Positronium Production and Scattering below Its Breakup Threshold

S. J. Brawley, S. E. Fayer, M. Shipman, and G. Laricchia[*]
UCL Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom

(Received 21 August 2015; published 24 November 2015)

Recent findings on the similarity between electron and positronium scattering at the same velocity [Brawley *et al.*, Science 330, 789 (2010)] have guided us towards the realization of a detectable flux of positronium atoms at beam energies five times lower than previously obtained, enabling total cross sections to be measured in the energy range ∼(1–7) eV for the first time. In collision with Ar and Xe, the total cross sections of positronium are found to be smallest at the lowest energy probed, approaching those of the Ramsauer-Townsend minima for electron projectiles. Additional structure has been observed in the case of positronium scattering at incident energies around 5 eV.

DOI: 10.1103/PhysRevLett.115.223201 PACS numbers: 34.80.Uv, 34.80.Bm, 36.10.Dr

Positronium (Ps) is the bound state of an electron and its antimatter partner, the positron. It is a neutral, hydrogenic atom with principal energy levels half those of hydrogen. Its instability against annihilation is characterized by a spin-dependent lifetime (namely, 125 ps for 1^1S_0 and 142 ns for 1^3S_1). It is formed abundantly in positron encounters with matter, and experimental methods for its production close to thermal energies include positron implantation into porous insulators (see, e.g., Ref. [1]), while a tunable high-energy beam (≃300–2000 eV) has been produced by the acceleration and photodetachment of positronium negative ions (see, e.g., Ref. [2]). At intermediate energies (≃7–400 eV), neutralization of a positron beam transmitted through a gas [3,4] has enabled the generation of tunable monoenergetic Ps beams (see, e.g., Refs. [5–10]), which have been employed to investigate fragmentation processes [11,12] and to measure total cross sections (Q_T^{Ps}) for a broad range of atomic and molecular targets (see, e.g., Refs. [6,13,14]). A review of these experimental and theoretical works may be found in Ref. [15].

Recent studies at UCL have uncovered an unexpected similarity between Q_T^{Ps} and the total cross section for equivelocity electrons (Q_T^-) at velocities (v) in the range (0.5–3.8) a.u., even in the vicinity of electron resonances [14,16], raising the intriguing question of whether Ps projectiles might also experience a Ramsauer-Townsend effect—a quantum mechanical phenomenon giving rise to "target transparency" [17].

The Ramsauer-Townsend effect was first observed in collisions of electrons with the heavy inert atoms in the velocity range (0.15–0.24) a.u. [18], a range which until now had been inaccessible with Ps projectiles due to a combination of poor production of collimated Ps, low associated detection efficiency, and intrinsic losses, including in-flight annihilation and scattering from the production gas. The selection of the latter, informed by the findings of Ref. [14], has now aided the generation of a measurable beam of positronium atoms below its breakup threshold and the first *direct* measurements of Q_T^{Ps} at velocities between (0.2–0.5) a.u., corresponding to incident Ps energy, $E_{\mathrm{Ps}} \sim (1\text{–}7)$ eV. This region is of interest not only because of the possible subtle quantum mechanical effects discussed above but also because of their relevance to precision measurements of fundamental Ps properties (e.g., lifetimes and energy levels) which often need to account for perturbations introduced by the production or residual gases [19–21].

The UCL Ps beam has been described in detail elsewhere (see, e.g., Refs. [6,9]). Briefly, positrons emerging from the Ps production cell are repelled electrostatically, while forward-going Ps may enter a second cell where the target under investigation is introduced. The kinetic energy of the Ps beam is related to that of the incident positron (E_+) by $E_{\mathrm{Ps}} = E_+ - E_I + 6.8/n^2$ eV, where E_I is the first ionization energy of the production target and $n = 1$, the beam consisting predominantly of ground state atoms [6,22]. Thus, the Ps energy spread is dominated by that of the incident positron beam (currently ∼1 eV FWHM from a solid neon moderator).

The Ps beam production efficiency (ϵ_{Ps}) has been shown to obey the relationship [8–10]

$$\epsilon_{\mathrm{Ps}} \propto [1 - \exp(-\rho L_+ Q_T^+)] \times \exp(-\rho L_{\mathrm{Ps}} Q_T^{\mathrm{Ps}}), \quad (1)$$

where the first term in the brackets corresponds to the total fraction of positrons scattered in a gas region of number density ρ and length L_+, and the second to the transmission probability of Ps through the gas region of length L_{Ps}, with Q_T^+ and Q_T^{Ps} being the (positron + gas) and (Ps + gas) total cross sections, respectively. Thus, a small Q_T^{Ps} aids the transmission of Ps through the production cell and enhances ϵ_{Ps}. Guided by the work of Brawley *et al.* [14], argon was tested as the Ps production gas because of the small value of Q_T^- at low energies arising from the Ramsauer-Townsend minimum at ≃0.3 eV ($v \simeq 0.15$ a.u.). Prior to measuring ϵ_{Ps}, a number of further adjustments were made to increase the Ps signal. These included (i) decreasing the distance between the Ps production point and the detector (while retaining the same angular resolution of $\simeq 1°$) in order to reduce the fraction of Ps annihilating in flight to the detector, (ii) replacing the channel electron multiplier array with a channeltron with a lower dark count rate, and (iii) repositioning the γ-ray counters to optimize signal detection while increasing internal and external shielding from stray γ rays. Collectively, these resulted in an improvement of the signal-to-background ratio by a factor of $\simeq 475$ at 1.4 eV. Finally, using Ar as the production gas resulted in an increase of ϵ_{Ps} by an order of magnitude in comparison with H_2 at 2.7 eV, with ϵ_{Ps} further doubling at 1.4 eV, whereas no signal was observed with H_2 at this energy. Thus, the use of Ar as a Ps convertor has resulted in a usable Ps beam flux down to velocities of $\simeq 0.2$ a.u.

The low-energy Q_T^{Ps} results for Ar and Xe are shown in Figs. 1 and 2, respectively, together with available theories and representative cross section measurements for electrons and positrons at the same velocity.

For Ar, there is good agreement between the current and previous measurements of Q_T^{Ps} in the velocity range (0.6–2.1) a.u. [6,14,23]. The new Q_T^{Ps} data increase with velocity before marking out a shoulder around (0.4–0.5) a.u. From 0.6 a.u., Q_T^{Ps} is close to Q_T^- for the remaining velocity range, forming a broad peak $\simeq 15\%$ lower than Q_T^- centered around (1.0–1.2) a.u. and decreasing to half of the peak value by the highest velocity investigated.

Also shown in the figure are the results of a number of theories. The coupled-pseudostate approximation by McAlinden *et al.* [33] assumed the target to be "frozen" but added target-inelastic processes calculated within a first Born approximation. A broad peak centered around 0.7 a.u. marks the point at which the theory and present results are close in magnitude. To the lower velocity side of the peak, theory is very similar to the Q_T^- measurements in shape and magnitude, perhaps surprisingly considering that exchange was absent in the description. This was remedied by the elaborate coupled-pseudostate expansion of Blackwood *et al.* [32]. This calculation, comprising 22 Ps states, was still carried out within the frozen-core approximation, but exchange effects were fully included and target-inelastic processes added via the first Born approximation, making this the most sophisticated theoretical treatment available for (Ps + Ar). However, the results display a different velocity dependence from the experiment, decreasing monotonically by a factor of 3 from zero to around 0.9 a.u., crossing experimental results at around 0.7 a.u. A minor peak near 1.1 a.u. is close in position to the experimental one but smaller by around a factor of 2. Notably, the neglect of virtual excitations of the target is likely to lead to an overestimate of elastic scattering below the target-inelastic theshold ($\simeq 11.5$ eV), as demonstrated in simpler systems

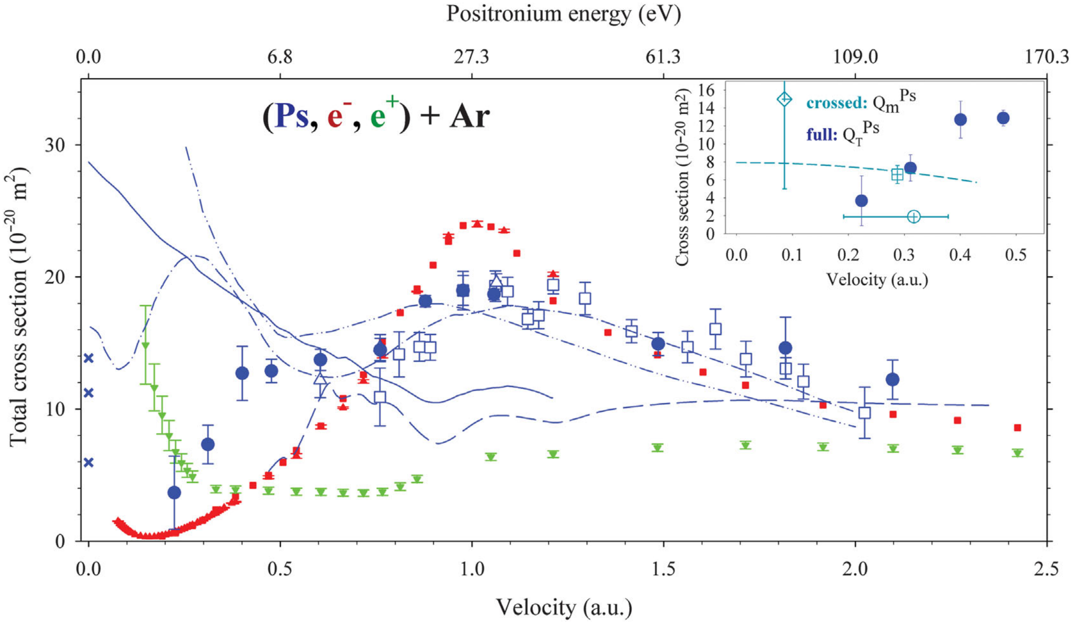

FIG. 1 (color). Q_T^{Ps} (blue) for Ar compared to available theories and a selection of Q_T^- (red) and Q_T^+ (green) for the same target. Also shown in the inset are Q_m^{Ps} (cyan) for collisions at less than 0.5 a.u. Experimental Q_T^{Ps}: circles, present results; hollow triangles, Ref. [14]; hollow squares, Refs. [6,23]. Experimental Q_m^{Ps}: crossed square, Ref. [24]; crossed diamond, Ref. [25]; short dash, Ref. [26]; crossed circle, Ref. [27]. Experimental Q_T^-: up triangles, Ref. [28]; squares, Ref. [29]; circles, Ref. [30]. Recommended experimental Q_T^+: down triangles, Ref. [31]. Theoretical Q_T^{Ps}: (solid line) coupled-pseudostate plus first Born approximation [32]; (long dashed line) coupled-pseudostate plus first Born approximation without exchange [33]; (crosses) stochastic variational method [34]; (dash double dotted line) impulse approximation [35]; (dash dotted line) pseudopotential approach [36].

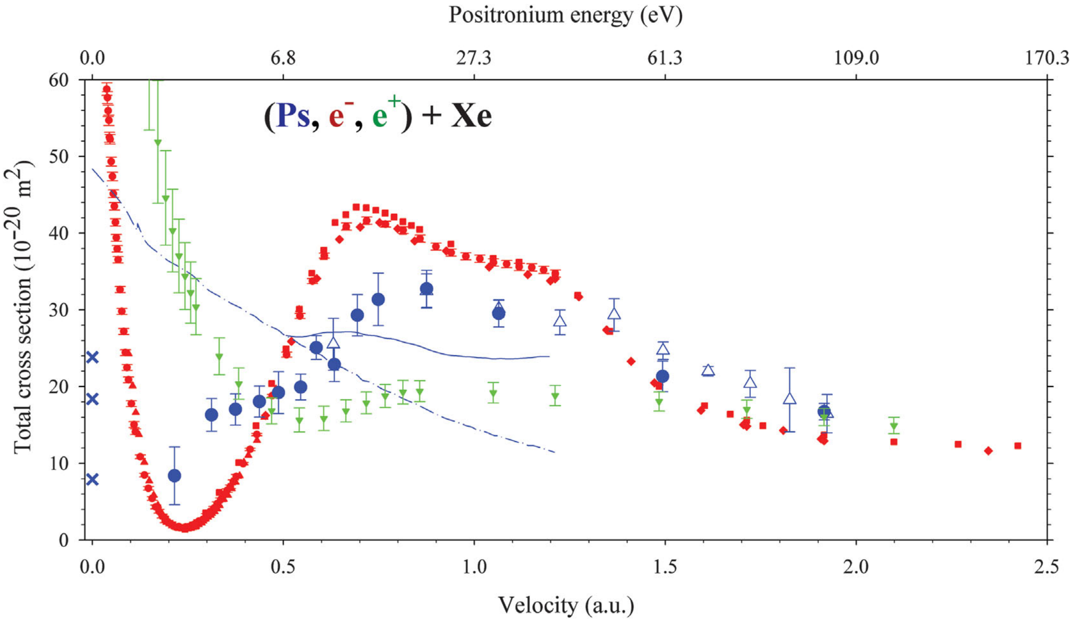

FIG. 2 (color). $Q_T^{\rm Ps}$ (blue) for Xe compared with available theories and a selection of Q_T^- (red) and Q_T^+ (green) for the same target. Experimental $Q_T^{\rm Ps}$: circles,) present results; hollow up triangles, Ref. [14]. Experimental Q_T^-: circles, Ref. [37]; up triangles, Ref. [28]; squares, Ref. [29]; diamonds, Refs. [38,39]. Recommended experimental Q_T^+: down triangles, Ref. [31]. Theoretical $Q_T^{\rm Ps}$: (dash dotted line) static exchange calculation [32]; (crosses) stochastic variational method [40]; (solid line) sum of static exchange and inelastic cross sections [32,41].

(i.e., H, He) by Refs. [42–44]. More recently, Fabrikant and Gribakin [35] have calculated elastic and Ps($n = 2$) excitation cross sections using the impulse approximation, in which Ps scattering is described as a coherent superposition of (electron + atom) and (positron + atom) scattering processes. The authors drew on the relatively weak (positron + atom) interaction to explain how Ps would interact mainly via its electron with the target [45], in turn dominated at intermediate energies by exchange [35]. By adding the Ps breakup cross section of Starrett *et al.* [46] to their results, close agreement with the experiment was found above ~0.5 eV. Below the Ps ionization threshold, the impulse approximation was subsequently supplemented by a pseudopotential approach for (positronium + atom) scattering, based on (electron+atom) and (positron+atom) phase shifts [36]. The calculation indicated that a Ramsauer-Townsend minimum should not be present for Ps scattering from Ar. The shape and magnitude of the prediction differ greatly from our measurements at these low energies; however, the authors warn that the position and magnitude of their maximum is uncertain.

Until the present work, the only experimental cross sections available for Ps scattering below 0.5 a.u. had been confined to indirect determinations of the momentum transfer cross sections ($Q_m^{\rm Ps}$) deduced from thermalization measurements [24–27] where

$$Q_m^{\rm Ps} = \int (1 - \cos\theta)\frac{dQ_{\rm el}^{\rm Ps}}{d\Omega}\, d\Omega, \qquad (2)$$

with θ being the scattering angle and $dQ_{\rm el}^{\rm Ps}/d\Omega$ the differential Ps elastic scattering cross section. At zero energy, where scattering is isotropic, $Q_m^{\rm Ps}$ is equal to the total cross section. It was pointed out that calculations show $Q_m^{\rm Ps}$ and $Q_{\rm el}^{\rm Ps}$ diverging very rapidly with increasing energy and, consequently, comparisons between the two may be misleading [32]. With that caution in mind, we note that $Q_m^{\rm Ps}$ has been determined via measurements of the angular correlation of annihilation radiation (ACAR) [25,26] and Doppler broadening [24,27], and we make a comparison to these results in the inset of Fig. 1. Around 0.3 a.u., at which $Q_m^{\rm Ps}$ is computed [32] as 50% of $Q_{\rm el}^{\rm Ps}$, the $Q_m^{\rm Ps}$ of Skalsey *et al.* [24] and Coleman *et al.* [26] have a similar magnitude to $Q_T^{\rm Ps}$, implying dominant s-wave scattering. Following the energy dependence predicted by Peach [47], a universal expression $Q_m^{\rm Ps} = (9 - \frac{1}{2}E_{\rm Ps})\pi a_0^2$ was extracted by Coleman and coworkers for He, Ne, and Ar [26], although the authors advise that these results should be taken as a guide only due to the large number of approximations made. The ACAR result of Nagashima *et al.* [25], while possessing a large uncertainty, is not inconsistent with the results of Coleman *et al.* at low energies, or with the fixed-core stochastic variational calculations of Mitroy and Ivanov [34], their three points obtained using various target polarization potentials. The results of Ref. [27] were obtained using the positron annihilation age-momentum correlation technique and assuming a constant $Q_m^{\rm Ps}$ between $E_{\rm Ps} = (1–3.9)$ eV (corresponding to $v \simeq 0.19–0.38$ a.u.), while $Q_T^{\rm Ps}$ increases by approximately a factor of 3 over the same range.

For Xe, a good agreement is found between the present and previous [14] measurements of $Q_T^{\rm Ps}$. The new measurements at velocities between 0.22 and 0.63 a.u. ($E_{\rm Ps} = 1.3$ to 10.9 eV) indicate a decrease of the cross section with decreasing velocity. As with Ar, a shoulder appears around (0.4–0.5) a.u. There are fewer theories available for Xe than for Ar. The stochastic variational method of Mitroy and Bromley [40] at zero energy is shown as a range of values which depend on the polarization potential used, as in the work of Mitroy and Ivanov [34]. The static exchange calculation of Blackwood *et al.* [32] was performed in the velocity range (0–1.2) a.u. ($E_{\rm Ps} = 0$–40 eV). In the figure, the inelastic contributions, calculated by Starret *et al.* [41] within the impulse approximation augmented by the first Born approximation, have been added to the static exchange calculation of Blackwood *et al.* [32]. The total shows a reasonable estimate of the magnitude of the experimental cross section at velocities (0.5–1.0) a.u. Interestingly, Coleman *et al.* [26] stated that a $Q_m^{\rm Ps}$ value for this target could not be extracted due to there being no evidence of the Ps atom slowing down, in turn suggesting a small cross section between the velocities of (0–0.5) a.u., which is consistent with the result of the present work. Skalsey *et al.* [24] also remarked on being unable to extract reliable thermalization results for Xe.

In conclusion, Ps total cross sections are reported at energies in the range ~(1–7) eV ($v \simeq 0.2$–0.5 a.u.) for Ar and Xe close to the region of the well-known Ramsauer-Townsend minima for electron scattering from these targets. The electronlike scattering of Ps observed in earlier investigations above the Ps breakup threshold [14,16] is discernible even at these energies, with the total cross section decreasing for both targets in a similar way to that for electrons. Additionally, a shoulder around $E_{\rm Ps} \sim 5$ eV ($v \simeq 0.43$ a.u.) is also observed for both targets.

It is pertinent at this point to speculate as to the possible cause of this feature. Thus, we note its proximity to the first excitation energy of Ps (5.1 eV) and that, however, theories predict only a small contribution from this process to the total cross section for Ps scattering from H [48], He [49], and Ne and Ar [32,35]. In this respect, it should also be pointed out that virtual target excitations are absent or approximate in these descriptions [32,36,48,49]. It is also worthwhile to remark that the interplay between the *s* and *p* waves might also give rise to structure below 6.8 eV [36,44,50]. Either hypothesis in relation to the experimental results would imply a small value of the Ps *s*-wave elastic scattering cross section not inconsistent with the occurrence of a Ramsauer-Townsend minimum for Ps. It is hoped that future theoretical and experimental investigations will clarify the underlying physics.

The data supporting this publication are available at UCL Discovery [51].

We wish to thank Ilya Fabrikant, Gleb Gribakin, John Humberston, Gillian Peach, László Sarkadi, Peter Van Reeth, James Walters, and Sandra Ward for interesting and helpful discussions. The Engineering and Physical Sciences Research Council is also gratefully acknowledged for supporting this work under Grant No. EP/J003980/1 and for providing both M. S. and S. E. F. with support through research studentships.

---

[*] g.laricchia@ucl.ac.uk

[1] D. B. Cassidy, T. H. Hisakado, V. E. Meligne, H. W. K. Tom, and A. P. Mills, Jr., Phys. Rev. A **82**, 052511 (2010).
[2] K. Michishio, T. Tachibana, R. H. Suzuki, K. Wada, A. Yagishita, T. Hyodo, and Y. Nagashima, Appl. Phys. Lett. **100**, 254102 (2012).
[3] B. L. Brown, Bull. Am. Phys. Soc. **30**, 614 (1985).
[4] G. Laricchia, M. Charlton, S. A. Davies, C. D. Beling, and T. C. Griffith, J. Phys. B **20**, L99 (1987).
[5] G. Laricchia, S. A. Davies, M. Charlton, and T. C. Griffith, J. Phys. E **21**, 886 (1988).
[6] A. J. Garner and G. Laricchia, Can. J. Phys. **74**, 518 (1996).
[7] S. Armitage, J. Beale, D. Leslie, and G. Laricchia, Nucl. Instrum. Methods Phys. Res., Sect. B **233**, 88 (2005).
[8] M. Shipman, S. Brawley, D. E. Leslie, S. Armitage, and G. Laricchia, Eur. Phys. J. D **66**, 96 (2012).
[9] M. Shipman, S. J. Brawley, L. Sarkadi, and G. Laricchia, Eur. Phys. J. D **68**, 75 (2014).
[10] M. Shipman, S. Armitage, J. Beale, S. J. Brawley, S. E. Fayer, A. J. Garner, D. E. Leslie, P. Van Reeth, and G. Laricchia, Phys. Rev. Lett. **115**, 033401 (2015).
[11] S. Armitage, D. E. Leslie, A. J. Garner, and G. Laricchia, Phys. Rev. Lett. **89**, 173402 (2002).
[12] S. J. Brawley, J. Beale, S. Armitage, D. E. Leslie, A. Kövér, and G. Laricchia, Nucl. Instrum. Methods Phys. Res., Sect. B **266**, 497 (2008).
[13] N. Zafar, G. Laricchia, M. Charlton, and A. Garner, Phys. Rev. Lett. **76**, 1595 (1996).
[14] S. J. Brawley, S. Armitage, J. Beale, D. E. Leslie, A. I. Williams, and G. Laricchia, Science **330**, 789 (2010).
[15] G. Laricchia and H. R. J. Walters, Riv. Nuovo Cimento **35**, 305 (2012).
[16] S. J. Brawley, A. I. Williams, M. Shipman, and G. Laricchia, Phys. Rev. Lett. **105**, 263401 (2010).
[17] Note: In partial wave analysis, the *s*-wave cross section Q_0 is proportional to ($\sin^2\delta_0$), with δ_0 being the *s*-wave phase shift. Thus, Q_0 goes through zero if, at low energies, $\delta_0 = m\pi$, where m is an integer (equal to zero in the case of the positrons). If the zero in Q_0 occurs at higher energies, contributions from higher partial waves may mask its presence in Q_T.
[18] H. S. W. Massey and H. S. Burhop, *Electronic and Ionic Impact Phenomena* (Clarendon, Oxford, 1952).
[19] A. Ishida, T. Namba, S. Asai, T. Kobayashi, H. Saito, M. Yoshida, K. Tanaka, and A. Yamamoto, Phys. Lett. B **734**, 338 (2014).
[20] R. S. Vallery, P. W. Zitzewitz, and D. W. Gidley, Phys. Rev. Lett. **90**, 203402 (2003).
[21] O. Jinnouchi, S. Asai, and T. Kobayashi, Phys. Lett. B **572**, 117 (2003).

[22] G. Laricchia, S. Armitage, and D. E. Leslie, Nucl. Instrum. Methods Phys. Res., Sect. B **221**, 60 (2004).
[23] A. J. Garner, A. Ozen, and G. Laricchia, Nucl. Instrum. Methods Phys. Res., Sect. B **143**, 155 (1998).
[24] M. Skalsey, J. J. Engbrecht, C. M. Nakamura, R. S. Vallery, and D. W. Gidley, Phys. Rev. A **67**, 022504 (2003).
[25] Y. Nagashima, T. Hyodo, K. Fujiwara, and A. Ichimura, in *The Physics of Electronic and Atomic Collisions*, edited by L. J. Dube, B. A. Mitchell, W. McConkey, and C. E. Brion, AIP Conf. Proc. No. 360 (AIP, New York, 1996).
[26] P. G. Coleman, S. Rayner, F. M. Jacobsen, M. Charlton, and R. N. West, J. Phys. B **27**, 981 (1994).
[27] Y. Sano, Y. Kino, T. Oka, and T. Sekine, J. Phys. Conf. Ser. **618**, 012010 (2015).
[28] J. Ferch, B. Granitza, C. Masche, and W. Raith, J. Phys. B **18**, 967 (1985).
[29] C. Szmytkowski, K. Maciag, and G. Karwasz, Phys. Scr. **54**, 271 (1996).
[30] S. J. Buckman and B. Lohmann, J. Phys. B **19**, 2547 (1986).
[31] L. Chiari and A. Zecca, Eur. Phys. J. D **68**, 297 (2014).
[32] J. E. Blackwood, M. T. McAlinden, and H. R. J. Walters, J. Phys. B **35**, 2661 (2002).
[33] M. T. McAlinden, F. G. R. S. MacDonald, and H. R. J. Walters, Can. J. Phys. **74**, 434 (1996).
[34] J. Mitroy and I. A. Ivanov, Phys. Rev. A **65**, 012509 (2001).
[35] I. I. Fabrikant and G. F. Gribakin, Phys. Rev. Lett. **112**, 243201 (2014).
[36] I. I. Fabrikant and G. F. Gribakin, Phys. Rev. A **90**, 052717 (2014).
[37] M. Kurokawa, M. Kitajima, K. Toyoshima, T. Kishino, T. Odagiri, H. Kato, M. Hoshino, H. Tanaka, and K. Ito, Phys. Rev. A **84**, 062717 (2011).
[38] M. S. Dababneh, W. E. Kauppila, J. P. Downing, F. Laperriere, V. Pol, J. H. Smart, and T. S. Stein, Phys. Rev. A **22**, 1872 (1980).
[39] M. S. Dababneh, Y. F. Hsieh, W. E. Kauppila, V. Pol, and T. S. Stein, Phys. Rev. A **26**, 1252 (1982).
[40] J. Mitroy and M. W. J. Bromley, Phys. Rev. A **67**, 034502 (2003).
[41] C. Starrett, M. T. McAlinden, and H. R. J. Walters, Phys. Rev. A **77**, 042505 (2008).
[42] A. Basu, P. K. Sinha, and A. S. Ghosh, Phys. Rev. A **63**, 052503 (2001).
[43] J. E. Blackwood, M. T. McAlinden, and H. R. J. Walters, Phys. Rev. A **65**, 032517 (2002).
[44] H. R. J. Walters, A. C. H. Yu, S. Sahoo, and S. Gilmore, Nucl. Instrum. Methods Phys. Res., Sect. B **221**, 149 (2004).
[45] L. Sarkadi, Phys. Rev. A **68**, 032706 (2003).
[46] C. Starrett, M. T. McAlinden, and H. R. J. Walters, Phys. Rev. A **72**, 012508 (2005).
[47] G. Peach, in *Proceedings of the NATO Advanced Workshop on Positron Scattering in Gases, Egham, Surrey, England, 1983*, edited by J. W. Humberston and M. R. C. McDowell (Plenum, New York, 1984).
[48] C. P. Campbell, M. T. McAlinden, F. G. R. S. MacDonald, and H. R. J. Walters, Phys. Rev. Lett. **80**, 5097 (1998).
[49] J. E. Blackwood, C. P. Campbell, M. T. McAlinden, and H. R. J. Walters, Phys. Rev. A **60**, 4454 (1999).
[50] D. Woods, S. J. Ward, and P. Van Reeth, Phys. Rev. A **92**, 022713 (2015).
[51] UCL Discovery, http://discovery.ucl.ac.uk/id/eprint/1472510.