S^0$  one (cross-sections of 1.7 and  $0.74 \cdot 10^{-22} \text{ m}^2$  at 200 eV, respectively). In the far ultraviolet (120–170 nm) the emission from excited  $\text{NO}^+$  ions dominates. The relative emission CS from dissociated fragments and the parent  $\text{NO}^+$  ion corresponds roughly to the dissociative ionization fraction: emission CS for ( $\text{NO}^+ X^1\Sigma^+ \rightarrow A^1\Pi$ ,  $v' = 0, 1$ ) transitions amounts to  $6.3 \cdot 10^{-22} \text{ m}^2$  at 200 eV (Ajello *et al.*, 1989a). In the middle ultraviolet (170–270 nm) emission from molecular bands is dominant. Cross-sections for  $A^2\Sigma^+$ ,  $C^2\Pi_r$ ,  $B'^2\Delta_i \rightarrow X^2\Pi_g$  transitions at 200 eV amount to 2.3, 1.0 and  $2.0 \cdot 10^{-22} \text{ m}^2$ , respectively (Ajello *et al.*, 1989b). Earlier, fragmentary CS for these molecular bands (Stone and Zipf, 1972; Imami and Borst, 1975) are underestimated by a factor of five, roughly.

Energy loss spectra have been obtained and numerous Rydberg and valence-excited states have been identified between 4 eV and 10.5 eV by Frueholz *et al.* (1978), Greteau *et al.* (1979a, b), Stubbs *et al.* (1986).

*Ionization cross-sections* measurements (Tate and Smith, 1932; Rapp and Englander-Golden, 1965) show that NO forms positive ions relatively more easily than  $\text{N}_2$ , CO or  $\text{O}_2$  (2.52, 2.66, 2.72 and  $3.15 \cdot 10^{-20} \text{ m}^2$  are the cross-section maxima for  $\text{N}_2$ , CO,  $\text{O}_2$  and NO, respectively). This reflects the ionization threshold values in these gases: 15.58, 14.01, 12.06, 9.25 eV, respectively. Appearance potentials for observation of  $\text{NO}^+$ ,  $\text{N}^+$  and  $\text{O}^+$  ions from NO are 9.3 eV, 19.3 eV and 20.0 eV, respectively (Hagstrum, 1955; Hierl and Franklin, 1967). Above 100 eV, dissociative ionization amounts to about 25% of the overall ionization (Rapp *et al.*, 1965) and  $\text{O}^+$  ions constitute less than 5% of the  $\text{N}^+$  ions (Tate *et al.*, 1935; Hanson, 1937; Kim *et al.*, 1981). The double ionization at 180 eV is almost two orders of magnitude less probable than a single one (Kim *et al.*, 1981). Formation of metastable ions was studied by Kadota and Kaneko (1977).

*Dissociative attachment cross-section* (for  $\text{O}^-$  yield) exhibits a broad peak between 6.5 eV and 10 eV (Rapp and Briglia, 1965; Dorman, 1966; Chantry, 1968; Paquet *et al.*, 1971; Harland *et al.*, 1973; Van Brunt and Kieffer, 1974; Mazeau *et al.*, 1978; Krishnakumar and Srivastava, 1988). The maximum value at 8.1 eV amounts to  $0.01 \cdot 10^{-20} \text{ m}^2$  (Rapp and Briglia). Orient and Chutjian (1989) measuring the kinetic energy of  $\text{O}^-$  ions have observed three overlapping peaks corresponding to the formation of N atoms in the fundamental ( ${}^4S$ ) and excited ( ${}^2D$  and  ${}^2P$ ) states. Unstable nitrogen ions  $\text{N}^-$  ( ${}^3P$ ) were observed at about 8 eV (Mazeau *et al.*, 1978).

*Resonances.* Strong resonant effects were observed below 2 eV in transmission (Boness and Hasted, 1966; Boness *et al.*, 1968; Hasted and Awan, 1969; Burrow, 1974), vibrational excitation (Ehrhardt and Willmann, 1967; Tronc *et al.*, 1975) and backward-scattered (Spence and Schulz, 1971) spectra. They have been explained (Teillet-Billy and Fiquet-Fayard, 1977; Tennyson and Noble, 1986) in terms of three short-lived ( $10^{-14} \text{ s}$ ) overlapping states of  ${}^3\Sigma^-$ ,  ${}^1\Delta$  and  ${}^1\Sigma^+$  symmetries.

Evidence of Feshbach resonances at about 10 eV was noticed in transmission spectra (Sanche and Schulz, 1972), in the electron attachment measurements (Mazeau *et al.*, 1978) and in the spectra of scattered electrons (Greteau *et al.*, 1977, 1979a, b).

*Sum check.* No sum check is possible on the basis of existing data for nitrogen oxide. In particular, no electronic excitation CS are available. Therefore, in table XVI

TABLE XVI. - *Integral cross-sections for electron scattering on nitric oxide (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic <sub>M</sub>	Vibrational <sub>M</sub>	Ionization <sub>R</sub>	Sum <sup>\$</sup>	Total <sub>SZ</sub>
1.5	8.75				12.1
3.0	8.38				9.45
5.0	8.09				9.30
7.5	7.68	0.028		7.71	9.58
10	7.50 9.0 <sub>K</sub>	0.086		7.59 9.1	10.3
15	7.68 9.2 <sub>K</sub>	0.343		8.02 9.5	11.6
20	7.09 10.7 <sub>K</sub>	0.119	0.81	8.02 11.6	11.3
30	6.92	0.022	1.52	8.46	10.8
40	5.37	0.014	2.48	7.86	10.3

\$ - No electronic-excitation data available.

M - Mojarrabi *et al.* (1995).

SZ - Szmytkowski *et al.* (1995) and Szmytkowski and Maciąg (1991).

K - Kubo *et al.* (1981), integrated in this work ( $\pm 20\%$  possible extrapolation error).

R - Rapp and Englander-Golden (1965).

we perform only an incomplete comparison. The difference between TCS (Szmytkowski *et al.*, 1995) and the sum of the elastic and vibrational CS (Mojarrabi *et al.*, 1995) would indicate that the electron excitation CS possibly amounts to 20% of TCS at 15 eV. On the other hand, an  $1/E$  extrapolation of the CS for emission from molecular bands (Ajello *et al.*, 1989b) down to 20 eV yields  $0.5 \cdot 10^{-20} \text{ m}^2$ , *i.e.* barely 5% of the TCS.

We note finally that for all energies above 5 eV the NO total cross-section (Szmytkowski *et al.*, 1995; Dalba *et al.*, 1980) is bound between the  $\text{N}_2$  and  $\text{O}_2$  cross-sections, as upper and lower limits, respectively.

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4'6. *Other diatomic gases.* – We are unaware of total or elastic CS measurements for other homonuclear gases ( $F_2$ ,  $Cl_2$ ,  $Br_2$ ). A semiempirical set of total and partial CS for the fluorine molecule has been derived from swarm data by Hayashi (1983a, b). Positive and negative ionization for this molecule was studied by Rao and Srivastava (1989). Theoretical elastic CS have been obtained by Schneider and Hay (1976), Rescigno *et al.* (1976) and Morgan and Noble (1984).

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## 5. – Light atoms

Experimental investigations of electron scattering on light atoms H, C, N, O require particular techniques for preparing these species and therefore have been carried sporadically. Additionally, the measurements are usually normalized to the molecular ( $H_2$ ,  $O_2$ ,  $N_2$ ) cross-sections. For atomic hydrogen one could expect some analogies with other open-shell atoms, like alkali metals.

5'1. *Atomic hydrogen (H).* – Electron scattering on atomic hydrogen is of fundamental theoretical interest. Atomic hydrogen possesses a relatively high dipole polarizability of  $0.67 \cdot 10^{-30} \text{ m}^3$  (compared to  $0.20 \cdot 10^{-30} \text{ m}^3$  for He and  $0.80 \cdot 10^{-30} \text{ m}^3$  for  $H_2$ ). First experiments in electron scattering on H dating from late fifties used microwave techniques for dissociation of molecular hydrogen. Sets of partial and total cross-sections have been estimated in numerous works (de Heer *et al.*, 1977; Callaway and McDowell, 1983; van Wyngaarden and Walters, 1986; King *et al.*, 1989; Scholz *et al.*, 1990). Our best knowledge of integral CS is summarized in fig. 31. Selected measurements of the molecular-hydrogen total cross-sections have been inserted in the figure to allow a comparison.

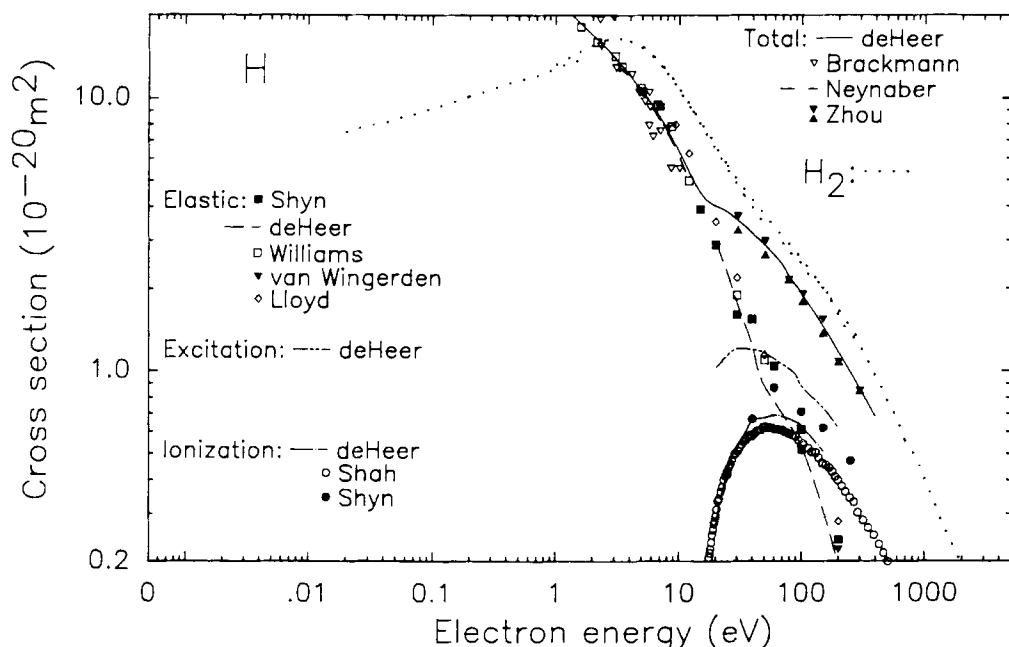


Fig. 31. – Integral cross-sections for electron scattering on H. *Total*: de Heer *et al.* (1977) semiempirical; Brackmann *et al.* (1958) integral elastic from  $90^\circ$  scattering (see text); Neynaber *et al.* (1961) normalized to  $H_2$ ; Zhou *et al.* (1994) absolute, upper (55% dissociation) and lower (100% dissociation) limits. *Elastic*: Shyn and Cho (1989) and Shyn and Grafe (1992); de Heer *et al.* (1977) semiempirical; Williams (1975a, b), integrated values from de Heer *et al.* (1977) and from numerical integration in the present work (15 extrapolation error); van Wingerden *et al.* (1977); Lloyd *et al.* (1974) from  $H/H_2$  ratios normalized to recent integral cross-sections for  $H_2$  (Nickel *et al.*, 1992 at 9.4 eV and 12 eV; Khakoo and Trajmar, 1986 at higher energies). *Excitation*: de Heer *et al.* (1977), semiempirical. *Ionization*: de Heer *et al.* (1977) semiempirical; Shah *et al.* (1987) absolute; Shyn (1992) integrated. *Total  $H_2$  cross-section*: selected measurements are shown for comparison (see fig. 18 for captions).

*Total cross-section.* First TCS have been obtained by Neynaber *et al.* (1961) at 3.1–12.3 eV in a relative measurement. The results were normalized to the to molecular-hydrogen CS (Brüche, 1927; Normand, 1930). As these latter values are lower than the more recent evaluations (by 15% on the average), also the atomic-hydrogen TCS of Neynaber are considered to be underestimated. Brackmann *et al.* (1958) have studied the signal of electrons scattered into a  $45^\circ$  half-apex cone with the axis perpendicular to the incident beam. They have obtained absolute integral values assuming an isotropic (*s*-wave) scattering and using the  $H_2$  DCS of Ramsauer and Kollath (1932). In fig. 31 we present values obtained by averaging those given by Brackmann *et al.* (1958) for each studied energy.

Only recently, Zhou *et al.* (1994) have measured absolute electron and positron TCS between 30 eV and 300 eV in a cell experiment. In their experiment the atomic hydrogen constituted at least 55% of the target gas in the cell; therefore the upper (assuming 55% dissociation) and lower (assuming 100%) limits on TCS have been established. It is worth noting that above 30 eV the two ( $e^-$  and  $e^+$ ) TCS coincide within experimental errors, in spite of an essentially different partitioning scheme.

(Positron-H total cross-sections exhibit a minimum at about 5 eV, similar to that observed for  $e^+$ -He scattering.) Measurements of Zhou *et al.* (1994) also indicate that the ratio between  $H_2$  and H total cross-sections remains constant above 30 eV and equals about 1.4, in contradiction with a hypothetical additivity rule (see subsect. 1'4).

Semiempirical TCS from sum of the partial values between 0.136 eV and 400 eV have been obtained by de Heer *et al.* (1977). Agreement between the semiempirical data and the recent experiment (Zhou *et al.*, 1994) can be considered very good.

*Elastic cross-section.* Teubner *et al.* (1974) and Lloyd *et al.* (1974) have measured ratios between  $H_2$  and H elastic differential cross-sections at 9.4–20 eV and 30–200 eV, respectively. Van Wingerden *et al.* (1977) reported integral elastic CS at 100 eV and 200 eV deduced from their measurements for molecular hydrogen and  $H_2$  over H ratios of Lloyd *et al.* (1974). Williams (1975a) has obtained absolute DCS at 10–150° angular and 0.5–8.7 eV energy ranges and at 10–140°, 20–680 eV (Williams, 1975b) by normalization to his He values. Both experimental and theoretical values at 10–30 eV were given by Callaway and Williams (1975). Hydrogen DCS normalized to  $H_2$  at angles from 12° to 156° have been measured by Shyn and Cho (1989) at 5–30 eV energies and by Shyn and Grafe (1992) at 40–200 eV. DCS of Williams and of Shyn and collaborators agree very well for all scattering angles at low energies but diverge somewhat at obtuse angles and collision energies larger than 20 eV. At 100 eV and 140° the DCS of Shyn and Grafe (1992) is a factor of 2 higher than the result of Williams (1975b). Note that, according to Shyn and Grafe (1992), DCS in atomic hydrogen even at 100 eV does not exhibit a Born-like shape but rises at scattering angles larger than 90°. This finding is in contradiction with various theories (see Shyn and Grafe, 1992; Scholz *et al.*, 1991; Bubulev *et al.*, 1995) as well as with the experimental data of Williams (1975b) and Lloyd *et al.* (1974).

In fig. 32 we compare the differential elastic cross-sections for H,  $H_2$  and He at 5 eV, 20 eV and 100 eV from measurements of Shyn and co-workers and for H only from Williams. One notes, at all considered energies, some analogies between atomic and molecular hydrogen. At 5 eV and obtuse scattering angles, the H differential cross-section is roughly a factor 1.25 smaller than the one of  $H_2$ . At 20 eV the low-angle DCS scale as 2:1, while high-angle DCS coincide within the experimental discrepancies. At 100 eV the small-angle (12–48°) DCS for  $H_2$  and H differ by less than 10%, while this difference is of a factor of two at 96°; consequently the  $H_2$ /H ratio for the integral values is merely 1.25 (Shyn and Sharp, 1981; Sharp and Grafe, 1992). At this energy the elastic DCS for atomic hydrogen falls by a factor of 200 in the 12–90° angular span; also in this respect the atomic hydrogen resembles molecular hydrogen more than helium.

*Excitation cross-sections* for the excitations to  $n = 2$  ( $2S + 2P$ ) states have been measured by Williams and Willis (1975) over the angular range from 20° to 140° for incident energies of 54 eV to 680 eV and by Williams (1976) at 13.9–19.6 eV. DCS for separate excitations to  $2S$  and  $2P$  states were studied by electron-photon coincidence techniques by Frost and Weigold (1980), Weigold *et al.* (1980) and Williams (1981) at 54.4 eV. Recent DCS for the  $n = 2$  state (Shyn and Grafe, 1993) agree at 15 eV with the measurements of Williams (1976) in the forward direction but disagree in the backward scattering; at 20 eV the two sets of data coincide within experimental errors. DCS of Doering and Vaughan (1986) for  $n = 2$  at 100 eV and scattering angle

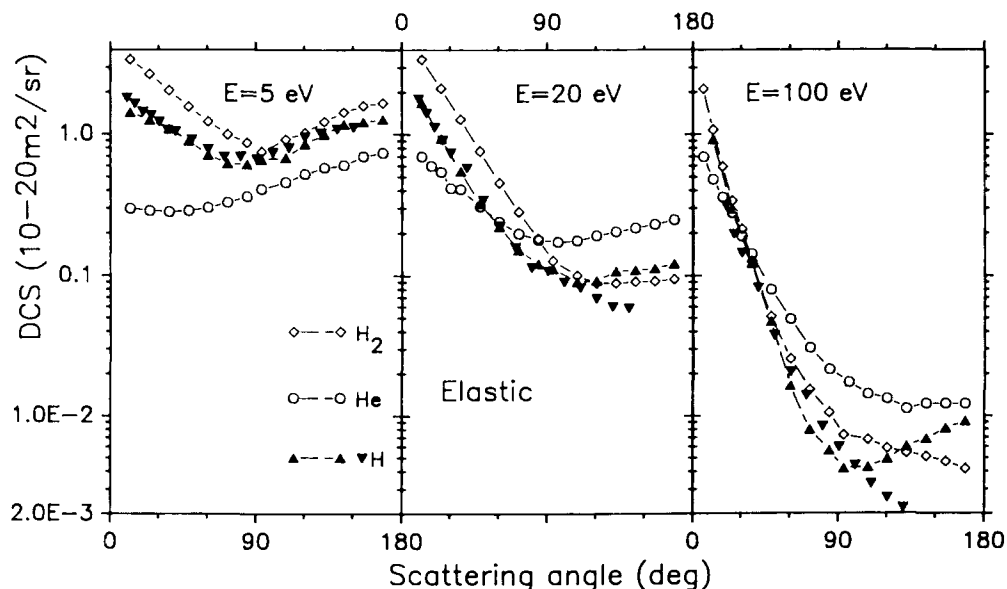


Fig. 32. – Differential cross-sections for elastic scattering of electrons on H, H<sub>2</sub> and He. Helium values from Shyn (1980). Molecular hydrogen from Shyn and Sharp (1981). Atomic hydrogen, triangles, Shyn and Grafe (1992) and Shyn and Cho (1989); inverted triangles, Williams (1975a) at 4.89 eV and Williams (1975b) at 20 eV and 100 eV.

of 120° are higher by a factor of 2 than the value of Williams and Willis (1975). Ratios between inelastic  $n = 2$  and elastic cross-sections at 100 eV and 200 eV have also been studied both experimentally and theoretically (in a close-coupling model) by Lower *et al.* (1987).

At intermediate and high energies the experimental excitation DCS do not contrast with the results from the Born approximation at low scattering angles but exceed them at higher angles (Williams and Willis, 1975).

Optical emission from 2P and 2S states has been studied in 1970 by Ott *et al.* and Kauppila *et al.*, respectively. Normalized values for the 2P state were obtained by Fite and Brackmann (1958b). Williams (1976) studied emission from 2S and 2P states near the threshold. The cross-section for the 2S state reaches a maximum of  $0.18 \cdot 10^{-20} \text{ m}^2$  at 11.4 eV; the one for the 2P state reaches a maximum of  $0.38 \cdot 10^{-20} \text{ m}^2$  at about 13 eV; resonant structures are well visible in optical-excitation functions (Williams, 1976). Absolute values of Williams are in good agreement with the earlier measurements (Ott *et al.*, 1970; Kauppila *et al.*, 1970). Relative emission cross-sections up to 500 eV from 3S, 3P and 3D states have been obtained by Mahan *et al.* (1976). Excitation functions for  $n = 2, 3$  states between 11 and 2000 eV have been recently studied by James *et al.* (1993).

*Ionization.* Early measurements of Fite and Brackmann (1958a), normalized to H<sub>2</sub> and extending up to 1000 eV, have been used by de Heer *et al.* (1977) to derive their semiempirical CS (see fig. 31). Recent absolute CS of Shah *et al.* (1987) are lower at the maximum (by 10% at 50 eV) than the semiempirical values, but agree very well with earlier experiments (Fite and Brackmann, 1958a; Rothe *et al.*, 1962) at high



TABLE XVII. – *Integral cross-sections for electron scattering on atomic hydrogen (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Excitation <sub>DH</sub>	Ionization <sub>SH</sub>	Sum	Total
5.0	10.6 <sub>S</sub>				10.6* <sub>DH</sub>
7.0	9.3 <sub>S</sub>				8.52* <sub>DH</sub>
15	3.9 <sub>S</sub>	0.6	0.076	4.58	4.57* <sub>DH</sub>
20	2.9 <sub>S</sub> 2.95 <sub>DH</sub>	1.03	0.293	4.22 4.27	4.02 <sub>DH</sub>
30	1.77 <sub>DH</sub>	1.21	0.506	3.49	3.48 <sub>Z</sub>
40	1.54 <sub>S</sub> 1.23 <sub>DH</sub>	1.20	0.581	3.32 3.01	3.15* <sub>Z</sub>
50	0.88 <sub>DH</sub>	1.16	0.626	2.67	2.82 <sub>Z</sub>
60	1.04 <sub>S</sub>	1.25	0.613	2.90	
100	0.61 <sub>S</sub> 0.53 <sub>DH</sub>	0.92	0.545	2.08 2.00	1.90 <sub>Z</sub>
200	0.24 <sub>S</sub> 0.19 <sub>DH</sub>	0.62	0.397	1.26 1.21	1.075 <sub>Z</sub>

\* – Interpolated value.

DH – de Heer *et al.* (1977), semiempirical.

S – Shyn and Cho (1989) and Shyn and Grafe (1992).

SH – Shah *et al.* (1987).

Z – Zhou *et al.* average values between 55% and 100% dissociation limits.

energies. On the other hand, the integral values obtained by Shyn (1992) from differential measurements are 30% higher than the values of Shah *et al.* (1987) at 100 eV.

Merging of the electron collision ionization cross-section with the analogous CS measured with protons (see Shah *et al.*, 1987) and antiprotons (Knudsen *et al.*, 1995) has been observed at high collision velocities (above 300 eV equivalent electron energy). On the other hand, as noticed by Shah *et al.* (1987), only above 1000 eV the  $e^-$ -H ionization cross-sections approaches the Born-Bethe values (Kingston, 1965).

*Resonances.* As already mentioned, resonant structures in optical-excitation functions have been observed between 10.2 and 12.05 eV by Williams (1988) and in elastic scattering by Warner *et al.* (1986). We refer the reader to the recent review of Buckman and Clark (1994) for a comprehensive comparison between theory and experiment on  $H^-$  resonances.

*Sum check* indicates a pretty good agreement between the sum of elastic CS of Shyn and co-workers, semiempirical excitation cross-sections of de Heer *et al.* (1977) and ionization of Shah *et al.* (1987), from one side and the absolute total values of Zhou *et al.* (1994) from the other. Elastic CS of Shyn slightly overestimate the summed

values at some energies above 20 eV, while those of de Heer *et al.* (1977), based essentially on measurements of Williams, underestimate them; this reflects the mentioned difference between the two sets of measurements at high scattering angles. Table XVII shows partial, summed and total CS at selected energies.

We note that for atomic hydrogen, similarly as for H<sub>2</sub> and He, the inelastic processes dominate the scattering just above 50 eV. In some analogy with alkali metals, the electronic excitation dominates over the ionization.

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5.2. *Atomic oxygen (O)*. – Interest for electron-collision cross-sections in atomic oxygen is caused by their importance for understanding processes in Earth's atmosphere. An extensive set of partial cross-sections for atomic oxygen has been reviewed by Itikawa and Ichimura (1990). Electron excitation and ionization CS have been reviewed by Laher and Gilmore (1990).

*Total cross-sections* at energies between 2.3 eV and 11.6 eV have been measured in a crossed-beam experiment by Neynaber *et al.* (1961). From normalization to the molecular-oxygen TCS of Brüche (1927) they obtained «a virtually constant» cross-section of  $(5.5 \pm 0.4) \cdot 10^{-20} \text{ m}^2$  in the examined energy range. A more recent recoil-beam determination of Sunshine *et al.* (1967) with a declared 20% error bar indicates a maximum TCS value of  $10.1 \cdot 10^{-20} \text{ m}^2$  at 8.75 eV. According to this work, in the whole energy range between 0.5 eV and 100 eV the total cross-section for atomic oxygen remains, differently than for the H-H<sub>2</sub> pair, lower than its molecular counterpart. In fig. 33 we present the data of Sunshine *et al.* (1967) as the O<sub>2</sub> reference at low energies even if they slightly differ from the more recent evaluations. The O<sub>2</sub>/O ratio of TCS between 10 eV and 100 eV amounts to 1.2, on the average (Sunshine *et al.*, 1967). The beam attenuation method, with both (electron and atomic) beams chopped, has been recently used at low (0.54–4.9 eV) energies by Williams and Allen (1989). These data agree pretty well with the experiment of Sunshine *et al.* (1967), apart from the lowest examined energy.

Joshipura and Patel (1994) used the optical model to calculate TCS for atoms (O, N, C) and used the obtained values to derive molecular (O<sub>2</sub>, O<sub>3</sub>, NO<sub>2</sub> etc.) cross-sections via the additivity rule. Their results for O agree pretty well with the determination of Sunshine *et al.* (1967) at 10 eV and at 50 eV but they are 20% lower at 100 eV. We recall that for alkali metals some of the recoil-beam experiments tend to overestimate TCS at intermediate energies. On the other hand, Joshipura and Patel's result for O<sub>2</sub> at 100 eV overestimates the experimental TCS (Zecca *et al.*, 1986).

*Elastic cross-sections* have recently been measured by Williams and Allen (1989) at 0.54–8.7 eV. Their integral CS, obtained from the experimental DCS via a

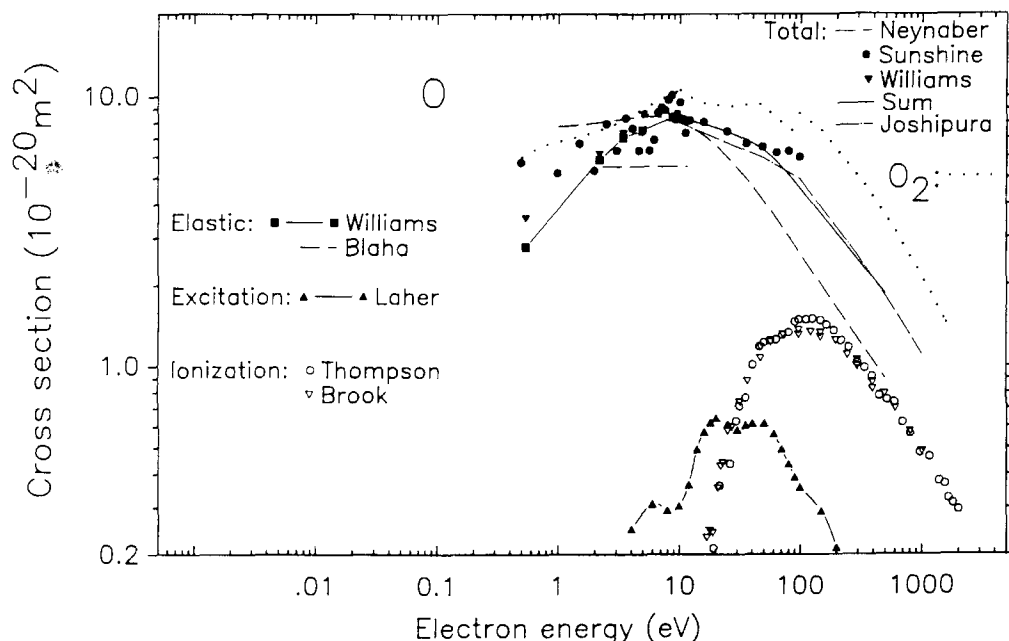


Fig. 33. – *Total*: Neynaber *et al.* (1961) crossed beams, normalized to O<sub>2</sub>; Sunshine *et al.* (1967) recoil beam; Williams and Allen (1989) crossed beams, absolute; Joshipura and Patel (1994) additivity rule; sum, semiempirical present (see table XVIII). *Elastic*: Williams and Allen (1989) experimental with phase-shift analysis; Blaha and Davis (1975) distorted-wave approximation. *Excitation*: overall excitation from review of Laher and Gilmore (1990). *Ionization*: Brook *et al.* (1978) absolute gross; Thompson *et al.* (1995) absolute counting, note the discontinuity at 90 eV due to lack of O<sup>2+</sup> data at lower energies. O<sub>2</sub> total: Sunshine *et al.* (1967) at 10–100 eV and a third-order regression line drawn through the experimental points below 10 eV; Dalba *et al.* (1980) above 100 eV.

phase-shift analysis, falls inside the experimental noise of the total CS of Sunshine *et al.* (1967) above 1 eV but is lower at 0.54 eV (see fig. 33).

DCS at low energies (up to 3.4 eV) descend monotonically with the scattering angle in the measured range (20–150°). At higher energies (8.7–15 eV) DCS exhibit a minimum at 120° (Williams and Allen, 1989; Dehmel *et al.*, 1976). At 4.9 eV the experimental DCS are in good agreement with the polarized pseudo-state method calculation of Tambe and Henry (1976) and with the distorted-wave approximation of Blaha and Davis (1975) but disagree with variational calculations of Thomas and Nesbet (1975) at small scattering angles. Early low-energy theoretical elastic CS have been reviewed by Nesbet (1977); cross-sections at high energies have been calculated by Riley *et al.* (1976) and Raj (1991).

*Electronic excitation cross-sections*, due to the importance of atomic oxygen for atmosphere chemistry, have been measured in numerous works. An exhausting review of the subject has been given by Laher and Gilmore (1990). We refer the reader to this article for details on different integral cross-sections and analytical fitting formulae. In fig. 33 we present the sum of all excitation CS from this work.

Among excitations to non-Rydberg states, the dipole-forbidden  $3P \rightarrow 2p^{41}D$  transition with threshold at 1.96 eV and peaking at 6 eV with an integral CS value of  $0.28 \cdot 10^{-20} \text{ m}^2$  is the dominant one. Among the dipole-allowed transitions, the  $3s^3S^0$  and the autoionizing  $2p^{53}P^0$  states with threshold at 11.1 eV and 14.1 eV and with maxima of  $0.11 \cdot 10^{-20} \text{ m}^2$  and  $0.14 \cdot 10^{-20} \text{ m}^2$  at 20 eV and 50 eV, respectively, are the most important. Excitations to the Rydberg states  $3s'^3D^0$ ,  $3d''^3S^0$ ,  $^3P^0$ ,  $^3D^0$  contribute to about  $0.05 \cdot 10^{-20} \text{ m}^2$  at 50 eV, each. The three distinct maxima visible in the overall excitation CS at about 6 eV, 20 eV and 50 eV correspond to peaks in the above-mentioned separate channels.

Differential cross-sections have been measured for the  $2p^{41}D$  metastable state by Shyn and Sharp (1985 and 1986) and Doering and Gulcicek (1989a); for the  $2p^{41}S$  metastable by Shyn *et al.* (1986) and Doering and Gulcicek (1989a); for the  $3s^3S^0$  state by Doering and Vaughan (1986) and Vaughan and Doering (1986); for the  $3s^5S^0$  state by Doering and Gulcicek (1989b); for the  $3d^3D^0$  state by Vaughan and Doering (1987) and Gulcicek and Doering (1988); for the  $3p^3P$  and  $3p^5P$  states by Gulcicek *et al.* (1988); for seven Rydberg transitions by Vaughan and Doering (1988). *R*-matrix calculations (Tayal, 1992) are only in vague agreement with the experiments.

*Optical-emission cross-sections* have been measured by Zipf and co-workers for different transitions (Zipf and Erdman, 1985; Zipf *et al.*, 1985; Zipf and Kao, 1986; Erdman and Zipf, 1987). The early work for the  $3s^3S^0$  state (Stone and Zipf, 1974) has been re-analysed more recently (Zipf, 1986). The emissions from the  $3s^3S^0$ ,  $3s'^3D^0$

TABLE XVIII. – *Integral cross-sections for electron scattering on atomic oxygen (in  $10^{-20} \text{ m}^2$  units).*

Energy (eV)	Elastic	Excitation <sub>L</sub>	Ionization <sub>B</sub>	Sum	Total
0.54	2.77 <sub>W</sub>				3.56 <sub>W</sub>
2.18	5.82 <sub>W</sub>				6.13 <sub>W</sub>
3.4	7.06 <sub>W</sub>	0.20*		7.26	7.31 <sub>W</sub>
4.9	7.48 <sub>W</sub>	0.27*		7.75	7.36 <sub>W</sub>
8.71	8.37 <sub>W</sub>	0.30*		8.67	10.0 <sub>S</sub>
10	8.06 <sub>B</sub>	0.30		8.36	10.6 <sub>S</sub>
20	6.6 <sub>B</sub>	0.72	0.32*	7.64	7.6 <sub>S</sub>
45	4.36 <sub>B</sub>	1.05*	1.1	6.51	6.5 <sub>S</sub>
100	2.60 <sub>B</sub>	0.64	1.31	4.55	5.9 <sub>S</sub> 4.92 <sub>J</sub>
500	0.88 <sub>B</sub>	0.19	0.785	1.85	1.81 <sub>J</sub>

\* – Interpolated value.

B – Blaha and Davis (1975), distorted waves.

J – Joshipura and Patel (1994), optical model.

L – Laher and Gilmore (1990).

S – Sunshine *et al.* (1967).

W – Williams and Allen (1989).

and  $3s^2 3P^0$  states have been also studied by Wang and McConkey (1992). The optical-emission CS in atomic oxygen have been reviewed by Heddle and Gallagher (1989) and Laher and Gilmore (1990).

*Ionization.* A good accord exists between earlier measurements (Fite and Brackmann, 1959; Rothe, 1962) normalized to  $O_2$  (Tate and Smith, 1932), the more recent (Brook *et al.*, 1978; Thompson *et al.*, 1995) absolute measurements and the theoretical (Chung *et al.*, 1993) determinations. In its maximum at about 130 eV the integral ionization CS (Brook *et al.*, Thompson *et al.*) amounts to about 2/3 of the theoretical elastic one (Blaha and Davis, 1975). At the same point the double  $O^{2+}$  ionization (Zeigler *et al.*, 1982; Zipf, 1985; Thompson *et al.*, 1995) amounts to 3% of the single one. Ionization to the  $O^+$  ( $^4S^0$ ,  $^4D^0$ ,  $^4P^0$ ) states and the inner ionization to the  $O^+$  ( $2s2p^4P$ ) state constitute 35%, 30%, 17% and 18% of the  $O^+$  yield, respectively, above 1000 eV (Laher and Gilmore, 1990).

*Resonances.* Several Feshbach resonant states were observed in the electron transmission spectra (Spence, 1975) between 8.8 eV and 15.5 eV; their assignment has been revisited by Buckman and Clark (1994).

*Summed values.* In fig. 33 the summed values obtained from the theoretical elastic (Blaha and Davis, 1975), overall excitation (Laher and Gilmore, 1990) and ionization (Brook *et al.*, 1978) CS are presented. A good agreement with the recoil-beam data (Sunshine *et al.*, 1967) at 20 eV and 45 eV has to be acknowledged. At 100 eV the summed value agrees better with the theoretical total one (Joshiyura and Patel, 1994) than with the experiment.

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**5.3. Other light non-metals (C, N, F).** – Very few experiments on electron scattering in atomic C, N, F have been performed. Some indirect results, on formation of negative ions in N for example, have been obtained from studies of the corresponding molecules. In the present subsection we also review the ionization cross-sections studied in a systematic way for several non-metals (including Si, P, S, Cl, As, Se, Br, Te, I, see Freund *et al.*, 1990).

*Total and elastic cross-sections.* Neynaber *et al.* (1963) have measured total cross-section in N from 1.6 eV to 10 eV. The measured TCS rises from about  $3.5 \cdot 10^{-20} \text{ m}^2$  to about  $6 \cdot 10^{-20} \text{ m}^2$ . However, within the error bars of  $\pm 20\%$  (Neynaber *et al.*, 1961, 1963) TCS for atomic nitrogen and oxygen do not differ in the 5–10 eV energy range. This contrasts with the theory (Blaha and Davis, 1975; Joshipura and Patel, 1994): according to these results, the total (elastic) cross-section for N at 10 eV should be 35–40% higher than the one for O. We note an opposite result of the calculation of Raj (1991), according to whom the integral elastic cross-sections at 100 eV rise in the series C, O, F. Low-energy theoretical results for C, N, O have been reviewed by Nesbet (1977), while high-energy data (above 1 keV) have been calculated by Riley *et al.* (1975).

*Electronic excitation and optical emission.* Stone and Zipf (1973) have measured emission from excited N atoms. Following them, the sum of the emission cross-sections for  $2s2p^4P \rightarrow 2s^22p^3S^0$  and  $2p^23s^4P \rightarrow 2p^3S^0$  de-excitations

amounts to as much as  $4 \cdot 10^{-20} \text{ m}^2$  at 20 eV. We note here that old measurements of Mumma and Zipf (1971) for Lyman emission from H are by 40% overestimated (see Woolsey *et al.*, 1986).

*Ionization.* Integral ionization CS for atomic nitrogen was measured by Smith *et al.* (1962). Recent years brought results for several atoms. Brook *et al.* (1978) indicated that the ionization for atomic species C, N, O scale in a similar way as for molecular gases containing these atoms (see discussion in subsect. 4'5). At 100 eV they amount to  $2.3 \cdot 10^{-20}$ ,  $1.6 \cdot 10^{-20}$  and  $1.3 \cdot 10^{-20} \text{ m}^2$  for C, N and O, respectively. (A similar sequence holds for the third and fourth rows of the periodic table, where maximum ionization cross-sections scale as 6.69, 5.26,  $4.50 \cdot 10^{-20} \text{ m}^2$  for Si, P, S and 6.12,  $5.90 \cdot 10^{-20} \text{ m}^2$  for Se and As (Freund *et al.*, 1990).)

Hayes *et al.* (1987) studied the single and multiple ionizations of halogen atoms. Overall ionization in the maximum varies from 0.98 to 3.47, 4.32 and  $5.55 \cdot 10^{-20} \text{ m}^2$  for F, Cl, Br and I, respectively. Hayes *et al.* noticed also that, for the single ionization, the ratios of CS for halogens and corresponding noble atoms remain constant with changing collision energy and depend on the orbital energy of the expelled electron, according to Thompson's (1912) classical model.

*Resonances.* Temporary negative ions  $\text{N}^-$  were observed in studies of  $\text{N}_2$  and NO dissociation (Hiraoka *et al.*, 1977; Mazeau *et al.*, 1978; Spence and Burrow, 1979). Near-threshold rise in the  $2p^2 3s^4 P$  excitation cross-section was observed by Spence and Burrow (1980).

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## 6. – Other diatomic molecules

In this section scattering from two «exotic» classes of diatomic molecules is discussed. Both classes are important for the study of fundamental aspects of the electron-molecule interaction. For alkali dimers the polarization potential (with a  $1/r^4$  dependence) and for alkali halides the dipole potential (a  $1/r^2$  dependence) dominate the low-energy scattering. Scattering from the (polar) HCl molecule will be discussed with other hydrides ( $\text{H}_2\text{O}$ ,  $\text{NH}_3$ ) in the second part of this review.

**6.1. Alkali metal dimers** ( $\text{Li}_2$ ,  $\text{Na}_2$ ,  $\text{K}_2$ ). – Alkali dimers are characterized by extremely high polarizabilities (see table XVII). As a result, the total cross-section at low energies (around 1 eV) are of the order  $(200\text{--}300) \cdot 10^{-20} \text{ m}^2$  for these targets.

*Total cross-sections.* TCS for alkali metal dimers have been studied by recoil techniques (Miller and Kasdan, 1973 at 0.5–50 eV; Miller *et al.*, 1982 at 0.5–10 eV). A 16–20% error bar has been quoted for these data. TCS are presented in fig. 34. Please note that the energy scale in this figure spans from 0.1 eV to 100 eV only. Miller and Kasdan noted that  $\text{Na}_2$  total cross-section is 30–35% higher than the monomer (Na) counterpart;  $\text{K}_2$  cross-section is 50–70% higher than for K. This loosely reflects the difference in polarizability values. As seen from the figure the energy dependence of the total cross-section for  $\text{Li}_2$  in the region 0.5–10 eV is close to  $E^{-1/2}$ , indicating the dominant influence of the polarization potential on the scattering, as predicted by classical theories (Vogt and Wannier, 1954). The energy dependence for  $\text{K}_2$  and  $\text{Na}_2$  is less steep than  $E^{-1/2}$ .

Simple analytical formulae for scattering on polarization forces (see, for example, McDaniel, 1989) regard an «orbiting» CS, *i.e.* only a part of TCS. It is outside the aim of the present review to investigate possible scaling laws for scattering on high-polarizability targets. However, in an attempt to evaluate the proportionality relation

$$(19) \quad \sigma_t(E) = A(\alpha/E)^{1/2}$$

we have plotted in fig. 34 the  $E^{-1/2}$  dependencies, for the three dimers, adjusting the proportionality parameter  $A$ . The parameter  $A$  for  $\text{Li}_2$  has been obtained by normalization to the experimental CS (Miller *et al.*, 1982) at 1 eV. The parameters  $A$  for  $\text{K}_2$  and  $\text{Na}_2$  have been obtained by linear scaling from the ratios of the literature values of  $\alpha^{1/2}$  (Weast, 1986) for these dimers and  $\text{Li}_2$ . As seen from fig. 34 the experimental points follow, within error bars, the proportionality relation (6.1) up to 10 eV.  $\text{Na}_2$  and  $\text{K}_2$  points at 20 and 50 eV lay above it. However, it is not to be excluded that, similarly as for alkali metals (see sect. 3), the recoil method overestimates TCS at intermediate energies. More measurements would be of importance.

*Elastic cross-sections.* We are not aware of any experimental elastic cross-section for alkali dimers. Calculations of Korsch *et al.* (1990) at 150 eV indicate a similar shape and approximately twice the magnitude of DCS for  $\text{Na}_2$  with respect to Na. At angles below  $30^\circ$  an interference pattern is predicted for  $\text{Na}_2$ .

*Rotational excitations.* Electron-sodium-dimers collisions at intermediate (150–300 eV) energies lead to selective excitation of rotational states (Ziegler *et*

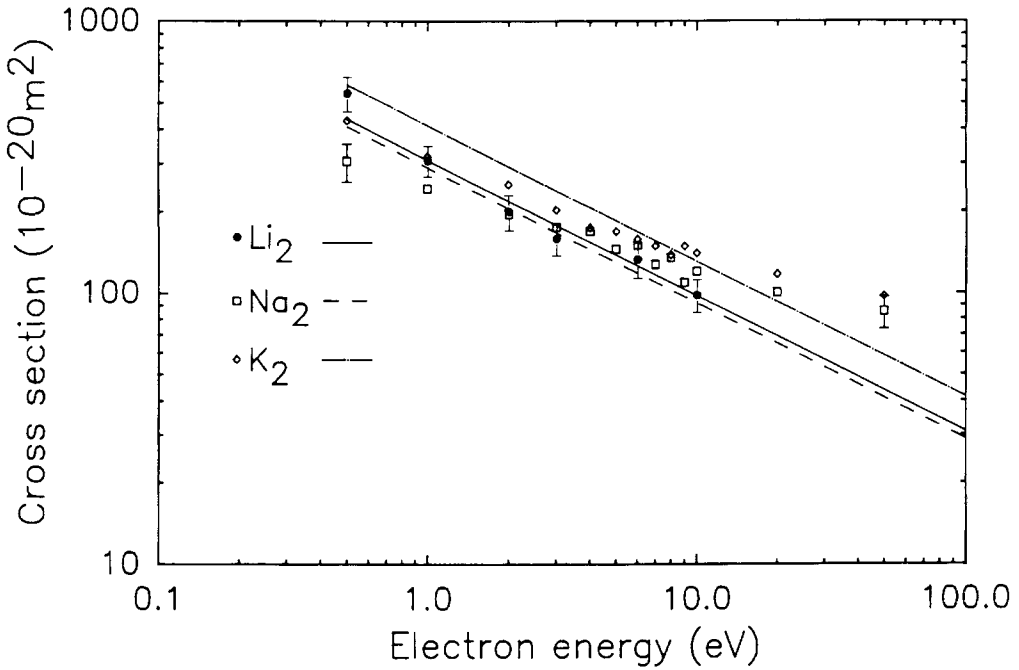


Fig. 34. – Total cross-sections for electron scattering on alkali dimers.  $\text{Li}_2$ , Miller *et al.* (1982);  $\text{Na}_2$  and  $\text{K}_2$  (Miller and Kasdan, 1973). Straight lines are drawn to evaluate the dependence of TCS on target polarizabilities (see text).

*al.*, 1987). Angular distributions for excitation of these states were studied and theoretically explained by Ziegler *et al.* (1990).

Rotational transitions from vibrationally excited ( $\nu = 2$  and  $\nu = 31$ )  $\text{Na}_2$  were studied by Kumar *et al.* (1991).

*Ionization* of alkali dimers ( $\text{K}_2$ ,  $\text{Rb}_2$  and  $\text{Cs}_2$ ) was studied by Korchevoi and Khil'ko (1978) in a low-current, low-pressure electrical discharge. A general rough conclusion, that the ionization rates are approximately the same for all the three dimers and are more than one order of magnitude higher than for alkali atoms, has been drawn.

TABLE XIX. – Comparison of polarizabilities and low-energy total cross-sections for electron-alkali dimers scattering.

Dimer	Polarizability $\alpha(10^{-30} \text{ m}^3)_W$	TCS/ $\sqrt{a}$ at 1 eV (arb. units)	TCS/ $\sqrt{a}$ at 10 eV (arb. units)
$\text{Li}_2$	34	53 <sub>M</sub>	17 <sub>M</sub>
$\text{Na}_2$	30	44 <sub>K</sub>	22 <sub>K</sub>
$\text{K}_2$	61	41 <sub>K</sub>	18 <sub>K</sub>

M – TCS from Miller *et al.* (1982).

K – TCS from Miller and Kasdan (1973).

W – Weast (1986), see also Tarnovsky *et al.* (1993).

The influence of the initial vibrational state on the low-energy ionization cross-sections in  $\text{Li}_2$  and  $\text{Na}_2$  has been studied by Fuchs and Toennies (1987) and Külz *et al.* (1995), respectively. A similar influence was also noted for electron attachment in  $\text{Na}_2$  (Külz *et al.*, 1993).

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**6'2. Alkali halides.** – Interest for electron scattering on alkali halides derives both from their possible practical applications in magneto-hydrodynamic generators, as well as from the fundamental aspects of electron collisions on highly polar molecules.

*Theory.* Alkali halides possess high momenta of inertia and consequently the thresholds for their rotational excitations are of the order of a few meV. They are also characterized by high dipole moments, rising with substitution of the halide atom with a heavier one, see table XX. For these reasons the direct rotational excitation dominates over elastic scattering at low collision energies.

Various theoretical approaches have been applied for scattering on polar molecules (see topical reviews of Itikawa, 1978; Norcross and Collins, 1982). The Born approximation (see subsect. 1'4, formula (14)) is the simplest one which has been applied to derive TCS for these molecules at low energies. The Born approximation predicts in particular a scaling of rotational excitation CS with the square of the dipole moment of molecules. DCS in the Born approximation are divergent at zero scattering angle. Therefore Born's formula has been modified, among others, by Dickinson (1977) who adopted classical perturbation theory at intermediate angles and a constant DCS value at high scattering angles. A conceptually similar method

TABLE XX. – *Dipole moments for halides of Li, K, Rb and Cs. References for total cross-section measurements are given in parenthesis.*

Li		K		Rb		Cs	
LiF	6.33 [T2]	KF	8.60	RbF	8.55	CsF	7.88 [S1]
LiCl	7.13	KCl	10.3	RbCl	10.5 [B1]	CsCl	10.4 [S2, B1, B2, T3]
LiBr	7.23 [B2]	KBr	10.4	RbBr	10.9 [B1]	CsBr	10.8 [B1]
LiI	7.43	KI	10.8 [T1, S3, B1]	RbI		CsI	

[B1] – Jaduszliwer *et al.* (1984).[B2] – Vušković *et al.* (1989).[S1] – Slater *et al.* (1974a).[S2] – Becker *et al.* (1974).[S3] – Slater *et al.* (1974b).[T1] – Rudge *et al.* (1976).[T2] – Vušković *et al.* (1978).

[T3] – Vušković and Srivastava (1981).

using the Born approximation for high  $l$ -waves and a multiple-scattering method was developed by Siegel *et al.* (1980, 1981). Rudge *et al.* (1976) used a model potential and a distorted-wave approximation for  $e^- + \text{KI}$  scattering.

*Total and elastic cross-sections.* Alkali halides melt at temperatures above 600°; this excludes experiments using cell methods. Essentially, two kinds of measurements yielded total and/or elastic CS: recoil-beam (Stern and collaborators, Bederson and collaborators) and crossed-beam (Trajmar and collaborators). The targets measured by these groups are tagged by S, B and T marks in table XX. Overall, eight alkali halides were investigated but only KI and CsCl by more than one group. Our best knowledge of the total (= elastic + rotational) cross-sections for alkali halides is shown in fig. 35 (note the reduced  $x$ -scale span with respect to other figures).

The recoil-beam method, monitoring the molecules flux in the presence of the electron beam, does not require the knowledge of the target density. However, the essential difficulty lies in the determination of the interaction-region geometry and in accounting for scattering events into small angles. Big discrepancies can be generated from wrong evaluations of these parameters (compare Jaduszliwer, 1983 and 1984 for CsBr; Slater *et al.*, 1972, 1974a for CsF).

The crossed-beam technique requires the use of normalization procedures due to the difficulty in measuring the target density. Trajmar and collaborators normalized their relative DCS at about 20° to different theories (Rudge *et al.*, 1976 for KI; Dickinson, 1977 for LiF; Siegel *et al.*, 1980 for CsCl).

The clustering of the experimental results in fig. 35 shows that discrepancies between different measurements are rather method-dependent and the specifics of a target (related for example to the dipole moment value) is hardly reproduced by measurements. First of all, we note different energy slopes between the data of Trajmar and collaborators and more recent measurements of Bederson and collaborators (Vušković *et al.*, 1989) on the one hand, and the remaining data on the other hand. We also recall that, due to the normalization procedure to Born-based theories, the data from Trajmar's group present *de iure* an  $E^{-1}$ -dependence. The measurements from Stern's group for CsF (Slater *et al.*, 1974a), CsCl (Becker *et al.*,

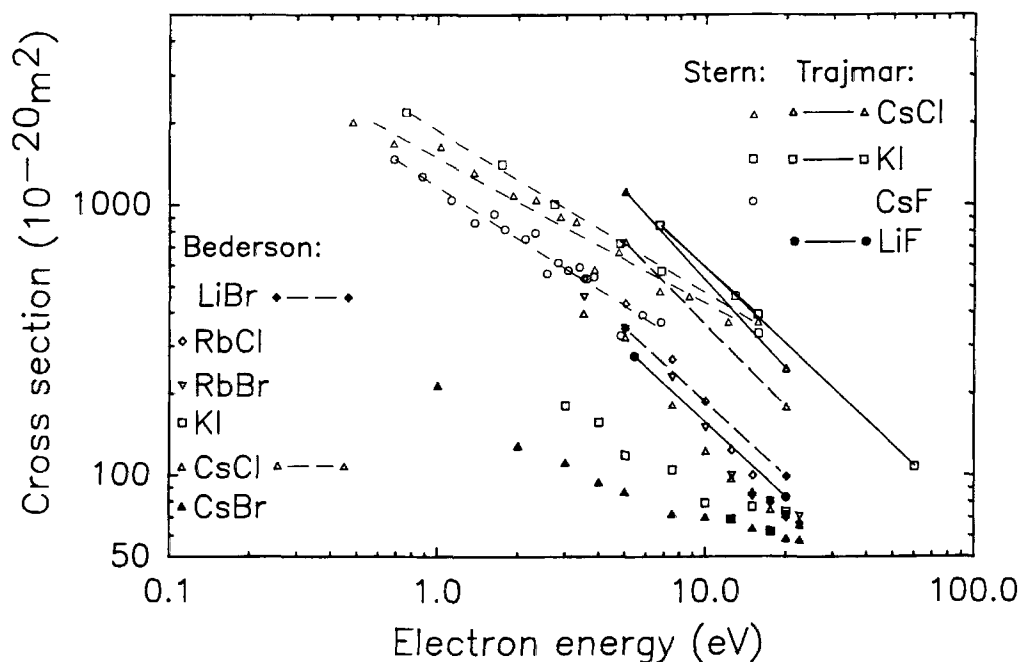


Fig. 35. – Integral cross-sections for electron scattering on alkali halides. *Total* (from recoil experiments): «Bederson» labels for Jaduszliwer *et al.* (1984) points and for Vušković *et al.* (1989) broken line and points; «Stern» labels for Slater *et al.* (1974a) in CsF, for Becker *et al.* (1974) in CsCl and for Slater *et al.* (1974b) in KI. *Elastic* (electronically elastic): «Trajmar» labels for Rudge *et al.* (1976) in KI, for Vušković *et al.* (1978) in LiF and for Vušković and Srivastava (1981) in CsCl.

1974) and KI (Slater *et al.*, 1974b) but also the CsBr and KI results of Jaduszliwer *et al.* (1984) would indicate a less steep dependence, closer to the one observed for alkali dimers (see fig. 34).

All five targets (CsBr, RbBr, CsCl, RbCl and KI) studied by Jaduszliwer *et al.* (1984) possess almost the same dipole moment. The moments of inertia change by less than a factor of 2. Therefore, following the Born approximation, at energies much higher than the rotational quanta, the five halides should exhibit close cross-section values. In the case of the measurements by Jaduszliwer *et al.* (1984), at an energy of 7.5 eV, TCS amount to  $72, 105, 183, 230, 268 \cdot 10^{-20} \text{ m}^2$  for CsBr, KI, CsCl, RbBr, RbCl, respectively.

On the other hand, a comparison between more recent recoil-beam TCS in LiBr and CsCl (Vušković *et al.*, 1989) indicates both an  $E^{-1}$  energy dependence as well as a  $D^2$  ( $D$ : dipole moment) scaling law between the targets ( $350 \cdot 10^{-20} \text{ m}^2$  and  $99 \cdot 10^{-20} \text{ m}^2$  for LiBr at 5 eV and 20 eV, respectively, and  $729 \cdot 10^{-20} \text{ m}^2, 178 \cdot 10^{-20}$  for CsCl at the same energies).

*Differential cross-sections* for alkali halides are due to Trajmar and collaborators. Generally, the rotationally summed elastic DCS follow the Born approximation (Allan and Dickinson, 1981; Bijker and Amado, 1986) at small scattering angles but oscillate around Born values for higher angles. The differences between the Born shape and

the measured one increase with rising energy: for KI the DCS agrees with the Born value at 40° but falls below it by almost two orders of magnitude at 70° (Rudge *et al.*, 1976). At 20 eV the effects in CsCl (Vušković and Srivastava, 1981) and LiF (Vušković *et al.*, 1978) are less pronounced. These «oscillations» around the Born shape have been explained (Siegel *et al.*, 1980) in terms of scattering on a molecular core and not only on the molecule long-distance dipole field.

*Electronic excitation* spectra have been obtained by Rudge *et al.* (1976) for KI, Vušković *et al.* (1978) for LiF and Vušković and Trajmar (1979) for KOH, Vušković and Srivastava (1981) for CsCl.

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