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To cite this article: D A Cooke et al 2010 J. Phys.: Conf. Ser. 199 012006

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Positronium formation cross-sections for Xe, CO$_2$, and N$_2$

D A Cooke, D J Murtagh and G Laricchia

UCL, Department of Physics and Astronomy, University College London, Gower Street, London, WC1E 6BT, UK
E-mail: g.laricchia@ucl.ac.uk

Abstract. The positronium formation cross-sections for Xe, CO$_2$, and N$_2$ have been measured using coincidences between $\gamma$-rays from positronium self-annihilation and the resultant ion. In the case of Xe, there is excellent agreement with previous experimental determinations. For CO$_2$, there is broad agreement in magnitude with previous measurements in contrast with N$_2$ where good shape agreement at low energies (<40 eV) is found though the magnitude of the present cross-section is significantly higher.

1. Introduction

When considering ionization by positron impact, there are two dominant channels: direct ionization ($e^+ + A \rightarrow A^+ + e^+ + e^-$) and positronium (Ps) formation ($e^+ + A \rightarrow A^+ + \text{Ps}$). For an atomic target, the total ionization cross-section ($Q_{ti}$) is defined as the sum of the Ps formation ($Q_{Ps}$) and direct ionization ($Q_{+i}$) cross-sections, contributions from higher order processes and from direct annihilation of a target electron are considered generally negligible [1]. This is illustrated in figure 1, which shows the partitioning of $Q_{t}$ for He into contributions from $Q_{+i}$ and $Q_{Ps}$. In the case of a molecular target, the dissociative ionization cross-section ($Q_{\text{diss}}$) must also be included in the sum for $Q_{t}$.

Recently, there have been experimental determinations of $Q_{Ps}$ for the noble gases [e.g. 2, 3] and the first experimental measurements of Ps formation into the 2$P$ state ($Q_{Ps}(2P)$) for He, Ar and Xe [4]. With the exception of He, there have been fewer theoretical determinations of $Q_{Ps}$, however, there are a number of cross-sections for excited-state Ps formation [e.g. 5, 6] and Ps formation from inner-shell electrons [e.g. 6–8].

Figure 2 shows the available experimental determinations of $Q_{Ps}$ and $Q_{Ps}(2P)$ for Xe compared with theory. There is a large distribution of magnitudes and shapes when considering all determinations. There is, however, convergence between two recent measurements, those of [2] and [3]. The determination of [16], measured using $\gamma$-ray–ion coincidences, reproduces the structure observed by [2] in energy dependence only—an absolute scale was set by normalizing the coincidence yield to this previous determination. These measurements also suffered from a systematic effect at high energies ($E > 16$ eV) whereby the magnetic field failed to contain scattered projectiles, yielding an excess of $\gamma$-rays from annihilation on the cell walls.

In the present work, $\gamma$-ray–ion coincidences have been used to measure $Q_{Ps}$ for Xe, N$_2$, and CO$_2$ with particular attention paid to confining all positrons after scattering. Unlike previous work [15], an absolute scale has been set on these measurements using $Q_{t}^i$. For Xe, there is good agreement between all determinations [see e.g. 17]; for the molecules, a concurrent measurement of $Q_{t}^i$ for Ar was used for normalization.
2. Experimental Method

The experimental apparatus used in the present work is shown in figure 3 and has been described in detail elsewhere [18, 19]. Briefly, fast $\beta^+$ particles emitted from a $^{22}$Na source are moderated by annealed W meshes producing a slow positron beam with $\Delta E \sim 2$ eV. The slow positrons are radially confined by a magnetic field ($\vec{B} \approx 100$ G) along the length of the beam-line (see black squares in figure 3). The beam passes through a bent solenoid, an electron repeller (repeller R1 in figure 3) and a Wien filter in order to reduce the number of unwanted $\gamma$-rays, secondary electrons and fast positrons transported to the interaction region. A positively-biased electrode (repeller R2 in figure 3) may be used to repel the slow portion of the beam, allowing measurement of the background produced by the remaining particles. The interaction region is a hemispherical gas cell constructed from polished Al. A small electrostatic lens held at $-500$ V extracts ions from the cell towards the detector, which consists of a channel electron multiplier (CEM) housed in a separately-pumped chamber. A CsI $\gamma$-ray detector is placed directly on top of the interaction region to detect annihilation quanta from the cell, and a second CEM is positioned at the end of the beamline for the detection of positrons. The photomultiplier tube mounted on an extension arm was used for the determination of $Q_{Ps}(2P)$.

The measurements were normalized by recording the total ion yield ($Y_i$) simultaneously with the $\gamma$-ray–ion coincidence yield. $Y_i$ is proportional to $Q_i^t$ via:

$$Q_i^t = \frac{1}{nl} \frac{\varepsilon_i}{\varepsilon_i} Y_i$$

where $n$ is the number density of the target gas, $l$ is the effective cell length and $\varepsilon$ refers to a detector efficiency. This normalization is performed similarly to that for $Q_i^+$ in [18], and allows the determination of $\frac{1}{nl} \frac{\varepsilon_i}{\varepsilon_i}$ for use in other normalizations. The error on this method is approximately $\pm 5\%$ [20]. The $\gamma$-ray–ion coincidence yield can then be normalized relative to the ion yield by correcting for the CsI detector efficiency which has been measured as $0.010 \pm 0.001$. This places an additional $\pm 10\%$ error on the absolute scale of the measured cross-sections.

Yield is defined as event per positron recorded
Figure 2. Review of experimental and theoretical determinations of $Q_{Ps}$ for Xe. 2(a), experimental: •—[2], ○—[3], ◊—[12], □—[13], ▽ and △—lower and upper limits of [14] respectively, □—[15], ⊕—$Q_{Ps}(2P)$ [4]. 2(b), theoretical: solid line—[6]×0.5, dashed line—[7]×0.5, dotted line—[8], solid grey line—$Q_{Ps}(2P)$ [6], ○—as 2(a).

3. Results
Figures 4, 5 and 6 show $Q_{Ps}$ for Xe, CO$_2$ and N$_2$, respectively. In the case of Xe (figure 4), the present determination of $Q_{Ps}$ peaks at $\sim$10 eV with a magnitude of $8.9 \pm 0.3 \times 10^{-16}$ cm$^2$. A shoulder feature is observed between $\sim$14 eV and 24 eV with the cross-section becoming negligible after $\sim$100 eV. In comparison with other determinations of $Q_{Ps}$, there is excellent agreement, within errors, between the present results and those of [2] and [3].

Figure 5 shows the present $Q_{Ps}$ for CO$_2$ compared with other experimental measurements. The present results peak at $\sim$23 eV with a magnitude of $4.1 \pm 0.1 \times 10^{-16}$ cm$^2$ and extend to 750 eV. In
Figure 3. The magnetically guided positron beam and interaction region, showing the placement of various detectors.

Figure 4. Determinations of $Q_{Ps}$ for Xe: ■—present measurement, ○—[3], continuous curve—[2] (representative error bars are displayed).

comparison with previous determinations, the present $Q_{Ps}$ displays fair agreement in the position and magnitude of the peak with the lower limit measurement of [22]. The present results are higher than the previous determination of [21] except in the peak region.

Finally, in the case of N$_2$ (see figure 6) the present measurement peaks at $\sim$25 eV with a magnitude of $3.57 \pm 0.06 \times 10^{-16}$ cm$^2$ and extends to 350 eV. In comparison with the data of [23] there is excellent agreement in shape up to 40 eV (see inset), though the magnitude disagrees by $30 \pm 15\%$. Unlike for CO$_2$ [18], the separation of dissociation products from the parent ion has not been achieved for N$_2$. The extent to which N$^+$ is detected will affect the absolute scale placed on the reported results, and is the subject of ongoing investigation.
Figure 5. $Q_{Ps}$ from CO$_2$: •—present measurement, ○—[21], △ and ▽—upper and lower limits of [22], respectively.

Figure 6. $Q_{Ps}$ from N$_2$: •—present measurement, □—[23]. Inset shows data normalized to each other for comparison of energy dependence (arbitrary units).
4. Conclusions
In the present work, γ-ray–ion coincidences have been used to determine $Q_{Ps}$ for Xe, CO$_2$, and N$_2$. In the case of Xe, excellent agreement has been found between the present results and the two most recent determinations [2, 3]. For CO$_2$, there are a number of determinations of $Q_{Ps}$, among which agreement is moderate. For N$_2$, there is an excellent agreement in shape between the present results and [23] up to 40 eV, although there is a $\sim$30% difference in magnitude. The apparent importance of Ps formation in molecules several hundred eV above threshold (in contrast to atoms) as implied by the present data is currently not understood, though it is noted that N$_2$ was found to be an efficient converter for positron-to-positronium beams up to $\sim$250 eV [24]. Clearly, further investigations are necessary.

5. Acknowledgements
We would like to thank J. Dumper and R. Jawad for technical assistance as well as EPSRC for funding this research.

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