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Total cross sections for positron scattering on benzene and nitrogen

G P Karwasz[1,2], D Pliszka[2], A Zecca[1] and R S Brusa[1]

[1] Department of Physics, University of Trento, 38050 Povo (TN), Italy
[2] Institute of Physics, Pomeranian Pedagogical Academy, 76-200 Słupsk, Poland

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Abstract

Total cross sections for positron scattering on benzene and nitrogen have been measured by an absolute, transmission method in the energy region 1–20 eV. The apparatus uses a weak guiding magnetic field (9–10 Gauss (G)) and is characterised by narrow apertures in the scattering cell (1 mm in diameter). Present results in nitrogen coincide with those from the Detroit laboratory (Hoffman *et al* 1982 *Phys. Rev.* A **25** 1393) above 8 eV but in the low-energy limit are somewhat higher. Present data in benzene show a rise in the zero-energy limit and agree well with the early data from Sueoka (1988 *J. Phys. B: At. Mol. Opt. Phys.* **21** L631) and qualitatively well with the theory of Occhigrossi and Gianturco (2003 *J. Phys. B: At. Mol. Opt. Phys.* **36** 1383) but disagree with the more recent experimental data of Sueoka and collaborators (Makochekanwa *et al* 2003 *Phys. Rev.* A **68** 32707–1).

1. Introduction

Positron scattering on atoms and molecules, in comparison to electron scattering, constitutes an important test for atomic structure. This is due to a partial compensation between the static (repulsive for positrons) and polarization (attractive for both electrons and positrons) interaction potentials. Therefore, total cross sections for positron scattering are, tendentially, lower than electron ones. In the limit of high velocity impact, the polarization potential becomes less important: positron and electron total cross sections merge. This merging starts at about 30 eV for H_2 [1], at about 100 eV for poliatomic molecules, such as CH_4 and benzene (see the review by Kimura *et al* [2]), at about 2000 eV for N_2 [3] and only at 4000 eV for Ar and Kr [4].

We recall here the definition of the total cross section

$$\sigma = 2\pi \int_{\theta_0=0}^{\pi} \frac{\mathrm{d}\sigma}{\mathrm{d}\omega} \sin\theta \, \mathrm{d}\theta \tag{1}$$

where $\mathrm{d}\sigma/\mathrm{d}\omega$ is the differential cross section and θ is the scattering angle (cylindrical symmetry is assumed). The total cross section comprises the sum of all possible processes, such as elastic

scattering, vibrational and rotational excitations, electronic excitation, electron attachment (or positronium formation), ionization. Alternatively (and much easier) the total cross sections can be measured in attenuation experiments, using scattering cells and the de-Beer–Lambert attenuation law:

$$I = I_0 \exp(-pl\sigma/kT) \tag{2}$$

where l is the length of the scattering cell, p is the gas pressure, T is the temperature of the gas, and k is the Boltzmann's constant.

Measurements of positron scattering total cross sections were pioneered, among others, by Kauppila, Stein and co-workers [5], Charlton *et al* [6], Sinapius *et al* [7]. Extensive studies on molecular targets have been conducted for 20 years in the Tokyo laboratory by Sueoka and collaborators [8–16]: some 70 targets have been measured in the energy range of 1–400 eV (see the review by Kimura *et al* [2]).

The essential difficulties in these measurements were low counting rates, due to weak radioactive sources (100 μCi of ^{22}Na by Sinapius *et al* [7], 50–100 μCi by Sueoka and collaborators [8–16]) and low efficiency of positron moderators (10^{-5} as stated by Sinapius *et al* [7] and Kimura *et al* [2]). Only the set-up from the Detroit laboratory [1, 5] used a strong 100 mCi source of ^{11}C. Low counting rates require the use of strong guiding magnetic fields and large entrance and exit apertures in the scattering cell. This leads to collecting some forward-scattered positrons as non-scattered ones—the lower integration limit in formula (1) is not the angle zero but a certain angle $\theta > 0$. As a result, the measured cross sections are underestimated; see, for example, the discussion by Wagenaar and de Heer [17].

Measured cross sections can be corrected for the forward-angle scattering error but differential cross sections for near-to-zero angles scattering into all open channels (elastic, rotational, vibrational) must be known. The cut-off angle θ in formula (1), determining the angular resolution error, is usually defined by the solid angle of the scattering chamber exit slit, as seen from the middle of it [17]. However, in the case of guiding magnetic fields, the exact evaluation of the angle θ is not an easy task; see the discussion by Kauppila *et al* [18]. Generally, the angular resolution error rises with the size of exit apertures and also with the intensity of the guiding magnetic field.

Large apertures cause also another problems—the gas outflow from the scattering cell changes the effective length of the interaction region, which is no longer equal to the geometrical length, l in (equation (2)), see the detailed discussion in [17]. Therefore, some experiments, including the recent ones from the Tokyo laboratory by Makochekanwa *et al* [15] and Kimura *et al* [16] use normalization procedures, for example, to the N_2 cross sections from other measurements [1] in order to determine the effective length of the scattering cell.

In this paper, we present total cross sections obtained in an absolute manner with an electrostatically guided low-energy positron beam at Trento University. The new set-up uses a strong (17 mCi) ^{22}Na radioactive source, an improved tungsten moderator and narrow entrance and exit slits (1 mm diameter) in the scattering chamber. Benzene has been chosen mainly in the view of the existing discrepancy between the recent theory by Occhigrossi and Gianturco [19] and recent experiments [15, 16]. In order to check the performance of apparatus, careful measurements were done in nitrogen. Argon was used additionally for some calibration checks.

2. Apparatus

Some details of the apparatus and preliminary checks have been described before [20, 21]. Briefly, the apparatus consists of two electrostatic optical columns (see figure 1), separated

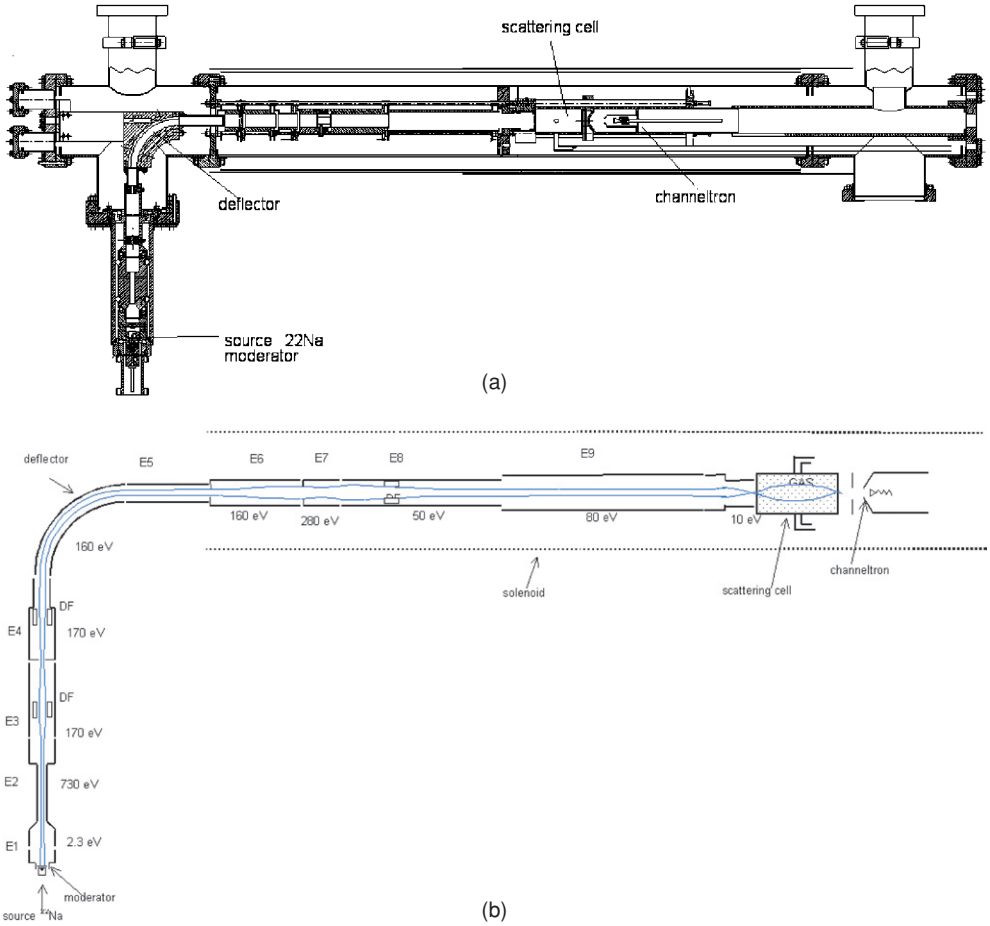

Figure 1. Schematic drawings of the apparatus. (a) Vacuum chambers, connections to pumps and technical drawings of the optics. (b) Scheme of the electron optics: E_i stand for electrodes, DF are deflection plates. Numbers (in eV) indicate kinetic energies of positrons at given points.

by a 90° bend. The ^{22}Na radio-isotope of 17 mCi activity is used to produce positrons and a transmission, 1 μm thick tungsten (100) monocrystal moderator is used to slow them down to thermal energies. The source–moderator assembly is the same as in our positron-microscope beam [22] and the slow positron beam for positron annihilation studies in solid state [23]. The moderator is treated *in situ* in a separate chamber by a 50 W telefocus electron gun at temperatures above 2000 °C (at 'bright white' colour, exceeding the temperature of incandescent lamp filaments). The ultimate vacuum in the apparatus is 4×10^{-8} Torr; the pressure during the moderator treatment does not exceed 5×10^{-7} Torr. Four turbo pumps (with their ultimate pressure of 10^{-9} Torr) are used in our system: 250 l s^{-1} and 120 l s^{-1} on the bend and in the moderator chamber, respectively, 1000 l s^{-1} in the scattering cell region and additional, 250 l s^{-1}, differentially pumping (through an internal sleeve) the detector and the exit of the scattering cell.

Positrons leaving the moderator are collected by the electrostatic field and accelerated to 700–800 eV (see figure 1(b)). Our standard efficiency of the moderator, the positron collecting and the transmission of the primary optics in this and previous machines [22, 23], gives about

1000 slow e^+ from 1 mCi source activity. It is higher by a factor of 2 just after the moderator treatment but then remains stable for a couple of weeks.

The first part of optics focuses the beam at the entrance of the 90° electrostatic bend. The reason for the bend is to prevent fast positrons from the radioactive source reach the detector. Entrance and exit apertures of the bend are chosen in a way to obtain $1/100$ energy selection $\Delta E/E$, where ΔE is the FWHM of the energy distribution of the beam and E is its energy inside the bend. The nominal energy of the beam in the bend is 200 eV but it has been changed in the course of the present experiment, as described later.

A longitudinal magnetic field (about 9–10 G) in the second part of the optics is used to facilitate guiding positron through the scattering cell. The field is adjustable slightly (±10% below 8 eV collision energy and ±15% above 8 eV) in a way to maximize the counting rate. Positrons are subject to few gyrations inside the scattering chamber and are focused on the exit aperture, for example 2.4 eV positrons perform three full gyrations at 10 G applied field. A careful check of possible dependences of the cross section on the magnetic field has been done—some results for different gases are shown in figure 2(a). We observe in the range of the low coil currents (1.4–1.6 A) that the cross section is independent of the magnetic field strength; at higher fields (2 A current) the measured cross section tends to diminish. However, high currents were not used because of the signal fall—our combined electrostatic/magnetic optics clearly loses its focusing properties at high magnetic fields.

The scattering cell made of non-magnetic nickel–copper alloy (arcap) is 10 cm long and has 1.0 mm diameter entrance and exit apertures. The angular acceptance of the detector—the solid angle defined by the exit aperture as seen from the centre of the scattering cell amounts to 3.1×10^{-4} sr. In front of the scattering cell, before the channeltron entrance, an additional aperture of 5 mm diameter is placed, see figure 1(b).

In the original design of the apparatus [20], positrons after the bend were to be accelerated to 2–5 keV energy, injected into a copper remoderator [25] and only those re-emitted with low energy were to be used for the scattering experiment. This solution uses the concept of brightness enhancement and should assure lower attainable energies than using positrons directly from the tungsten moderator. However, the practical implementation of high quality copper films is not easy and in present measurements the machine is used in the configuration of 'inverted' optics. Positrons in the second optical column, instead of being accelerated from 200 eV to 2–10 keV, are decelerated by the same ratio, down to 4–20 eV. The loss of the positron intensity in this decelerating mode is mainly due to the angular selection at the entrance of the scattering cell. In this way, from about 4000 e^+ s^{-1} after the bend, the total beam intensity at the exit of the scattering cell falls by a factor of about 100, depending on energy. In order to facilitate the decelerating mode of operation, the kinetic energy inside the deflector has been lowered from the nominal value of 200 eV to 160 eV.

As a result we managed to obtain still reasonably high counting rates, ranging from 10 e^+ s^{-1} at 1 eV to 100 eV e^+ s^{-1} at 10 eV collision energy. We note that such counting rates are probably higher than in the apparatus of Sueoka and collaborators [8] who used 80 μCi positron source and a tungsten mesh as the moderator. The glass-based channel electron multiplier is used to detect positrons. Thanks to a good shielding between the detector and the radioactive source the background counts in our apparatus are extremely low, less than 0.05 e^+ s^{-1}.

Present apparatus, due to construction reasons (the scattering cell with its housing and the electrodes before and after the cell are on the ground potential), does not use the retarding field analyser. As discussed later, the analyser would not assure sufficient energy resolution in a few eV energy range for experiments in molecular gases. Its use becomes more important in the intermediate energy range. From the growth of the positron signal in the zero-energy limit

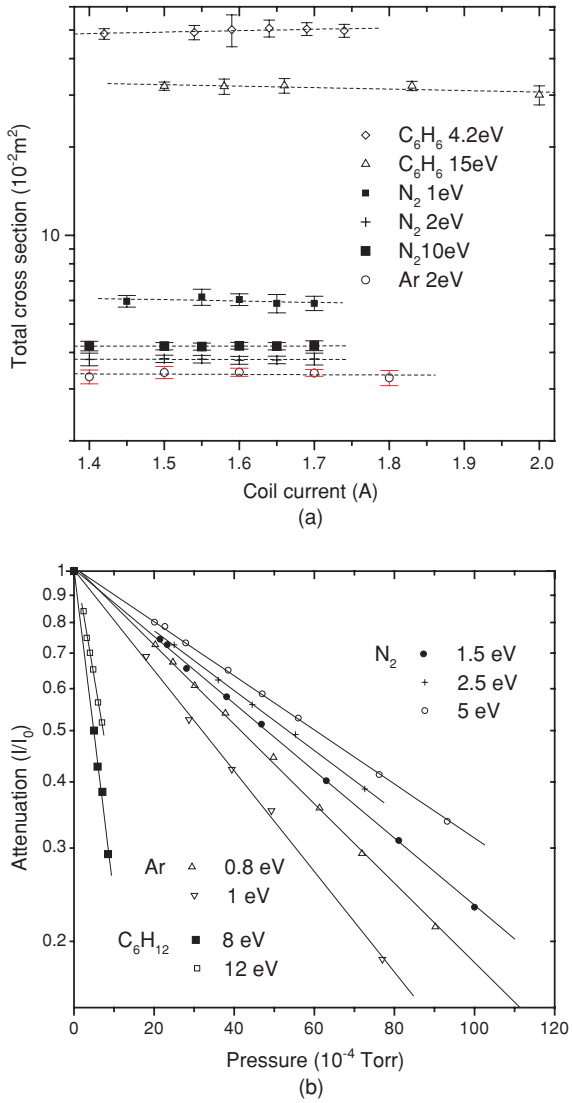

Figure 2. Tuning checks of the low-energy positron set-up. Check of the independence of the measured cross section from the value of the guiding magnetic field. The 1.4–2.0 A coil currents correspond to 8.8–12.5 G field. Typically, measurements were done with 9–10 G field. (b) Check of the independence of the measured cross section on the pressure value (attenuation factor). Pressures used for total cross sections in each gas and energy were below the upper limit of the range presented on this figure.

(i.e. when a net retarding potential of about +2 eV is applied to the scattering cell as compared to the moderator) and from the observation of the vibration structure in the $^2\Pi_g$ shape resonance for electron scattering on N_2 [20], we deduce that the energy resolution of the apparatus is not worse than 150 meV. Note that standard tungsten moderators in the form of macroscopic mesh or vanes have about 1–2 eV FWHM positron energy distribution, as confirmed by Sueoka [13] in direct measurements by the retarding field analysed. On the other hand, it was checked in high-resolution measurements with a cylindrical spectrometer, that W monocrystals can yield slow positron beams with about 50 meV FWHM energy distribution [24].

Different from measurements for benzene by Sueoka [10] and Makochekanwa *et al* [15] we assume the length of the interaction region equal to the geometrical length of the scattering cell. On the basis of detailed discussion made by de Heer and Wagenaar [18] we evaluate that in our case (a long gas cell and small apertures) the effect of the gas outflow is less than 1%. The numerical simulation of the beam geometry shows that injection angles into the scattering cell are low (less than 15°) and a possible elongation of the electron trajectory inside the scattering cell is also negligible, say at 2 eV projectile energy it does not exceed 1% of the geometrical length.

The pressure in the scattering cell was evaluated from Leybold Inficon CR091 membrane capacitance meter. The gas pressure used depends on the cross section values in order to maintain conditions of single scattering events (the ratio I/I_0 kept between 0.3 and 0.8). Applied pressures were in the range of (2–8) $\times$ 10^{-3} Torr for nitrogen and one order of magnitude smaller in benzene. In figure 2(b), the dependences of the attenuation ratio on pressure in N_2 and benzene (and additionally in Ar) are presented. The measured linear dependence $\log I/I_0\,(p)$ for all checked gases and different energies indicate that some possible systematic errors—due to the pressure read-out (such as non-linearity of the read-out and the zero-shift) and the multiple scattering—can be neglected (see, for example, [18, 26] for detailed discussions of errors in total cross section measurements).

However, the pressure read-out precision ($2\frac{1}{2}$ significant digits) is still the main source of possible systematic error in our data—we assume the total 5% uncertainty for it. No correction was done for the thermal transpiration, in spite of the fact that the temperature of the gauge was stabilized at 318 K. According to the formula of Knudsen the real pressure in the scattering cell p_s would be lower than the pressure p_m measured by the gauge

$$p_s = p_m\sqrt{T_s/T_m} \tag{3}$$

where T_s (= 296 K) and T_m are the temperatures of the gas cell and the pressure gauge, respectively. Therefore a maximum correction to the measured cross section, in the case of the pure molecular flow regime would be +3%. However, as discussed by Poulter *et al* [27], in practice the corrections in measurements of cross sections are lower, down to null, depending on the type of gas and the pressure used. The present apparatus is equipped with short and wide tubes in gas connectors and therefore we assume a total 6% value for the possible error in gas pressure determination (a quadratic sum of the read-out and the thermal transpiration).

For each experimental point 6–10 runs were performed; in each run 20 values of I and I_0 were averaged over 10 s periods. Generally, experimental procedures are similar to those used in our electron-benzene measurements [28]. The statistical error bars (the mean standard deviations of the measured values) are on average 4% for nitrogen cross sections and 8% for benzene cross sections. The points on calibration curves are subject to somewhat higher errors because of poorer statistics. The overall systematic error, defined as a quadratic sum of all contributions, is 7% (coming mainly from the pressure determination, with other sources of error such as the length of the scattering path and the temperature determination being much smaller). Measurements in nitrogen, due to higher pressures used, are subject to a smaller overall systematic error, about 5%.

The energy calibration was done against the threshold for positronium formation in molecular nitrogen (8.8 eV). However, as our total cross section in N_2 shows a slight rise starting from 8.5 eV (similarly to the total cross section in CO in measurements by Sullivan *et al* [29]), we have performed an additional energy calibration using argon (against the positronium formation threshold at 8.9 eV). In argon the rise of the cross section has a sharp onset, observed within 0.1 eV step of present measurements and in agreement with the threshold measurements by Moxom *et al* [30]. The energy shift of our scale established from

Table 1. Total cross sections for positron scattering, together with statistical errors (one standard deviation from the mean value).

Energy (eV)	TCS (10^{-20} m^2)	Statistical error (10^{-20} m^2)	Energy (eV)	TCS (10^{-20} m^2)	Statistical error (10^{-20} m^2)
	Nitrogen			Benzene	
0.8	7.38	0.67	1.4	96.4	8.2
0.9	6.25	0.35	1.5	92.6	7.8
1.0	5.80	0.16	1.8	80.8	7.1
1.2	4.99	0.23	1.9	78.1	6.0
1.4	4.45	0.25	2.1	69.1	4.9
1.6	4.14	0.26	2.3	65.3	5.5
1.8	3.99	0.22	2.6	61.8	4.8
2.0	3.90	0.21	2.9	58.2	5.2
2.2	3.83	0.17	3.1	55.7	4.9
2.4	3.81	0.18	3.4	53.7	4.3
2.6	3.76	0.26	3.6	51.1	3.7
3.0	3.76	0.07	3.7	51.6	3.4
3.5	3.82	0.21	3.9	51.3	3.5
4.0	3.75	0.08	4.1	50.6	3.9
5.0	3.70	0.05	4.4	47.6	3.6
6.0	3.74	0.08	4.9	46.6	3.1
7.0	3.75	0.08	5.9	42.6	3.2
8.0	3.76	0.08	6.9	39.1	3.5
8.5	3.86	0.08	7.9	38.9	3.4
9.0	3.99	0.08	8.9	38.3	2.8
9.5	4.10	0.22	9.9	37.4	2.7
10.0	4.29	0.23	10.9	36.9	2.8
10.5	4.54	0.24	11.9	35.2	2.6
11.0	4.78	0.24	14.9	32.6	2.3
12.0	5.24	0.26	20.3	32.3	2.8
13.0	5.58	0.27			
14.0	5.93	0.28			

these comparisons is +2.3 eV. This shift includes the work function of the moderator and the effective contact potential between the moderator and the scattering cell and is close to the work function of the literature for positrons in tungsten [24]. A possible systematic error on the energy scale is ± 0.1 eV.

Data in nitrogen have been checked in three independent measurement sessions in the course of several months. Relatively more points were measured in the low (below 2 eV) energy region. Measurements in argon were also done, for the sake of the check of the apparatus but will be reported separately.

3. Results

Present data are together with statistical errors (one standard deviation from the mean value) are shown in table 1. In figure 3 we compare present results for nitrogen (the three independent series from present measurements are plotted as distinct points) with other experiments: Hoffman *et al* [1], Charlton *et al* [6], Sueoka and Mori [8], Sueoka and Hamada [12], and some recent theories. Agreement with data of Hoffman *et al* down to 5 eV is very good, within our total-error bar. Note that Hoffman *et al* used a long (109 cm) scattering cell and a

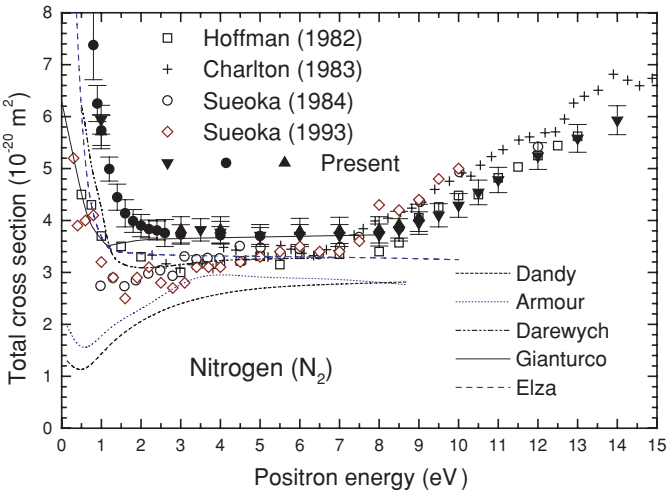

Figure 3. Comparison between present data for N_2 (full points with different shapes correspond to different measurement runs) and those by Hoffman *et al* [1] (open squares), Charlton *et al* [6] (crosses), Suoeka and Mori [8] (circles) and Sueoka and Hamada [12] obtained with better angular resolution and lower guiding magnetic field than in [8]. For present data an energy shift of +2.3 eV has been applied. Total (statistical plus systematic) error bars are shown. Theory: short dash, Danby and Tennyson [35] *R*-matrix calculations with static, polarization and 22 pseudostates; dotted, Armour and Plummer [34] Kohn-variational method, two-channel calculation for Σ symmetry; dash-dot, Darewych [33] with variable range polarization; solid, Gianturco *et al* [31] Hartree–Fock with correlation–polarization potential from local density approximation, outer ($>6\ a_0$) cut-off radius; dash, Elza *et al* [32] long-range cut-off function for polarization.

(This figure is in colour only in the electronic version)

narrow-pass-band retarding field analyser, and made detailed evaluation of possible angular-resolution errors.

At lower energies our data are higher than those of Hoffman *et al* with the difference of 15% at 2 eV. Data of Sueoka and Mori [8] in N_2 below 3 eV seem to diverge down from present measurements, from those of Hoffman *et al* [1] and of Charlton *et al* [6]. On the other hand, the agreement with measurements of Sueoka and Hamada [12] is much better, even at the lowest measured energies (see figure 3). As stressed by Sueoka and Hamada, in their experiment, compared to that by Sueoka and Mori [8], narrower slits (6 mm diameter versus 8 mm), longer scattering chamber (120 mm versus 79.7 mm) resulting in the better geometrical angular resolution (7.9 msr versus 31.6 msr) and a much weaker magnetic field (1.8 G versus 9 G) were used. Therefore the data of Sueoka and Hamada [12] should be subject to a smaller angular-resolution error than those of Sueoka and Mori [8].

Agreement between present data and the most recent theories—Gianturco *et al* [31] with correlation–polarization potential derived from local-density approximation and Elza *et al* [32] with a long-range polarization with a cut-off formula—is good. These theories (and also by Darewych [33]) indicate the cross section rising in the limit of low energy, although with somewhat different amplitudes. The *R*-matrix calculations by Danby and Tennyson [34] and Kohn-variational method by Armour and Plummer [35] in Σ symmetries would indicate the presence of the Ramsauer minimum, but as shown by Elza *et al* such a minimum could be an artefact, due to a weak polarization potential used.

In benzene we are aware of five sets of data from the Tokyo group (Suoeka [10], Sueoka *et al* [14], Kimura *et al* [2], Makochekanwa *et al* [15], Kimura *et al* [16]), we make comparison

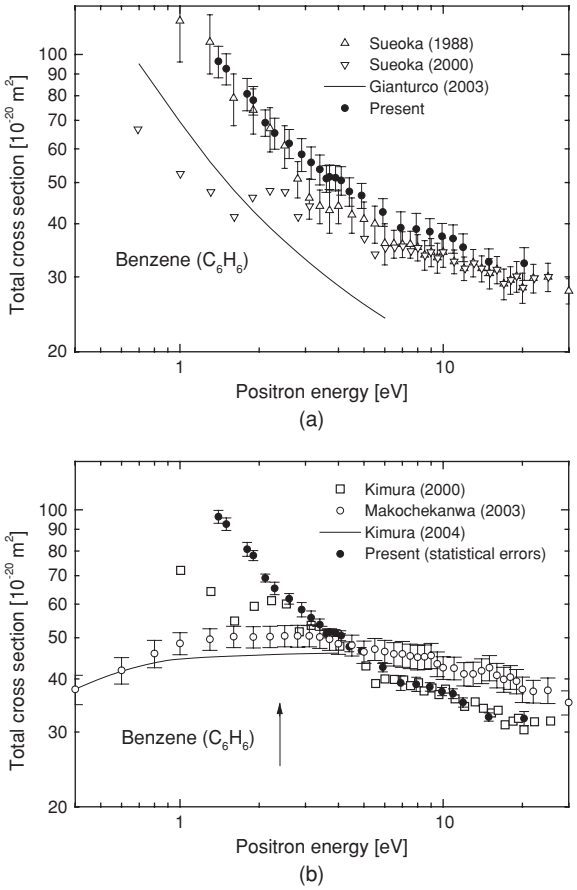

Figure 4. Total cross sections for positron scattering on benzene. Full circles: present measurements. (a) Error bars on present data refer to total (statistical and systematic) uncertainties; triangles, Sueoka early data [10] obtained with magnetic field scaling with energy (see text), error bars refer total experimental uncertainty; inverted triangles, Sueoka *et al* [14], probably with 9 G magnetic field; theory, Occhigrossi and Gianturco [19] in Hartree–Fock with multiterm polarization and local-density correlation potential. (b) Present data with statistical error bars—note the better statistics in the 3–4 eV region showing a bump slightly above the positronium formation threshold (the arrow at 2.4 eV); squares, data from review by Kimura *et al* [2]; circles, data from [15, 16] corrected there for the angular resolution error. Theory, continuum-multiple scattering model [16].

on two figures, figures 4(a) and (b). In the 5–20 eV energy range present data are higher than the early data of Sueoka [10], with the difference 10–20% remaining within the combined error bar (see figure 4(a)). For electron scattering the difference between cross sections of Sueoka [10] and of Możejko *et al* [28, 36] is 18% at 1 eV and 15% at 4 eV, compatible with the presently noted difference for positrons.

On the other hand, present results at 5–20 eV practically coincide with one of the recent reports from the Tokyo lab [2] obtained with the apparatus using the retarding field analyser (see figure 4(b)). A difference rising with energy is observed with the data of Makochekanwa *et al* [15] and with data of Kimura *et al* [16], apparently identical to the former. The 5 eV energy turns to be a crossing point for all the three sets of data (present, [15, 16]), but at 15 eV the present value is lower than that of Makochekanwa *et al* [15] and Kimura *et al* [16]

by 25% (figure 4(b)). This difference is outside the combined error bar and comes probably directly from the measurements: the correction applied by Makochekanwa *et al* for the forward scattering in this energy range is only +8% to +12%.

Below 2.5 eV, present data coincide with those of Sueoka [10] within our error bar (see figure 4(a)). The agreement with more recent data, in particular those by Sueoka *et al* [14], Makochekanwa *et al* [15] and Kimura *et al* [16], is not so good (see figure 4(b)). At 1.9 eV the value of Makochekanwa *et al* is lower than ours by 35%, and at our lowest-energy point (1.4 eV) this difference is as high as 50%. The most recent data [15, 16] differ from the sets by Sueoka [10], Sueoka *et al* [14], Kimura *et al* [2] and present data, showing a descend of the cross sections towards zero energy.

For electron scattering the recent results from the Tokyo lab [15, 16] extend down to 0.8 eV and it is difficult to judge on agreement with other experiments [28, 37, 38] in the very low-energy limit.

The reason for the discrepancy on the very shape of the cross section energy- dependences for positrons is not clear. First, we recall the difference in the (geometrical) angular resolution between the two machines: 3.1×10^{-4} sr in the present set-up and, taking the length of the scattering cell from the paper by Sueoka *et al* [8], and slit diameters (6 mm) from [15], 1.7×10^{-2} sr in the Tokyo machine. The comparison of the angular resolutions solely indicates a potentially higher error, which can underestimate the measurements by Makochekanwa *et al* [15].

However, it is probably a combination of the geometrical angular resolution and the magnetic field used which is decisive for the quality of data. Sueoka [10] discussed extensively the choice of magnetic field in different energy ranges. He shows in benzene that cross sections in the low-energy region are highly influenced by the choice of magnetic field: at 1 eV he measured the cross section of about 120×10^{-20} m^2 for 3.6 G field, descending to 105×10^{-20} m^2 while using 4.5 G field and 55×10^{-20} m^2 for 9 G field. Sueoka [10] also showed that the use of very strong magnetic field in their apparatus (23 G) yields even a descending cross section in the zero-energy limit but effects little the cross sections above 5 eV (see the inset in his figure 1). Therefore for the final table, Sueoka [10] chooses the 3.6 G values below 2.5 eV, 4.5 G for 2.8–6.0 eV, the averaged values for 4.5 G and 9 G at 6.5–7.5 eV and the 9 G values above 8 eV. We note also that the data shown by Suoeka *et al* [14] are close to those by Sueoka [10] but obtained with the 9 G field in the whole energy range. Note also that the cyclotronic radius for 1.0 eV electrons in 9 G field is as small as 3.7 mm; it means that with such apertures all positrons scattered into angles below 90° would be detected as 'non-scattered'.

Unfortunately, no details on the strength of the magnetic fields used are given in the recent papers [2, 14–16]. In our system, at 1 eV collision energy, positrons scattered elastically only below 7° are guided to the detector by the magnetic field. Assuming uniform in angle differential cross sections, this would correspond to 0.9% underestimation of the total cross section. The use of wide apertures in the scattering cell [15, 16] is the most plausible explanation of the discrepancy between present results below 5 eV and those by Makochekanwa *et al* [15] and Kimura *et al* [16].

We note also that due to different scattering potentials, differential cross sections for positron and electron scatterings can diverge much, both in shape and in absolute values, see, for example, the results of Reid and Wadehra [39]. Therefore the use of electron scattering cross sections for correcting positron data can introduce serious errors. On the other hand, the use of the retarding field analyser is essential at intermediate energies but in the very-low energy region probably not: as shown by Sueoka *et al* [13] their set-up is probably not able to discriminate positrons scattered inelastically with the energy loss corresponding to excitation

of vibrational levels of the C_6H_6 target. Our data, not using retarding field analyser, can be underestimated in our high-energy limit, depending on the contribution from the electronic excitation cross section (unknown) to the total one.

Comparison with the theory does not help much in resolving the discrepancy between the present and the recent Tokyo results [15, 16]: as far as the calculation by Occhigrossi and Gianturco [19] indicate a rising cross section towards zero energy, the model by Kimura *et al* [16] shows a descending tendency with lowering energy. Occhigrossi and Gianturco [19] used Hartee–Fock electron densities in the fixed-nuclei approximation and single-centre expansion for the static part of the scattering potential and the multiterm polarization potential at large distances with the correlation potential derived from local-density approximation at small distances. Their data for C_2H_2 and C_2H_4 agree well with the experiment by Sueoka and Mori [11]. High values of the elastic cross sections in benzene in the low-energy limit have been attributed by Occhigrossi and Gianturco [19] to the high value of the dipole polarizability $\left(69.6\, a_0^3\right)$.

Kimura *et al* [16] used the continuum multiple-scattering method but no details of the potential were given. The results for electron scattering in the same model give the general shape of the cross sections reproducing the experimental data but are lower by about 30% at 2 eV. However, as noted in the introduction, the scattering potentials for positrons and electrons are different, so agreement with the electron data is far from being conclusive for positron scattering theories.

From all these comparisons we suppose that the most probable reason for the discrepancy below 5 eV is the use of a too strong (for the given apertures in the scattering cell) magnetic field in the recent Tokyo measurements. Above 5 eV one reason for the discrepancy could be an excessive correction for forward scattering on one hand, but also a lack of the retarding field analyser in our set-up, leading possibly to an underestimation of the cross section.

Present data, although descending monotonically with energy, show some changes of the slope at certain energies. Kimura *et al* [16] stated that 'although hard to distinguish visually, we have observed several weak structures due to positronium formation, electronic excitation and ionization in the neighbourhood of 4–10 eV'. As the data of Suoeka *et al* [14] and Kimura *et al* [2] show a distinct maximum just around the threshold for positronium formation (2.1 eV), we have explored this region with additional measurement runs; we do not confirm the existence of such a maximum.

Our data show some changes of the slope between 6 eV and 7 eV which are not related to any instrumental effect (like a change of the magnetic field applied). A similar change of the slope is visible in all sets of data from the Tokyo lab. This could be due to some contribution from the positronium formation or some low-laying electronic excitation channel (the three lowest triplet levels between 3.5 and 5.8 eV [40] and the singlet $^1B_{2u}$ at 4.8 eV [41]). Our additional measurements indicate a small, bump-like structure, slightly above the positronium formation, outside the statistical error (see figure 4(b) where statistical error bars are reported only). The amplitude of this structure above the monotonic descend of the cross section is 5×10^{-20} m^2. Note that Sueoka [10], in direct measurements (confining scattered positrons with a high magnetic field), evaluated the positronium formation cross section at 2 eV as about 6×10^{-20} m^2. Exact confirmation and/or explanation of these structures would require explicit studies of the positronium formation channel [42].

4. Conclusions

In the present experiment total cross sections for positron scattering in nitrogen and benzene at low energies have been measured, with an apparatus characterized by good beam stability

and angular resolution. The statistical error bar on present data in N_2 is less than 4%, and the systematic uncertainty in absolute values is less than 7%. Present data in nitrogen agree rather well with other experimental determinations down to 1.5 eV. Present data in benzene down to 2 eV agree very well with the results of Kimura *et al* [2] obtained with the apparatus with a retarding field analyser but without corrections for forward scattering. They also agree with the tendency of *ab initio* calculations of Occhigrossi and Gianturco [19]. Agreement with the most recent data in benzene, corrected for angular resolution [15, 16] and with the theory of [16], is poor.

Positron-scattering total cross sections on molecules at low energies still require additional measurement. The question of low energy rise of the total cross section for positron scattering on targets such as N_2 and H_2 still remains open, indicated by majority of theories, but not confirmed by experiments apart those from the Detroit lab. Experiments done by the Tokyo group [12] in N_2 (and CO, CO_2) in the set-up with a low magnetic guiding field and with a good angular resolution show a rise of the cross section, in agreement with the data from the Detroit lab [1, 41] and the theory [31, 32]. Data obtained in a set-up with high guiding fields and worse angular resolution, although some corrections are used [16] do not show such a rise. Independent experimental checks are essential.

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Endnotes

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