IONIZATION AND POSITRONIUM FORMATION IN NOBLE GASES

J. P. MARLER, J. P. SULLIVAN⁺ AND C. M. SURKO

University of California, San Diego

9500 Gilman Dr., La Jolla, CA, 92093, USA

⁺*Present address: RSPHysSE, Australian National University
Canberra, Australia*

E-mail: csurko@ucsd.edu

This paper reviews key results of our recent study [Marler *et al.*, Phys. Rev. A 71, 022701 (2005)] of direct ionization and positronium formation in the noble gases from the thresholds for these processes to 90 eV. Results for argon and xenon are emphasized. The original study also reports similar results for neon and krypton. The experiment uses a cold, trap-based positron beam and scattering in a strong magnetic field to make absolute cross section measurements. Comparison with a detailed set of previous measurements yields reasonably good absolute agreement. A third, independent analysis was used to resolve the remaining discrepancies to a < 5% level in argon, krypton and xenon. Key aspects of the work, comparison with available theory, and open questions for future research are discussed.

1. Introduction

While positron interactions with matter play important roles in many physical processes, the study of positron interactions is much less well advanced, particularly at low energies than that of the analogous electron-matter interactions [1]. In part, this has been due to the relative unavailability of good sources of low-energy positrons. The advent of trap-based positron beams has provided new opportunities to study a variety of processes. In this paper, we describe the results of a recent study of ionization in noble gases [2]. These targets were chosen because they are relatively simple atoms for theoretical calculation, and because they are also among the simplest atoms to study experimentally.

Positrons can ionize atoms and molecules through three processes, direct ionization, positronium (Ps) formation, and direct annihilation. The first two have cross sections on the order of a_0^2 , where a_0 is the Bohr radius, whereas direct annihilation has a cross section that is orders of magnitude

smaller[1]. Consequently, it is neglected in the present study.

Comparison of the measured direct ionization cross sections with available theoretical calculations yields quantitative agreement at the 20% level[2]. However comparison of the measured positronium formation cross sections with available theoretical predictions yields only modest and qualitative agreement[2]. The lack of quantitative agreement between theory and experiment highlights the need for further consideration of this important and fundamental process.

2. Experimental Techniques

The experimental technique for forming a cold, trap-based positron beam using a ^{22}Na source, frozen neon moderator and buffer-gas trap is described in detail elsewhere[3, 4]. The scattering technique and further details of the experimental procedures are described in detail in Ref. [2]. Due to limited space, we refer the reader to these references for additional details.

Figure 1. Schematic diagram of the electrode structure (above) and the electric potentials (below) used to study scattering with a trap-based positron beam.

The beam formation and scattering apparatus are illustrated schematically in Fig. 1. The positron beam is magnetically guided through a scattering cell and retarding potential analyzer (RPA). The positron beam energy in the scattering cell, $\epsilon = e(V - V_S)$, where V_S is the potential of the scattering cell, can be varied from ~ 0.05 eV to 100 eV. The apertures on the gas cell are sufficiently small so there is a well defined interaction region in which the pressure and the potential are constant, and the path length can be accurately determined. The electrical potential, V_A , on the RPA can be

varied to analyze the energy distribution of the positrons that pass through the scattering cell. The energy resolution of the positron beam used in the experiments described here is ~ 25 meV (FWHM).

The ionization and positronium formation cross section measurements presented here were done using a technique that relies on the fact that the positron orbits are strongly magnetized[5, 6]. For the experiments described here, the magnetic field in the scattering region, B_S , and in the analyzing region, B_A , can be adjusted independently. When $B_S \gg B_A$, the invariance of the quantity, $\xi = E_{\perp}/B$ (where $E_{\perp}$ is the energy in the particles gyromotion in the plane perpendicular to the magnetic field) allows us to measure the total positron energy using the RPA [5, 6].

For direct ionization measurements, the RPA is set to exclude positrons that have lost an amount of energy corresponding to the ionization energy or greater. The absolute direct ionization cross section is then calculated from the number of positrons rejected by the RPA and the intensity of the positron beam [5, 6].

Since positronium is a neutral atom that is not guided by the magnetic field, positrons that form positronium in the scattering cell either annihilate in the cell or drift to the cell walls and annihilate there. Thus positronium formation results in a loss of positron beam current. This loss in intensity and the intensity of the incident positron beam is used to obtain the absolute Ps formation cross section [6].

3. Experimental Results

Shown in Fig. 2 are measurements of the direct ionization cross sections for argon and xenon. Also shown is a comparison with the experimental results of Refs. [7, 8] renormalized as described in Ref. [9]. The data from Refs. [7, 8] are derived from relative cross section measurements made in a crossed beam experiment using a coincidence technique and then normalized to the analogous electron cross sections at higher energies.

The two data sets shown in Fig. 2 agree reasonably well. The only qualitative difference is that, generally, the cross section values presented here are somewhat larger than those of previous measurements, ranging from $\sim 15\%$ in argon and xenon to $\sim 30\%$ in krypton[2].

The present measurements of positronium formation cross sections for argon and xenon are shown in Fig. 3. The data are generally featureless, reaching a maximum and then decreasing monotonically at higher energies. The only exception is a possible "shoulder" in the data for xenon that

ever systematic discrepancies, most notably in argon and krypton (i.e., see Ref. [2]) at energies greater than the peak in the cross sections. Since the differences begin at approximately the energy threshold for direct ionization, and the direct ionization cross section was used in Ref. [9] to obtain their positronium formation cross sections, this led us to consider a possible resolution of the remaining discrepancies.

4. Total Ionization and Further Analysis

As discussed in Ref. [2], when the present, direct measurements of the direct ionization and positronium formation cross sections are combined to calculate the total ionization cross sections, the resulting total cross sections are in extremely good absolute agreement with those reported in Ref. [9] (i.e., $\pm$ a few percent over most of the range studied). Thus we concluded that we could use the total ionization cross sections of Ref. [9] and our direct measurements for direct ionization to obtain an independent measurement of the Ps formation cross sections. The results of this analysis, shown by the solid lines in Fig. 3 agree well with the present, direct measurements (i.e., an independent measurement).

We conjecture that the remaining difference between these two determinations of the cross section and the determination from Ref. [9] (open squares in Fig. 3) could be due to an under counting of ions in the (coincidence-technique based) direct ionization measurements reported in Ref. [9]. While the data sets are in reasonably good absolute agreement over most of the energy range studied, there are, for example, significant differences in argon. In argon, the data of Ref. [9] show a second peak in the cross section at energies beyond the main peak, i.e., at $\epsilon \sim 25$ eV, tentatively attributed to excited-state positronium, that is not seen in the present measurements. Similar but less pronounced peaks in the cross sections for krypton and xenon were reported in Ref. [9]. They are not seen in the present measurements, with the exception of a shoulder in the cross section in xenon beginning at ~ 15 eV (see inset, Fig. 3).

For the direct ionization cross sections, we subtracted our positronium formation cross sections from the total ionization cross sections of Ref. [9] to obtain another, independent measurement of the direct ionization cross sections. The results (solid lines in Fig. 2) show excellent agreement between these two independent measurements for argon, krypton and xenon [2]. For neon, the additional analysis does not improve the situation [2].

Figure 2. Direct ionization cross sections ($\bullet$) as a function of positron energy for argon and xenon from Ref. [2]. These data are compared with two other determinations of these cross sections: ($\square$) the direct ionization measurements from Refs. [7, 8]; and ($-$) using the total ionization from Ref. [9] minus the present measurements for the positronium formation. Also shown for comparison for argon are (Δ) the experimental data from Ref. [10].

Figure 3. The present direct measurements ($\bullet$) of the positronium formation cross sections for argon and xenon as a function of incident positron energy from Ref. [2]. These data are compared with two other determinations of these cross sections: ($-$) $-$ $-$ $-$ the method of Ref. [9] using the total ionization of Ref. [9] minus the direct ionization measurements from Refs. [7, 8]; and ($-$) using the total ionization from Ref. [9] minus the present measurements for the direct ionization. The inset shows a "shoulder" observed in the present data for xenon on an expanded scale.

is shown on an expanded scale in the inset. Also shown in Fig. 3 is a comparison with the results of Ref. [9]. The experiment of Ref. [9] measured total ionization and direct ionization, and then used the difference to obtain an indirect measure of the Ps formation cross section.

The two sets of measurements of positronium formation cross sections shown in Fig. 3 are in fairly good, quantitative agreement. There are, how-

5. Comparison with Theory

In Fig. 4, we compare the direct ionization cross section measurements presented here with available theoretical calculations. The agreement between the measurements and theory is reasonably good. For further discussion, see Ref. [2].

Figure 4. Comparison of the present measurements of the direct ionization cross sections ($\bullet$) as a function of positron energy for argon and xenon [2] with the theoretical predictions of (---) CPE model of Ref. [11, 12], (—) CPE4 model of Ref. [11, 12], and (---) Ref. [13].

In Fig. 5, the present results for Ps formation are compared with the calculations of Refs. [14] using a coupled static-exchange approximation. Also shown are the results of a distorted-wave Born approximation (DWBA) calculation [15], that includes positronium formation in higher excited states. The static exchange model [14] agrees fairly well with the absolute magnitudes of the maxima of the measured cross sections, but the predicted dependence of the cross sections on positron energy are not in such good agreement with the measurements [2]. The predictions rise too quickly near threshold then fall more quickly, and finally, with the exception of neon, they are larger than the measured cross sections at higher values of energy (i.e., $\epsilon \gtrsim 50$ eV).

As shown in Fig. 5, sizable scale factors are required to match the magnitudes of the DWBA calculations [15] to the measurements, but the shapes of the cross sections as a function of positron energy are in reasonably good agreement with the present measurements [2]. We note that neither of the calculations predict a second maximum similar to those reported in Ref. [9] and most pronounced in the argon data (c.f., Fig. 3 above, open squares).

Figure 5. Comparison of the present measurements ($\bullet$) of the positronium formation cross section for argon and xenon [2] with the theory of (---) Ref. [14]. Also shown is the theory of (---) Ref. [15], scaled by factors of 0.51 (argon) and 0.31 (xenon), so that the maximum values are equal to the maximum values of the experimental data.

6. Summary and Concluding Remarks

We review here the highlights of recent absolute measurements of the positronium formation and direct ionization cross sections in the noble gases for positron energies from the thresholds to 90 eV. Comparison of the present measurements of the cross sections for direct ionization and positronium formation with those of Ref. [9] show good quantitative agreement for many features but some systematic differences. In order to resolve these remaining discrepancies, a third, independent analysis for both cross sections was performed that agrees very well with the present measurements over most of the range of energies studied for argon, krypton and xenon. In the case of neon, some discrepancies remain between the different data sets at the $\pm 15\%$ level.

Previous data for positronium formation cross sections in argon, krypton and xenon [9] showed some evidence of a second peak in the cross section at energies 20 - 30 eV, with this feature being most prominent in argon. The present data show no evidence of these features. We conjecture that these peaks could be due to an undercounting of ions produced by direct ionization in the previous experiment. There is a remaining feature in the present data for Xe, perhaps best described as a "shoulder" in the cross section (see inset of Fig. 3). The onset at ~ 15 eV is somewhat below the threshold for positronium formation from the 5s shell electrons at 16.7 eV.

Comparison of the direct ionization cross section measurements with available theoretical predictions indicates reasonable absolute agreement over most of the range of energies studied. The exception is near threshold where the predicted cross sections of Refs. [12, 16] in argon, krypton and

xenon are significantly larger than those observed.

Comparison of the measured positronium formation cross sections with theoretical predictions yields qualitative, but not quantitative agreement. More theoretical work to understand this unique and very important process would be most welcome.

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