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A novel set-up for positron scattering in gases

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Abstract

A very low-energy positron spectrometer for scattering measurements in gases is presented. The apparatus uses electrostatic optics, two stages of positron moderation, magnetic focusing in the scattering chamber and a pseudo-random time-of-flight correlation technique.

1. Introduction

Investigations of low-energy positron scattering on atoms and molecules are an active area of studies (see for e.g. Tanaka et al., 1999; Kimura et al., 2000).

However, at low energies, a few measurements breaking the limit of 1 eV (Kauppila and Stein, 1990), make this energy range practically unexplored. Current scientific questions of interest involving low-energy positrons include the possibility of bound states of positrons with atoms and molecules, the role of vibrational excitation in the formation of long-lived positron-molecule resonances, and the fragmentation following the positron annihilation (Iwata et al., 1995). This range of low-energy positron scattering is also of interest for the investigation of Ramsauer–Townsend minima. There are only some indications for the existence of such minima in molecular gases like N_2, in contrast with the electron scattering case, see (Kauppila and Stein, 1990).

At Trento University a new experimental set-up has been developed which will allow the measurement of total cross sections for positron (and electron) scattering on molecules at low energies (0.1–20 eV). This apparatus contains several solutions, to our knowledge not used before in positron-molecule scattering experiments, like the remoderation stage and the pseudo-random correlation technique.

The major difficulty of scattering experiments is related to the very low brightness of positron sources. In present machine we use a brightness enhancement stage (Mills, 1980). Typically, standard radioactive sources used for positron beams (for example from Amersham) have the activity of about 20–30 mCi, deposited on 3–4 mm diameter spot. In the best configuration, i.e. the moderator practically touching the source, about 1000 slow positrons can be obtained from 1 mCi activity, but this emission is distributed on about 5–6 mm diameter spot (Zecca et al., 1995). Compared to about 1 mA electron emission from thermionic cathodes of about 1–2 mm spot, this gives the brightness of the positron source lower by a factor of 10^{-14} than the electron one (we assume the same angular divergence of the beams). In practical conditions, i.e. in the presence of gamma rays originating from the source, the counting rate of the useful signal at the detector can be lower than the background signal (Sueoka and Mori, 1984). The brightness enhancement stage rises the ratio between signal/noise only by a factor of about 10, but is essential for the feasibility of the cross sections measurements.

In this technique a slow positron beam from a first moderator, accelerated to a few keV energy is focussed on a remoderator. Positrons are re-emitted at energy of a few eV. The reemission process involves non-conservative forces. This fact allows to circumvent the Liouville theorem and to increase the brightness of the beam after the second moderation.

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A second solution we have adopted to obtain higher counting rates at the detector is the time-of-flight technique (Ferch et al., 1980). Thanks to this technique it is not needed to pre-select positrons and/or electrons with a well-defined energy but it is possible to use simultaneously positrons with different energies, performing then the time deconvolution of the arrival spectra. However, in a standard time-of-flight technique, the duty cycle is about 10% (the gate open only 10% of the cycle time), what reduces the advantage of this method. In a pseudo-random technique (Bewig et al., 1996), the gate open signal has a variable length, coded following a pre-defined pattern. The detector is locked into the same pattern. The electronic circuitry performs intrinsically decoding of the spectra. In this way the duty cycle can be close to 50%.

2. Apparatus

The layout of the set-up is shown in Fig. 1. The optical system of the apparatus consists of four major optical sections: first accelerator stage, deflector, remoderator stage, injection and gas cell.

2.1. Positron source

The positron source consists of the encapsulated $Na^{22}Cl$ salt, deposited in a cage in 8 mm tungsten cylinder and closed by a 5 μm Ti window. In front of the Ti window a 1 μm W monocrystal foil is placed. The W foil requires in situ conditioning with a 50 W, 8 kV electron beam obtained from a telefocus gun (Brusa et al., 1997). This gun allows obtaining the temperature of the film of about 3000 K at 10^{-7} Pa or better vacuuming conditions. The baking of the film is performed in a special chamber separated by a valve from the source region. The annealing procedure assures a moderation efficiency in the high 10^{-4} range (Brusa et al., 1997; Zecca et al., 1998).

The source unit provides also secondary electrons, which are used to have a reference measurement of the electron cross section. During the apparatus set up, a 3 mm spot NaCl source is used; during the measurements a 30 mCi source with a 2 mm spot will be used.

2.2. Electron optics design

The first accelerator consists of three cylindrical elements and assures the extraction of the beam from the moderator. We have assumed the $\pm 15^{\circ}$ angular limit for the beam in designing this accelerator. Positrons are first accelerated to 800 eV energy and then decelerated to 200 eV before injecting into the deflector. The first accelerator is built in a machinable W alloy, in order to improve the radiation shielding.

The deflector is a 90° electrostatic spherical prism used to prevent high-energy positrons from the source reaching the target. The mean radius of the deflector is 100 mm, and the distance between the two spherical electrodes is 20 mm. The beam, after the deflection is projected at the real exit aperture of 3.5 mm diameter. Positrons come out from the deflector with energy of 200 eV.

2.3. Remoderator stage

Our remoderator stage constitutes the system of three electrostatic lenses, which transports the beam to the remoderator. The accelerator produces a demagnified spot onto the remoderator and positrons emerge from a smaller spot with a higher brightness. The acceleration energy is tunable from 2 to 6 keV. This stage contains also an electron gun, formed by a circular W wire inside one of the electrodes, what allows in situ conditioning of the remoderator.

We use for remoderators a 2–5 μm Cu films prepared at Trento University (Brusa et al., 2000). The remoderation stage allows to the source of remoderated positrons down to the 0.5 mm diameter and consequently to

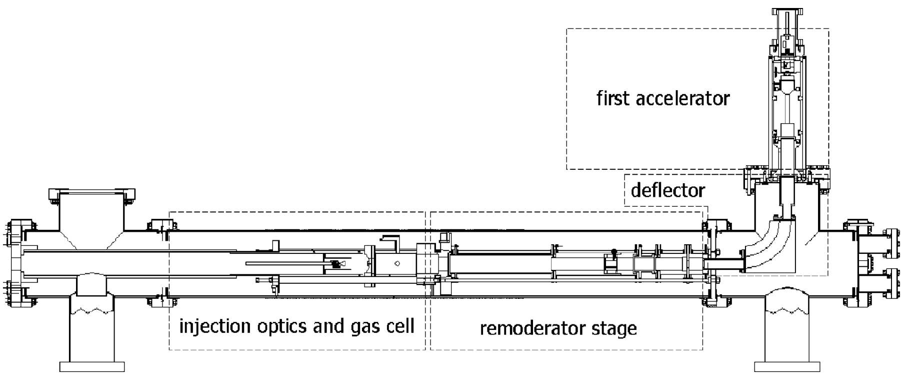

Fig. 1. Schematic drawing of the low-energy positron spectrometer.

reduce the size of the scattering chamber apertures (also 0.5 mm now). This last requirement is important for measurements below 1 eV: here some gases, like Ne or O_2, are known to exhibit very low values of total cross sections for electron scattering (Zecca et al., 1996). We guess that similar low values can be expected for positron cross sections. In such instances, high pressures in the scattering chamber will be needed.

2.4. Time-of-flight optics

The electron optics after the remoderator is extremely compact, occupying in total less than 2 cm in length. It contains an anode with a real aperture, a Soha electrode, a specially shaped pulse electrode and a focusing one. The shape of the electrodes has been designed to optimize the coupling of the high frequency gating signal. The scattering cell is 100 mm long, with entrance and exit apertures of 0.5 mm diameter. It is separated from the injection optics by a 2 cm long dummy cell, in order to improve the pumping efficiency.

In order to guide the low-energy positrons, a weak longitudinal magnetic field is used, in a lens-like configuration (Sueoka and Mori, 1984). All the optical elements after the remoderation stage are immersed in this field. This configuration, as we proved before (Zecca et al., 1996), allows an almost 100% transmission efficiency over the defined trajectory length. The system shows monochromating features, transmitting only positrons, which completed an integer number of gyrations between the entrance and exit apertures of the scattering cell. Compared to strong guiding fields (Sueoka and Mori, 1984; Kauppila et al., 1977) this system has no problems with non-adiabatic "explosion" of the beam at the end of the field region. It also changes insignificantly (less than few per cent, depending on energy) the effective length of the projectiles in the scattering cell.

2.5. Vacuum and shielding

The apparatus is shielded by an external μ-metal box, which around the secondary (i.e. after the deflector) beam has a form of a double cylinder. The shield allows to reduce the stray magnetic fields to below 0.2×10^{-7} T. Additionally, the Earth's field is compensated by a set of triple Helmholtz coils (Grisenti and Zecca, 1981).

The apparatus is working in a vacuum close to 10^{-9} mbar. The vacuum system is based on four turbo pumps: one 800 l/s for pumping the scattering chamber region, two 250 l/s each for the electron-optical column and for the channeltron region; one 70 l/s is used to pump the first moderator conditioning chamber. All vacuum tubes and flanges are machined from AISI 316 LNR stainless steel. The entire optics of the spectrometer has been fabricated from a non-magnetic copper–nickel alloy (Arcap-France).

3. Results of the tests

All elements of the system have been tested successfully. Both the primary and secondary beam optics work according to the calculated voltages. The pseudo-random electronics constructed entirely at Trento University works up to 66 MHz, giving some problems with stray reflections of the signal only at higher frequencies. Software packages have been compiled and tested successfully. The work is in progress in order to reduce the dimensions of the generators and detector electronics.

The focusing properties of the magnetic-field optics are shown in Figs. 2 and 3 which show the apparatus transmission function as measured with the electron and positron beam. The presence of well-defined single peaks proves the absence of any liasing and de-lineation of axes. Note that different contact potentials for positrons and electrons reflect in different positions of the peaks vs. the magnetic field.

Remoderator films have been tested on a separate apparatus (Brusa et al., 1997) and remoderation efficiencies of 10–12% have been proved. Heating of the remoderator has been also tested successfully, allowing obtaining the temperatures of the central spot up to 700°C, sufficient for annealing of Cu.

The transmission efficiency of the secondary optics is about 75% for positrons. Unfortunately, the test source has a too big diameter and the major part of emitted positrons cannot be transmitted using the designed optical parameters. At the moment, we lack the final strong source, which delivery is delayed by more than six

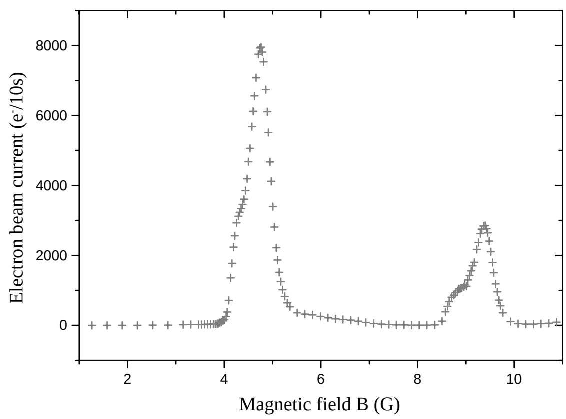

Fig. 2. Apparatus transmission function as measured with an electron beam. The presence of the peaks is determined by the focussing properties of the axial magnetic field.

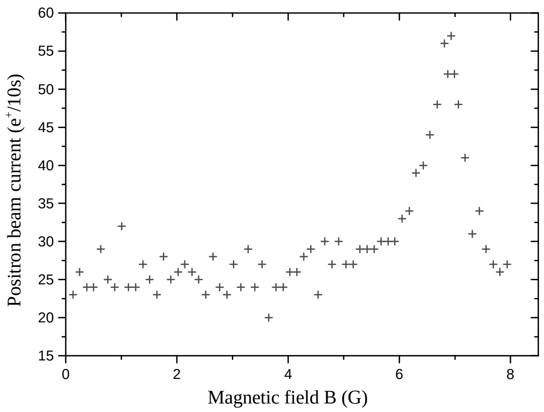

Fig. 3. Apparatus transmission function as measured with a positron beam: note the scale change. The position of the peak is different from the position in Fig. 2 due to the different emission energies.

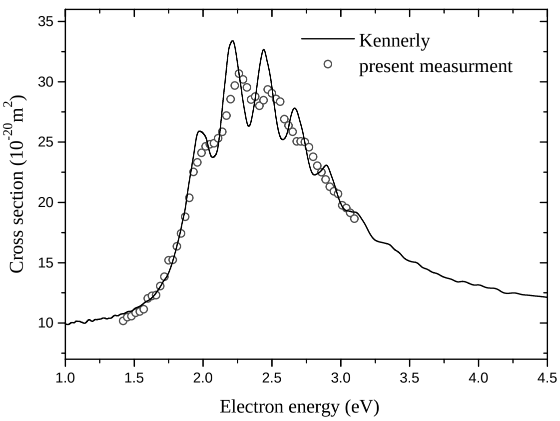

Fig. 4. Total cross section for electron scattering on N_2: the present measurements are compared with the data of Kennerly (1980). This measurement allows to determine the apparatus energy resolution as ($\Delta E/E \sim 130/2$ meV/eV).

month due to new security procedures in air transportation.

Finally, the apparatus was tested with electrons for the overall energy resolution of the secondary beam. We have measured cross sections for the $^2\Pi_g$ resonant structure in N_2 obtaining results in a good agreement (within 10%) with those of Kennerly (Kennerly, 1980). The energy resolution of our apparatus as deduced from these measurements is about 130 meV, see Fig. 4.

4. Conclusions

The concept and first, partial test results of a novel experimental set-up for low-energy positron measurements are presented. The second part of the beam, a time-of-flight set-up, shows a good transmission efficiency. The energy resolution of this part, tested for electrons, falls perfectly into expectations of the chosen solution, i.e. the use of a weak, longitudinal magnetic field in a lens-like mode. The field "cuts-off" the energy spread from the thermionic cathode from more than 1 eV, down to a few hundreds meV range. A similar "cut-off" is expected for positrons—as far as the energy spread from some moderators, like Ni is below 1 eV, commonly used W moderators show similar to thermionic cathode, about 2 eV energy spread of re-emitted positrons (Vehanen, 1987).

The expected energy resolution in the tested configuration is worse than the recent results from San Diego laboratory (Greaves and Surko, 2002), about 25 meV. However, that apparatus uses a rather complicated, several step, positron slowing down system, a strong radioactive source (100 μCi) and Ne-solid moderator. The present set-up is rather simple and compact.

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