Strong Suppression of the Positronium Channel in Double Ionization of Noble Gases by Positron Impact

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(Received 19 February 1998)

Positron-induced double ionization of helium and neon has been studied at energies from threshold to 900 eV. A remarkable difference between the near-threshold behavior of the single and double ionization cross sections is found: Single ionization is dominated by positronium (Ps) formation, while for double ionization the Ps channel is absent or strongly suppressed. Absolute cross sections for the two targets have been derived and are compared to a modified Rost-Pattard parametrization. Good agreement is found, showing that this type of model can be extended from single to double ionization. [S0031-9007(98)06524-7]

PACS numbers: 34.50.Fa, 34.70.+e, 34.80.Dp, 36.10.Dr

Even though atomic collisions have been studied for almost a century, new and fundamental insight is still being obtained in this very active field of research. Especially, it has recently been realized that investigations of particle/antiparticle impact phenomena are fruitful for studies of many-body dynamics [1]. Here we present an experimental investigation of ionization of noble gas atoms caused by positron impact.

Double ionization of an atomic gas by positron impact has contributions from both direct ionization (1) and ionization with positronium formation (2), i.e.,

$$e^+ + A \rightarrow A^{2+} + e^+ + 2e^-, \qquad (1)$$

$$e^+ + A \rightarrow A^{2+} + \mathrm{Ps} + e^-, \qquad (2)$$

having threshold energies at E_I^{2+} and E_{Ps}^{2+}, respectively. E_{Ps}^{2+} is 6.8 eV lower than E_I^{2+} due to the binding energy of positronium (Ps). The positronium formation channel is also referred to as transfer ionization. A third possible process [which is indistinguishable from (2) in our experiment] involves the formation of the positronium negative ion Ps^-. Comparing to equivelocity proton data [2–4], the cross section for this double electron capture is expected to be very small, and it will not be considered further here.

The total double ionization cross section $\sigma_{\mathrm{tot}}^{2+}$ including both channels (1) and (2) has been measured with emphasis on the threshold behavior. In particular, by measuring $\sigma_{\mathrm{tot}}^{2+}$ in the energy range between E_{Ps}^{2+} and E_I^{2+}, where (2) is the only open channel, the importance of the positronium channel has been investigated.

In single ionization a similar situation exists, with the processes corresponding to (1) and (2) being

$$e^+ + A \rightarrow A^+ + e^+ + e^-, \qquad (3)$$

$$e^+ + A \rightarrow A^+ + \mathrm{Ps}, \qquad (4)$$

with thresholds referred to as E_I^+ and E_{Ps}^+, respectively. The single ionization cross section, both including the positronium channel (σ_{tot}^+) and excluding it (σ_I^+), has previously been measured for helium and neon [5–9]. The results are shown in Figs. 1(a) and 1(b). Notable is the rapid rise in σ_{tot}^+ with increasing energy above E_{Ps}^+ in comparison with the rather slow increase of σ_I^+ above E_I^+. Clearly positronium formation dominates single ionization over several tens of eV above threshold. A similar behavior was expected for double ionization. One argument for this expectation is that double ionization near threshold results in a slow positron and electron leaving the target. Here one would expect efficient capture as in single ionization. Another argument is that previous positron measurements on heavy noble gases (Ar, Kr, and Xe) have claimed to show that positronium formation accompanied by ionization of an additional electron may contribute significantly to the total double ionization at low incident energies [10]. [In that study, however, emphasis was not placed on the threshold behavior where only a few data points were taken with a poor positron energy resolution (around 5 eV FWHM) [11]]. Furthermore, for proton impact on He at velocities corresponding to the near threshold region for positrons, the cross section for double ionization with capture is observed to be almost as large as the observed total ionization cross section at its maximum [12]. This body of information appears to present a consistent picture of transfer ionization being significant if not dominant at low impact velocity.

The quantity measured in this experiment was the ratio $R_{\mathrm{tot}}^{(2)}$ between the total double and single ionization cross sections, $R_{\mathrm{tot}}^{(2)} = \sigma_{\mathrm{tot}}^{2+}/\sigma_{\mathrm{tot}}^+$ which is independent of beam intensity, gas pressure, and the geometry of the interaction region. The experiment was performed using an electrostatic slow positron beam based on a 750 MBq ^{22}Na source. Around 30 000 positrons per sec were obtained using a moderator consisting of four annealed tungsten meshes. This intensity fell by a factor of 5 at the lowest energies used in this investigation. A retarding field analyzer was used to measure the positron impact energy and the energy spread, which was typically

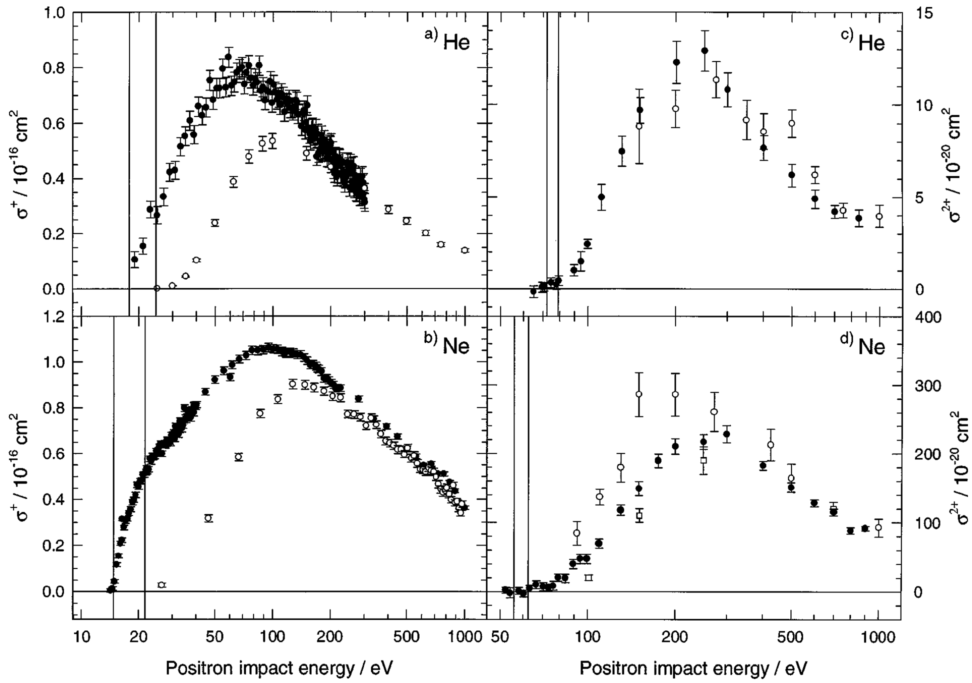

FIG. 1. (a) Single ionization of He by e^+ impact: (●) σ^+_{tot}, Moxom *et al.* [5]; (○) σ^+_I, Jacobsen *et al.* [6]. This cross section was also measured by Moxom *et al.* [7], but as their results agree with those of Jacobsen *et al.*, they are not shown in this figure. (b) Single ionization of Ne by e^+ impact: (●) σ^+_{tot}, Laricchia [8]; (○) σ^+_I, Kara *et al.* [9]. This cross section was also measured by Jacobsen *et al.* [6], but as their results agree with those of Kara *et al.*, they are not shown in this figure. (c) Double ionization of He by e^+ impact: (●) $\sigma^{2+}_{\mathrm{tot}}$, the present data; (○) σ^{2+}_I derived from data by Charlton *et al.* [15] and Jacobsen *et al.* [6]; (d) Double ionization of Ne by e^+ impact: (●) $\sigma^{2+}_{\mathrm{tot}}$, the present data; (○) σ^{2+}_I derived from data by Charlton *et al.* [16] and Jacobsen *et al.* [6]; (□) σ^{2+}_I, Kara *et al.* [9]. The two vertical lines indicate the relevant values of the threshold energies E_{Ps} and E_I.

~1.5 eV (FWHM). The dc positron beam was chopped by pulsing an in beam cylindrical mirror analyzer for around 1 μs at a rate of 100 kHz. The beam was then passed through a gas cell typically held at a pressure of 0.2 Pa. This assured single collision conditions. Shortly after each positron pulse an electric extraction field was applied across the cell and any ions created in the target gas were detected. A time-of-flight analysis was used to obtain the charge/mass of each ion. The ratio $R^{(2)}_{\mathrm{tot}}$ was found as the number of doubly to singly charged ions. Since the final state of the positron was not detected, ions produced by all processes (1)–(4) were included and $R^{(2)}_{\mathrm{tot}}$ is therefore the ratio between the total ionization cross sections. Further experimental details will be presented elsewhere [13].

Our results are presented in Figs. 1(c) and 1(d). The absolute cross sections have been obtained by multiplying the measured ratio $R^{(2)}_{\mathrm{tot}}$ with σ^+_{tot} from Figs. 1(a) and 1(b). The error bars represent the statistical uncertainty in our data only, and do not include the uncertainty in σ^+_{tot}.

A striking difference is observed in the near-threshold behavior of σ^+_{tot} and $\sigma^{2+}_{\mathrm{tot}}$. In contrast to σ^+_{tot}, no significant Ps formation is observed for $\sigma^{2+}_{\mathrm{tot}}$ in the region between E^{2+}_{Ps} and E^{2+}_I. We find $\sigma^{2+}_{\mathrm{tot}}$ to be $(2.4 \pm 2.3) \times 10^{-21}$ cm^2 and $(-1.8 \pm 5.1) \times 10^{-20}$ cm^2 for helium and neon, respectively, in this energy range. For helium, we find $\sigma^{2+}_{\mathrm{tot}}$ at E^{2+}_I to be around 4% of its maximum value, and for neon we find the corresponding number to be less than 2%. These values should be compared with the corresponding values for single ionization of ~30% and ~45%, respectively. Furthermore, the near-threshold energy dependence of $\sigma^{2+}_{\mathrm{tot}}$ is quite different from that of σ^+_{tot}, rising far more slowly with increasing energy. As will be discussed later, this energy dependence is in agreement with that expected from the Wannier theory for σ^{2+}_I. It is also much like that observed for electron impact [14], where the only available process is direct ionization.

In Figs. 1(c) and 1(d) we also show values for σ^{2+}_I as derived from measurements of σ^{2+}_I/σ^+_I by Charlton *et al.* [15,16] and σ^+_I by Jacobsen *et al.* [6]. Figure 1(d) also includes values of σ^{2+}_I obtained by Kara *et al.* [9]. At the highest energies our data agree with the direct ionization data, which is expected, since the contribution from the positronium formation channel should vanish at these energies, and, therefore, $\sigma^{2+}_{\mathrm{tot}}$ should equal σ^{2+}_I. For helium the two data sets also agree within the combined errors at lower energies, indicating a suppression of the Ps formation channel (2). It should, however, be noticed that the σ^{2+}_I data do not extend to the near-threshold region, where (2) is expected to make its most significant contribution. For neon a large discrepancy between the two sets of direct double ionization data is observed. This was attributed by Kara *et al.* [9] to an inadequate discrimination by Charlton *et al.* [16] against the Ps formation channel. Kara *et al.* therefore concluded that Ps formation made a significant contribution to double ionization. As can be seen from Fig. 1(c) our measured values for $\sigma_{\mathrm{tot}}^{2+}$ lie between the two determinations of σ_I^{2+}. This is in contradiction to the arguments of Kara *et al.* The discrepancy between the two determinations of σ_I^{2+} remains unexplained.

It seems clear that the Ps formation channel in double ionization by positron impact on helium and neon is strongly suppressed. The main contribution to our measured cross sections is therefore the direct ionization channel (1).

The basis of threshold theories for double ionization like the extended Wannier theory [17] is the four particle breakup in the direct ionization channel (1). The theory predicts that the cross section behaves as

$$\sigma(E) \propto E^{\alpha}, \tag{5}$$

where E is the positron excess energy above the relevant threshold energy E_I, and α is the so-called Wannier exponent. Calculations of α have been published for the $e^+ + \mathrm{H}^-$ system by Poelstra *et al.* [18], and recently Mendez and Feagin have extended the calculations to a neutral target. Assuming an infinite atomic mass, they found a value of $\alpha = 3.613$ [19]. This should be valid for both helium and neon. The value has recently been supported by a calculation by Kuchiev and Ostrovsky, which uses a different approach to the problem. This theory also predicts a power law dependence as in (5), and they find a value $\alpha = 3.838$ [20] in good agreement with the result of Mendez and Feagin.

Rost and Pattard [21] have shown that for single ionization it is possible to incorporate the threshold behavior of the Wannier theory with the high energy behavior of the first Born approximation to form a parametrization depending only on the Wannier exponent. This describes the cross section of all targets for a given projectile over a large range of energies. The cross sections fall on a common curve if plotted in the dimensionless variables E/E_M and σ/σ_M. σ_M is the cross section maximum which is found at the energy E_M. Energies E and E_M are excess energies above E_I. Values of E_M and σ_M can be found by a fit to the measured cross section. This scaling is one of the important aspects of the Rost-Pattard model, showing that energy should be scaled in terms of E_M rather than of E_I.

In Fig. 2 we have transformed our data to the above mentioned dimensionless variables. One observes that this scaling causes our data for helium and neon to agree extremely well. This shows that Rost and Pattard's observation of the importance of E_M as a scaling parameter of the energy is also valid in this case of double ionization. Since our data range from threshold to high energies, a modified

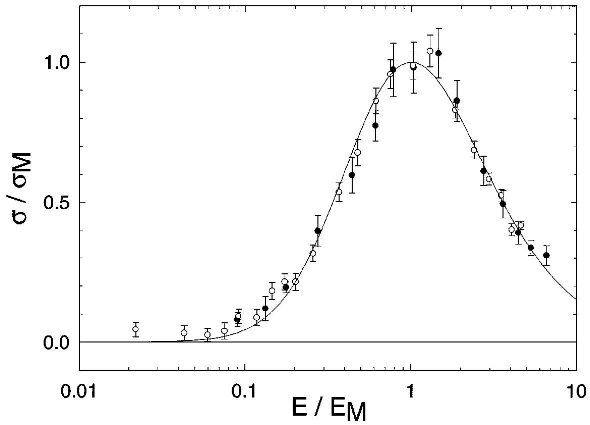

FIG. 2. The present results scaled relative to E_M and σ_M: (●) helium; (○) neon; (—) modified Rost-Pattard model with $\alpha = 3.613$ and $\beta = 1.5$.

Rost-Pattard parametrization has been developed, which can be applied in this case. It is based on the function

$$f(E) = \frac{1}{(E + E_0)^{\beta}} \left(\frac{E}{E + E_0}\right)^{\alpha}, \tag{6}$$

where $E_0 = E_M \beta/\alpha$. The additional parameter β is given by the high-energy dependence $E^{-\beta}$ of the cross section. The cross section is given by

$$\sigma(E) = \sigma_M \frac{f(E)}{f(E_M)}. \tag{7}$$

Double ionization at high velocity impact can take place following a single interaction between the projectile and a target electron, accompanied by subsequent release of the other electron. This mechanism has an energy dependence corresponding approximately to $\beta = 1$. At somewhat lower velocities double ionization can also be caused by the interaction between the projectile and each of the two active target electrons. This mechanism has an energy dependence corresponding to $\beta = 2$. Here, we have chosen an intermediate value of $\beta = 1.5$. For a further discussion of double ionization mechanisms, see Knudsen and Reading [1]. The Rost-Pattard model for single ionization has $\beta = 1$. In Fig. 2 we have plotted the universal curve obtained from (6) and (7). It is based on the Wannier exponent ($\alpha = 3.613$) of Mendez and Feagin. One observes a good agreement between our data and the curve. We could also have obtained α and β through a fit to the data. This yields $\alpha = 2.43$ and $\beta = 1.70$, but the agreement with the data is not significantly improved. The fact that our data conform so well to the Rost-Pattard model, which is valid only for direct ionization, shows again that Ps formation is suppressed in double ionization.

Measurements have been presented for the total double ionization cross sections for helium and neon by positron impact with emphasis on the threshold behavior. Surprisingly, double ionization with positronium formation is strongly suppressed. Comparison to a Rost-Pattard-type model for direct ionization, incorporating Wannier threshold theory, has given extremely good agreement with the data. This shows that this type of treatment may be valid not only for single ionization but also for double ionization.

The authors thank J. M. Feagin for discussions on Wannier theory and for drawing our attention to the Rost-Pattard model, G. Laricchia for providing unpublished data and valuable discussions, M. Charlton and V. N. Ostrovsky for useful discussions, P. Aggerholm for technical assistance, and the Carlsberg Foundation and the Danish Natural Science Research Council for funding.

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[1] H. Knudsen and J. F. Reading, Phys. Rep. **212**, 107 (1992).
[2] M. B. Shah and H. B. Gilbody, J. Phys. B **18**, 899 (1985).
[3] M. B. Shah, P. McCallion, and H. B. Gilbody, J. Phys. B **22**, 3037 (1989).
[4] C. F. Barnett *et al.*, *Atomic Data for Controlled Fusion Research* (Oak Ridge National Laboratory, Oak Ridge, TN, 1977), Vol. 1.
[5] J. Moxom, G. Laricchia, and M. Charlton, J. Phys. B **28**, 1331 (1995).
[6] F. M. Jacobsen, N. P. Frandsen, H. Knudsen, U. Mikkelsen, and D. M. Schrader, J. Phys. B **28**, 4691 (1995).
[7] J. Moxom, P. Ashley, and G. Laricchia, Can. J. Phys. **74**, 367 (1996).
[8] G. Laricchia (unpublished).
[9] V. Kara, K. Paludan, J. Moxom, P. Ashley, and G. Laricchia, J. Phys. B **30**, 3933 (1997).
[10] S. Helms, U. Brinkmann, J. Deiwiks, R. Hippler, H. Schneider, D. Segers, and J. Paridaens, J. Phys. B **28**, 1095 (1995).
[11] J. Paridaens, D. Segers, M. Dorikens, and L. Dorikens-Vanpraet, Nucl. Instrum. Methods Phys. Res., Sect. A **287**, 359 (1990).
[12] P. Hvelplund, H. Knudsen, U. Mikkelsen, E. Morenzoni, S. P. Møller, E. Uggerhøj, and T. Worm, J. Phys. B **27**, 925 (1994).
[13] H. Bluhme *et al.* (to be published).
[14] See, e.g., E. Krishnakumar and S. K. Srivastava, J. Phys. B **21**, 1055 (1988); M. B. Shah, D. S. Elliott, P. McCallion, and H. B. Gilbody, J. Phys. B **21**, 2751 (1988).
[15] M. Charlton, L. H. Andersen, L. Brun-Nielsen, B. I. Deutch, P. Hvelplund, F. M. Jacobsen, K. Knudsen, G. Laricchia, M. R, Poulsen, and J. O. Pedersen, J. Phys. B **21**, L545 (1988).
[16] M. Charlton, L. Brun-Nielsen, B. I. Deutch, P. Hvelplund, F. M. Jacobsen, H. Knudsen, G. Laricchia, and M. R. Poulsen, J. Phys. B **22**, 2779 (1989).
[17] See, e.g., J. M. Feagin and R. D. Filipczyk, Phys. Rev. Lett. **64**, 384 (1990); Ref. [15].
[18] K. A. Poelstra, J. M. Feagin, and H. Klar, J. Phys. B **27**, 781 (1984).
[19] J. C. Mendez and J. M. Feagin (private communication).
[20] M. Y. Kuchiev and V. N. Ostrovsky, Phys. Rev. A (to be published).
[21] J. M. Rost and T. Pattard, Phys. Rev. A **55**, R5 (1997).