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Total cross sections for positron scattering in argon, nitrogen and hydrogen below 20 eV

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Abstract

Total cross sections for positron scattering on argon, nitrogen and hydrogen have been measured at 0.4–20 eV by an absolute, transmission method. The apparatus uses a weak magnetic field but is characterised by small entrance and exit apertures of the scattering cell, assuring a good angular resolution down to the sub-eV energy range. Present measurements in all three gases show a fall of the cross section from the zero energy limit, then constant cross section values, within the error bar, up to the positronium formation threshold. Agreement with other experiments and theories is good but present data in the low energy limit are generally higher.

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Keywords: Positron scattering; Argon; Nitrogen

1. Introduction

Positron scattering in gas phase, in addition to electron collision, constitutes an important test for atomic and molecular structure. Electron scattering is well documented, see [1], and it allowed important discoveries, like the optical-like transparency of some atoms (argon, krypton, xenon) for low-energy electrons (so-called Ramsauer–Townsend effect [2]) or temporary negative ions (resonances) in non-attaching electrons gases like He and N_2 [3]. Positron scattering, due to much less bright sources is currently under studies only in few laboratories, and first data on total cross sections came only in seventies [4].

Positron total cross sections are, generally, lower than electron ones. This is due to a partial compensation between the static (repulsive for positrons) and polarisation (attractive for both electrons and positrons) forces in the case of positron scattering. Presence of Ramsauer minimum for positron scattering is discussed from the very first works, like those by Kauppila, Stein and collaborators, see [5]. Total cross sections for positrons and electrons merge in the limit of high energy, where the polarisation interaction becomes weak. This merging is clearly seen for molecules at energies above 100 eV (see [6]) but for Ar and N_2 only above 3000 eV [7].

In this paper we present results from a positron beam assembled and tested at Trento University in the framework of the Italian ''Istituto Nazionale per la Fisica della Materia'' fund and the EU ''Electron and Positron Induced Chemistry'' programme. Benchmark gases, nitrogen, argon and hydrogen have been measured. Our data agree in general with previous results, but they present some important refinements, changing also basic notions, including the ''Ramsauer minimum'' for positrons.

2. Apparatus

Some details of the apparatus have been described before [8]. Shortly, the apparatus consists of two electrostatic optical columns, see Fig. 1, separated by a 90° bend. The positron source is 17 mCi ^{22}NaCl encapsulated salt,

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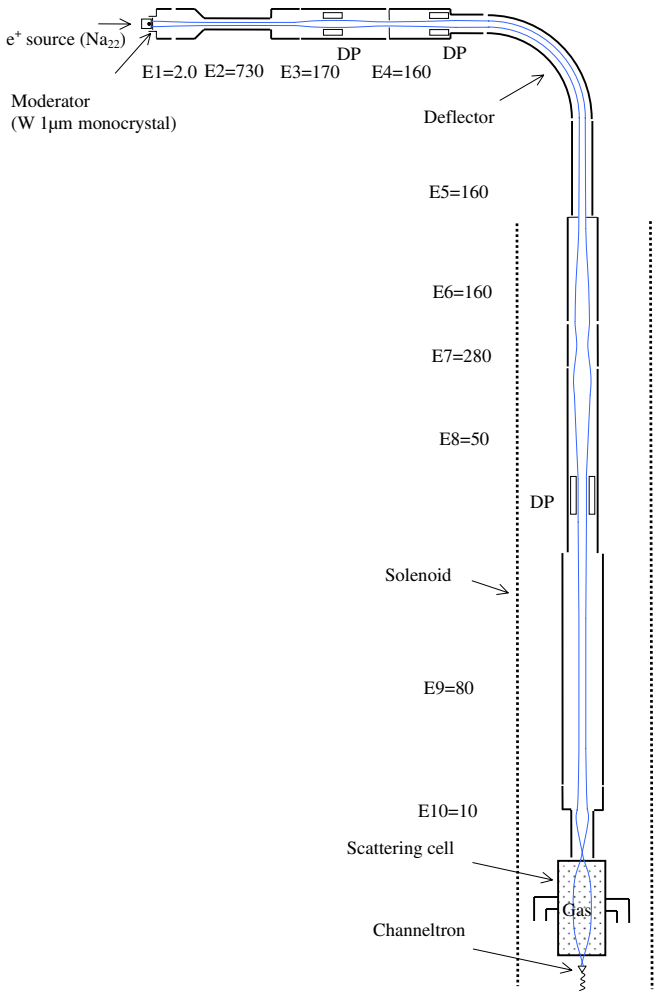

Fig. 1. Schematic drawing of the present apparatus – layout of the source, electrostatic optics and the scattering cell. "E_i" numbers refer to energies of positrons in eV; DP stays for deflection plates.

deposited in a 5 mm diameter cage and closed by 5 μm Ti window. The moderator is 1 μm thick W(100) foil from Aarhus University. The moderator assembly, made of pure tungsten, slides laterally into the first electrode. It can be extracted and treated in situ in a separate chamber. The first accelerator consists of three cylindrical elements, performing extraction of moderated positrons and their injection to the bend. The bend is formed by a spherical condenser; positrons travel at a constant velocity inside it and are transported to the exit aperture if their energy matches exactly the conditions determined by the field. Entrance and exit apertures of the bend are chosen in a way to obtain 1/100 energy selection $\Delta E/E$, where ΔE is FWHM of the energy distribution of the beam and E is its energy inside the bent. In the present experiment the bend was operated at 160 eV pass-by energy, assuring the energy distribution width within 1.6 eV FWHM.

A weak longitudinal magnetic field in the second part of the optics is used to facilitate guiding positron through the scattering cell. The field is kept at about 9 Ga, with slight adjustments (±10%) in a way to obtain an integer number of gyrations of positrons inside the scattering cell. For example, with 10 Ga applied positrons of 2.4 eV energy perform three full gyrations inside the cell. 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. The region of the scattering cell is differentially pumped.

In the preliminary design of the apparatus [9] the second optical column was to be used for accelerating positrons up to 2–5 keV energy and their injection into a copper remoderator. This solution, based on the remoderation concept [10] was abandoned in the present experiment, as technically too complex. For the present operation the optics of the second accelerator has been inverted and is working in a deceleration mode, see Fig. 1. This obviously leads to a loss of the intensity, from about 4000 e^+/s after the bend, down to 20 e^+/s at 1 eV and to 100 e^+/s at 10 eV collision energy. 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.

Measurements have been done in absolute method, monitoring the gas pressure, its temperature and the positron beam intensity I with and I_0 without gas in the scattering cell. The cross section σ is obtained from de Beer–Lambert's attenuation law

$$I = I_0 \exp(-pl\sigma/kT), \tag{1}$$

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

The pressure in the scattering cell was evaluated from Leybold Inficon CR091 membrane capacitance meter. The used gas pressure depended on the cross section values, in order to maintain conditions of single scattering events and varied between 2×10^{-3} and 2×10^{-2} Torr. The pressure read-out precision (not worse than 5%) is the main source of possible systematic error in our data. No correction was done for the thermal transpiration, in spite of the fact that the temperature of the gauge was stabilised 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

$$p_s = p_m \sqrt{(T_s/T_m)}, \tag{2}$$

where T_s (=296 K) and T_m are temperatures of the gas cell and of the pressure gauge, respectively. A maximum correction to the measured cross section, in the case of the molecular flow regime would be +3% but, as discussed by Poulter et al. [11], in practice the corrections in measurements of cross sections are lower, down to zero, depending on the type of gas. In the present apparatus we used short and wide tubes in gas connectors and therefore we assume a total 6% value for a possible error in gas pressure

determination (the read-out and thermal transpiration). The elongation of the scattering path due to magnetic field does not exceed 0.5%.

Possible dependencies of the cross section on the attenuation factor in Eq. (1) and on the guiding magnetic field were carefully checked in different experimental conditions; we observed none of such dependencies, see Fig. 2(a) and (b) and Fig. 3(a), respectively. A more difficult in our set-up is the estimation of the energy resolution. We cannot apply a retarding field analyser as the last electrode before, the scattering cell and the exit electrode are on ground potential. However, we measured the rise of the current at the zero energy, i.e. with the retarding potential between the scattering cell and the source, until the current goes to zero. Derivatives of these curves are shown in Fig. 3(b), for freshly treated and aged moderator. The FWHM of these curves is about 150–200 meV for fresh moderator, enlarging to 200–250 meV after some days from the treatment.

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. The statistical error bar is less than 3% and the overall systematic error defined as a quadratic sum of contributions is 7% (coming mainly from the pressure determination, with other sources of errors, like the length of the scattering path and the temperature determination being much smaller).

The energy calibration was done against the threshold for positronium formation in argon, see the upper inserted data in Fig. 5 – the cross section at this threshold shows a clear steep. Measurements in nitrogen were used additionally for the determination of the energy scale; however the energy step in our N_2 data is not so tiny as in Ar, see Fig. 6. The energy shift of our scale established from these

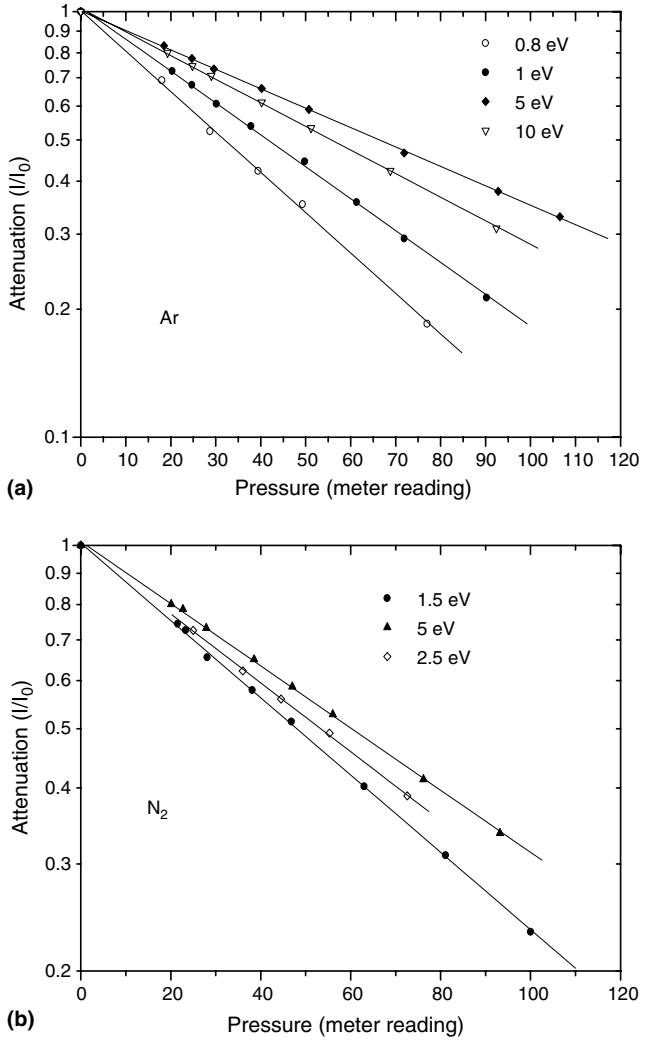

Fig. 2. Tests for total cross section measurements. Dependence of the attenuation ratio on the pressure (in 10^{-4} Torr) in argon and N_2.

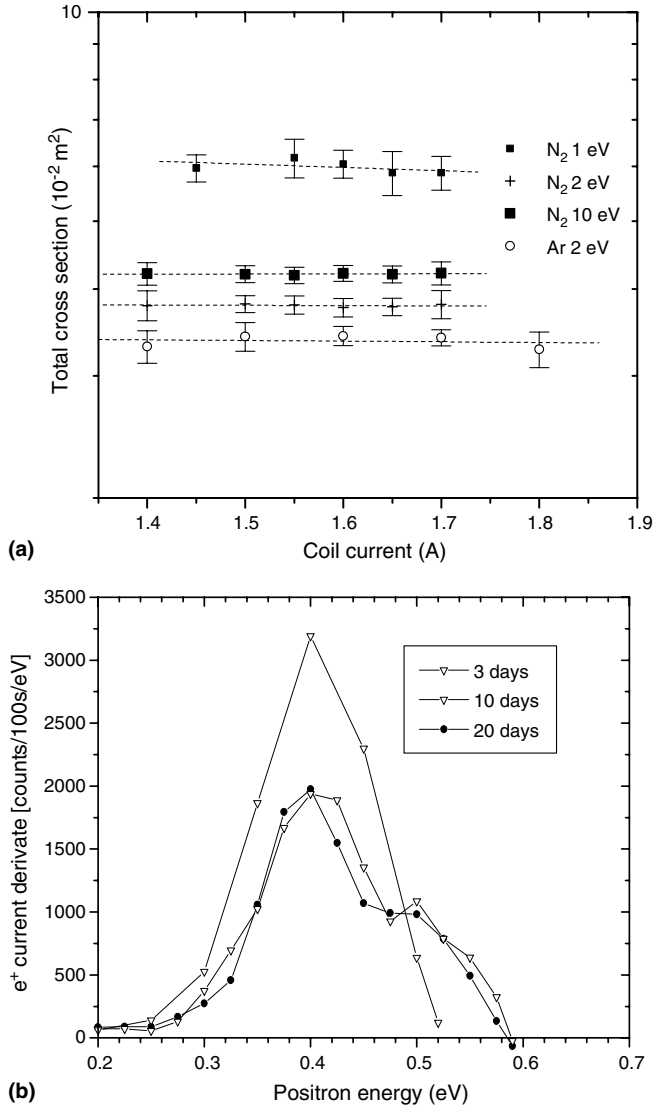

Fig. 3. Tests for total cross section measurements: (a) no dependence of the cross section on guiding magnetic field is observed (1.6 A coil current corresponds to 10 G magnetic field) and (b) pseudo-retarding field measurements – dependence of the derivative of the counting rate on the retarding potential between the moderator and the scattering cell in the limit of zero kinetic energy (the positron energy of 0.2 eV corresponds to +2.2 retarding potential applied). Measurements done 3, 10 and 20 days after the moderator treatment.

comparisons is +2.4 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 literature work function for positrons in tungsten [12]. A possible systematic error on the energy scale is ±0.1 eV.

The main progress in this machine, as compared to other positron beams is the compact source–moderator assembly [13], allowing electrostatic extraction of moderated positrons with no magnetic guiding fields and in situ treatment by high power (50 W) telefocus electron beam, also developed in our previous set-ups [13,14]. Our moderator efficiency is lower than for solid neon but the energy spread is much lower; compared to W mesh moderators we obtain both a higher efficiency as well as a better collection, in terms of initial angular spread of the beam. With an extremely high beam stability of our beam the pressure determination remains the main source of possible errors on total cross sections.

The angular resolution error will be discussed with nitrogen data, but in our apparatus, using relatively weak magnetic field and narrow entrance and exit apertures in the scattering cell (1 mm in diameter, compared to 8 mm in apparatus of Suoeka and Mori [15] and 4.75 mm in apparatus of Kauppila et al. [16]) it is much smaller than in earlier experiments. Narrow slits make in particular the measurements reliable below 1–2 eV, differently from some earlier set-ups, as will be discussed later.

3. Forward scattering error – nitrogen

In nitrogen, recent tabulated differential cross sections calculated in the whole 0–180° range down to zero energy [17] allow to determine precisely the possible angular resolution error in present (and other) data. Let express the total cross section in terms of the integrated differential cross section $d\sigma/d\omega$ over the solid angle 4π and divide it into two components, as below

$$\sigma = 2\pi\left[\int_0^{\theta_1} \frac{d\sigma}{d\omega}\sin\theta\, d\theta + \int_{\theta_1}^{\pi} \frac{d\sigma}{d\omega}\sin\theta\, d\theta\right]. \quad (3)$$

The angular resolution error consists in counting electrons (positrons) scattered into forward angles, below some "cut-off" angle θ_1, as non-scattered (first component in Eq. (3)). In this way, the cross sections is underestimated by the factor being the ratio of the second component of the sum in Eq. (3) to this overall sum.

The angle θ_1 changes with the position of the scattering event inside the cell, so the correction depends on geometrical factors but also, for example, on the attenuation rate. In electron scattering it is common and synthetic manner to evaluate the possible error by so-called angular acceptance, being the solid angle of the exit aperture as seen from the center of the scattering cell. This value in present apparatus is by a factor of 100 better than, for example, in the machine by Sueoka and Mori [15]. However, as already stressed by Kauppila et al. [16] in positron measurements another definition of the angular resolution error is more appropriate, based on the ratio between the cyclotron radius of positrons and the radius of the exit aperture.

In detail, we note that once the differential cross sections for positron scattering are known, the calculation of the error is even easier than for electron scattering. Namely, one can assume that the guiding magnetic field recaptures all positrons scattered, if their cyclotron radius (defined by the transversal velocity, acquired in the scattering event) is smaller than the exit apertures. For example, at 10 Ga the cyclotron radius of 1 eV positrons is 3.45 mm: with 4 mm slits [15] all positrons with the transverse energy below 1.3 eV will be counted as non-scattered. Therefore the error in the few eV energy range varies rapidly: at 2 eV collision energy the 1 eV transverse energy corresponds to $\theta_1 = 30°$, while at 1 eV collision energy *all* positrons scattered into angles $\theta_1 < 90°$ will be considered as "non-scattered". In the case of differential cross section uniform in angle, the correction at 1 eV would be by a factor of two. Calculations of de Carvalho et al. [17] show that this correction is even much higher.

This happens because of a particular interplay of scattering potentials. In electron scattering at energies of the 1 eV order, the differential cross sections tend to be uniform in angle, or at least, at Ramsauer minimum, be p-wave like, i.e. with a minimum at 90°, see [1] for comparisons for noble gases and diatomic molecules. According to calculations of de Carvalho et al. for positron scattering the differential cross sections become uniform only at energies below 0.1 eV, see Fig. 4. At 0.5 eV they are forward centered, with the forward scattering ($\theta_1 < 90°$) contribution (first component of the sum Eq. (3)) being about 85% of the integral cross section. At 1 eV, the use of 10 Ga field

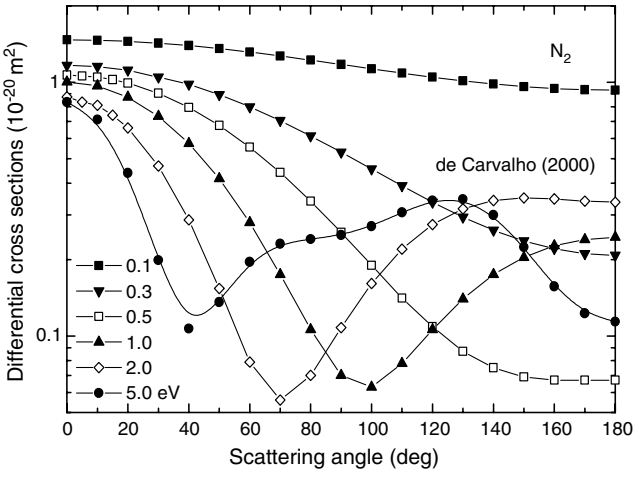

Fig. 4. Differential cross sections of de Carvalho et al. [17] for positron scattering on nitrogen at energies 0.1–5 eV (from upper to lower curves at zero angle) used presently for forward-scattering correction, see also Fig. 6. The data of [17] have been used as exclusive because they constitute an unique, to our knowledge, set of tabulated differential cross sections from 0.001 eV to 10 eV energy; these data agree well with the experiment, see [17].

and 4 mm radius slits underestimates the cross section by more than the factor of three.

The use of narrow slits cuts this error drastically. In our apparatus, at 1 eV, the magnetic field recaptures inside the radius of 0.5 mm only positrons scattered into angles below 1.2°; therefore the correction is negligible, thanks also to the sinus factor in formula (Eq. (3)). At 0.4 eV, the correction to our data would be somewhat +2–3% with a big error on this evaluation due to interpolation.

4. Results

First we present results for argon, where many experimental data exist, then nitrogen, where correction for forward scattering is possible and finally for hydrogen, where surprisingly little experiments were done.

4.1. Argon

Present results for argon are shown in Fig. 5; the insert of upper full points in Fig. 5 shows series in which the energy scale has been determined. Present data agree well with other determinations, laying somewhat in-between. In the energy range between 2 and 10 eV they almost coincide with the data of Charlton et al. [18], Canter et al. [19] and more recent data from the Detroit laboratory [20] and are slightly lower than those of Sinapius et al. [21] but by about 20% higher than those of Coleman et al. [22] and early data from the Detroit laboratory [23]. Above the positronium formation threshold our data agree best with those of Kauppila et al. [23] and Coleman et al. [22]. Below 2 eV present data agree well with measurements of Sinapius et al. but are higher than the early data from the Detroit lab [23], with the discrepancy rising in the limit of zero energy.

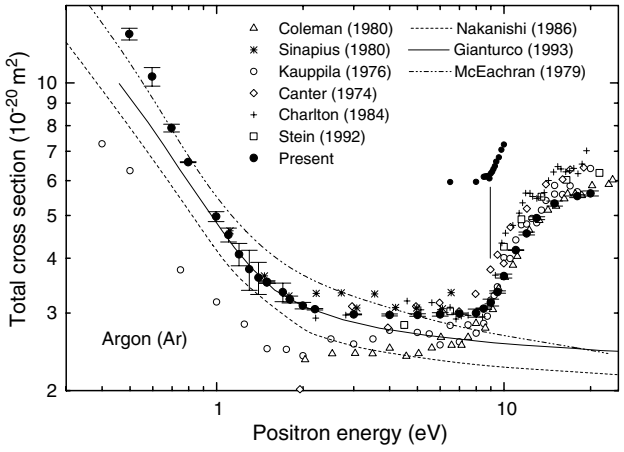

Fig. 5. Total cross sections for positron scattering on argon: triangles Coleman et al. [22]; stars, Sinapius et al. [21]; open circles, Kauppila et al. [23]; rhombuses, Canter et al. [19]; crosses Charlton et al. [18]; squares, Stein et al. [20]; points with statistical error bars, present. The upper insert shows series in which the energy scale was determined; the vertical bar shows the positronium formation threshold. Theory: solid line, Gianturco et al. [24], electron polarisation potential from free-electron-gas derivation with dipole potential; dash-dot line, McEachran et al. [25]; broken line, Nakanishi and Schrader [26].

Agreement with the theory is also perfectly "in the middle" – with Gianturco's [24] data coinciding with our measurements at 1–3 eV but the model of McEachran [25] agreeing better below 1 eV. All three theories [24–26] tend to constant values but at higher energies than the present experiment. Note, that from 3 eV up to the positronium threshold present data are *constant*, within our statistical error bar, in this region reduced below 2% by additional measurement series. Measurements with 0.1 eV pass show a sharp rise of the cross section at the positronium threshold. The point at 8.9 eV seems to be slightly lower than points at 8.7 eV and 8.8 eV what would confirm existence of a threshold cusp, postulated by Meyerhof and Laricchia [27], but additional measurements would be needed. (First two points on the insert in Fig. 5 were obtained in separate series – although they fall inside the 1% error bar with the rest of points, the uncertainty on pressure determination which is the main source of error at present, is well visible.)

Present data above the positronium threshold agree also well with the recent positronium-formation measurements by the San Diego group [28]. They measured at 12 eV the positronium formation cross sections of about 1.75×10^{-20} m^2 while the difference between our total cross section at 12 eV and the "constant" value below the positronium threshold (about 3.0×10^{-20} m^2) amounts to 1.55×10^{-20} m^2; at 18 eV the San Diego data is 2.6×10^{-20} m^2 and our difference 2.53×10^{-20} m^2.

4.2. Nitrogen

For nitrogen few measurements exist, data of Hoffman et al. [29] start at 0.5 eV and those of Charlton et al. [30] at 2.3 eV energy. Two sets of data are due to Suoeka and collaborators: in the first measurements 9 Ga field was used and 4 mm radii of apertures in the scattering cell [15], in the second a "typical" field of 1.8 Ga and 3 mm radius apertures [31]. Above the positronium formation threshold, present data agree very well with those of Hoffman et al. and Sueoka and Mori [15]. The latter perfect agreement can be partially an artifact, as Sueoka and Mori normalized their results to those by Hoffman et al. by adopting an "effective" scattering cell length, 18% longer than the geometrical one. This lowers the cross sections by the same factor. Our cross sections at 2–9 eV are by 10–15% higher than those of Hoffman et al.

Below 1 eV our data diverge up from all other. For data of Sueoka and Mori we have performed, tentatively, forward scattering corrections, assuming 9 Ga field and 4 mm radius apertures, see full rhombuses in Fig. 6. Such corrected data would coincide with our at 1.5 eV but would be even higher than present at lower energies. Obviously, any a-posteriori corrections are subject to big errors. However, as discussed in par. 3. no doubts exist that data obtained with large slits are heavily underestimated at energies below 2 eV. We are also not aware of the values of the

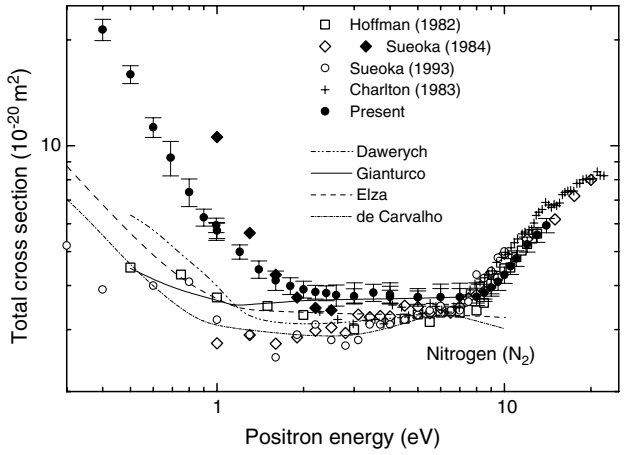

Fig. 6. Total cross sections for positron scattering on nitrogen: squares, Hoffman et al. [29]; rhombuses, Suoeka and Mori [15] with 4 mm radius scattering cell apertures and 9 Ga field, full rhombuses their points corrected (present work) by the angular resolution error using their experimental conditions and differential cross sections of de Carvalho et al. [17], an error bar of 30% is to be attributed to the correction procedure itself; a similar correction on present data is merely +2–3% at 0.4 eV; open circles, Sueoka and Hamada [31] measurements done with narrow slits (3 mm in radius) and weak (1.9 Ga) magnetic field; crosses, Charlton et al. [30]; points with statistical error bars, present. Theory: dash-dot-dot, Dawerych [34]; solid, Gianturco et al. [32], excited-atom correlation potential with outer cut-off radius; broken line, Elza et al. [33], ab initio polarisation potential; thin dash-dot line, de Carvalho et al. [17], Schwinger variational method.

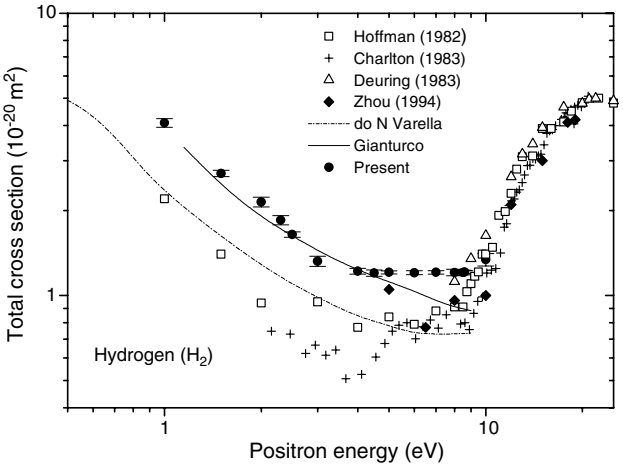

Fig. 7. Total cross sections for positron scattering on hydrogen. Experiments: squares, Hoffman et al. [29]; crosses, Charlton et al. [30]; triangles, Deuring et al. [37]; rhombuses, Zhou et al. [38]; points with statistical error bars, present (preliminary data). Theory: dash-dot, do N Varella et al. [39] effective-configuration approach; solid line, Gianturco et al. [32], excited-atom correlation potential with outer cut-off radius.

magnetic field used by Hoffman et al. – they quote a "cut-off" angle of 30°, what would underestimate the cross by about 30% at 0.5 eV (using differential cross sections of de Carvalho et al.).

Agreement between present data and the most recent theories – Gianturco et al. [32] with correlation–polarisation potential derived from local-density approximation and Elza et al. [33] with a long-range polarisation with a cut-off formula, is good. Different authors [32–34] show that the use of a too weak polarisation potential in the intermediate interaction region leads to low values of cross sections, and even to appearance of the Ramsauer minimum like in the *R*-matrix calculations by Danby and Tennyson [35]) and Kohn-variational method by Armour and Plummer [36], not shown in Fig. 6 for clarity.

4.3. Hydrogen

Present data in hydrogen have been obtained in fewer runs, therefore have poorer statistics. The point at 10 eV coincides with measurements of Hoffman et al. [29], the point at 8 eV would agree with that of Deuring et al. [37] but they have not extended measurements to lower energies. Below positronium formation threshold our data are lower by 15–30% than those of Hoffman but differently than for N_2 this difference remains constant in the limit of low energies. The newer data from the Detroit lab [38] would agree at 5 eV within 10% within present, but the overall scatter is higher. Decisively, more experiments in H_2 are needed.

Our data confirm in H_2 the same trend as in Ar and N_2, of the constant cross section from a few eV, up to the positronium-formation threshold. Note that as far at 5 eV the cross section in H_2 is lower by a factor of three than that of N_2, at 1 eV this difference is only by 30%.

Agreement with the theory proves to be the best with Gianturco et al. [32]. Out of two approaches to the correlation potential and the inner or outer cut-off radius studied by Gianturco et al. we show in Fig. 7 the one with excited-atom model and the outer radius. Note that this is the model which also in N_2 shows correctly the rise of the cross section in the limit of zero energy, see Fig. 6. Effective-configuration approach [39] follows essentially the data of Hoffman et al. [29].

Differently than in the case of nitrogen, we are not able to discuss the angular resolution correction. The theoretical differential cross sections, in Kohn variational method [40] and distributed positron model [41] are almost uniform at 0.5 eV while the recent experiments [42] show a forward-centered distribution.

5. Conclusions

Total cross sections for positron scattering on argon, nitrogen and hydrogen are presented at 0.5–20 eV (1–10 eV for H_2). In the region above the positronium threshold, present data and majority of other experiments agree well. At a few eV range present data in argon lay in-between other experiments; in nitrogen are the highest set of data, with difference of about 10–15%; in hydrogen they are higher by 20–25%. In this energy range present data are *constant* within the statistical error bar. This would correspond to scattering on a hard-sphere (and in particular in classical mechanics model).

Below 2 eV in argon and nitrogen and below 3 eV in hydrogen, the cross section rises towards zero energy, similar as in measurements by the Detroit group, but with present data being higher. Present data in argon and hydrogen at lowest energies agree well with the models by Gianturco and collaborators. In nitrogen we show, using differential cross sections by de Carvalho et al. [17], that previous experimental data *must* be underestimated, as they confine with the magnetic field the forward-scattered positrons. Strangely, the same theory [17] seems to be underestimated as far integral cross sections are concerned.

Concluding, all the targets studied, Ar, N_2, H_2 show three regimes of the total cross section:

(1) the low-energy fall, where differential cross sections are forward-centred, indicating scattering on a long-range (polarisation?) potential,
(2) a constant cross section at a few eV, predicted roughly by theories, indicated by previous experiments but now confirmed within 2–3% statistical error bar; this constant cross section *is not* a Ramsauer minimum, which is narrow and placed at lower energies, see [1,5],
(3) a rise of the cross section, seems piled-up above the constant elastic value, at energies above the positronium formation threshold.

All these indications are already present in early measurements, in particular by Kauppila, Stein and collaborators, see [5], but we find that both new experiments and theories are still needed.

References

[1] G.P. Karwasz, A. Zecca, R.S. Brusa, La Rivista del Nuovo Cimento 24 (4) (2001) 1;
A. Zecca, G.P. Karwasz, R.S. Brusa, La Rivista del Nuovo Cimento 19 (5) (1996) 1.
[2] C. Ramsauer, Ann. Phys. (Lepizig) 66 (1921) 546.
[3] G.J. Schulz, Phys. Rev. Lett. 10 (1963) 104;
G.J. Schulz, Phys. Rev. 125 (1962) 229.
[4] D.G. Costello, D.E. Groce, D.F. Herring, J.Wm. McGowan, Can. J. Phys. 50 (1972) 23.
[5] W.E. Kauppila, T.S. Stein, Adv. At. Mol. Opt. Phys. 26 (1990) 1.
[6] M. Kimura, O. Sueoka, A. Hamada, Y. Itikawa, Adv. Chem. Phys. 111 (2000) 537.
[7] G.P. Karwasz, M. Barozzi, R.S. Brusa, A. Zecca, Nucl. Instr. and Meth. B 192 (2002) 157.
[8] E. Rajch, A. Zecca, R.S. Brusa, S. Mariazzi, G.P. Karwasz, The International Society for Optical Engineering, Proc. SPIE 5258 (2003) 190.
[9] G. Karwasz, R.S. Brusa, M. Barozzi, A. Zecca, Nucl. Instr. and Meth. B 171 (2000) 178.
[10] R.S. Brusa, W. Deng, R. Checchetto, G.P. Karwasz, A. Zecca, Appl. Phys. Lett. 76 (2000) 1476.
[11] K.F. Poulter, M.-J. Rodger, P.J. Nash, T.J. Thompson, M.P. Perkin, Vacuum 33 (1983) 311.
[12] G. Amarenda, K.F. Canter, D.C. Schoepf, J. Appl. Phys. 80 (1996) 4660.
[13] G.P. Karwasz, A. Zecca, A. Piazza, P. Sperr, Deposition procedures for high brightness ^{22}Na radioactive sources, European Community Research Project BREU-CT 90-0347, Final Technical Report, June 1995, Appendix C4.
[14] R.S. Brusa, G.P. Karwasz, M. Bettonte, A. Zecca, Appl. Surf. Sci. 116 (1997) 59.
[15] O. Sueoka, S. Mori, J. Phys. Soc. Jpn. 53 (1984) 2491.
[16] W.E. Kauppila, T.S. Stein, J.H. Smart, M.S. Dababneh, Y.K. Ho, J.P. Downing, V. Pol, Phys. Rev. A 24 (1981) 725.
[17] C.R.C. de Carvalho, M.T. do N. Varela, M.A.P. Lima, E.P. da Silva, J.S.E. Germano, Nucl. Instr. and Meth. B 171 (2000) 33.
[18] M. Charlton, G. Laricchia, T.C. Griffith, G.L. Wright, G.R. Heyland, J. Phys. B 17 (1984) 4945.
[19] K.F. Canter, P.G. Coleman, T.C. Griffith, G.R. Heyland, J. Phys. B 6 (1973) L201;
K.F. Canter, P.G. Coleman, T.C. Griffith, G.R. Heyland, Appl. Phys. 3 (1974) 249.
[20] T.S. Stein, W.E. Kauppila, C.K. Kwan, S.P. Parikh, S. Zhou, Hyperfine Interact. 73 (1992) 53.
[21] G. Sinapius, W. Raith, W.G. Wilson, J. Phys. B 13 (1980) 4079.
[22] P.G. Coleman, J.D. McNutt, L.M. Diana, J.T. Hutton, Phys. Rev. A 22 (1980) 2290.
[23] W.E. Kauppila, T.S. Stein, G. Jesion, Phys. Rev. Lett. 36 (1976) 580.
[24] F.A. Gianturco, A. Jain, J.A. Rodriguez-Ruiz, Phys. Rev. A 48 (1993) 4321.
[25] R.P. McEachran, A.G. Ryman, A.D. Stauffer, J. Phys. B 12 (1979) 1031.
[26] H. Nakanishi, D.M. Schrader, Phys. Rev. A 34 (1986) 1823.
[27] W.E. Meyerhof, G. Laricchia, J. Phys. B 30 (1997) 2221.
[28] J.P. Marler, J.P. Sullivan, C.M. Surko, Phys. Rev. A 71 (2) (2005), Art. No. 022701.
[29] K.R. Hoffman, M.S. Dababneh, Y.-F. Hsieh, W.E. Kauppila, V. Pol, J.H. Smart, T.S. Stein, Phys. Rev. A 25 (1982) 1393.
[30] M. Charlton, T.C. Griffith, G.R. Heyland, G.L. Wright, J. Phys. B 16 (1983) 323.
[31] O. Sueoka, A. Hamada, J. Phys. Soc. Jpn. 62 (1993) 2669.
[32] F.A. Gianturco, P. Paioletti, J.A. Rodriguez-Ruiz, Z. Phys. D 36 (1996) 51.
[33] B.K. Elza, T.L. Gibson, M.A. Morrison, B.C. Saha, J. Phys. B. 22 (1989) 113.
[34] J.W. Dawerych, J. Phys. B. 15 (1982) L415.
[35] G. Danby, J. Tennyson, J. Phys. B 24 (1991) 3517.
[36] E.A.G. Armour, M. Plummer, J. Phys. B 24 (1991) 4463.
[37] A. Deuring, K. Floeder, D. Fromme, W. Raith, A. Schwab, G. Sinapius, P.W. Zitzewitz, J. Krug, J. Phys. B 16 (1983) 1633.
[38] S. Zhou, W.E. Kauppila, C.K. Kwan, T.S. Stein, Phys. Rev. Lett. 72 (1994) 1443.
[39] M.T. do N. Varella, D.L. Azevedo, M.A.P. Lima, J. Phys. B 35 (2002) 3531.
[40] E.A.G. Armour, M. Plummer, I. Shimamura, Hyperfine Interact. 89 (1994) 309.
[41] T.L. Gibson, J. Phys. B 25 (1992) 1321.
[42] J.P. Sullivan, S.J. Gilbert, J.P. Marler, L.D. Barnes, S.J. Buckman, C.M. Surko, Nucl. Instr. and Meth. B 192 (2002) 3.