Near-Threshold Ionization of He and H_2 by Positron Impact

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The single ionization cross sections for He and H_2 by positron impact have been measured in the first few eV above threshold and found to exhibit a different energy dependence from the corresponding electron results. If the data, between 1 and 3 eV above threshold, are fitted by a power law, exponents of 1.99 ± 0.19 and 1.70 ± 0.11 are obtained for He and H_2, respectively. This agrees qualitatively with extensions of the Wannier theory in that the exponent is larger than for electron impact. The quantitative disagreement with the predicted value of 2.65 might indicate that the range of validity of this theory is smaller than expected. [S0031-9007(96)00865-4]

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The study of the near-threshold behavior of two-electron escape from a positive ion continues to attract experimental and theoretical interest [1]. Some recent results [2,3] have cast doubts on the validity of the "ridge state" characterization of the correlated e^- pair. In this model the e^- are approximately equidistant from the ion and escape from it almost collinearly and with a uniform energy distribution, as described by Wannier [4]. Theoretically, the problem has also been considered in the case of positron impact ionization [5–12]. In this case, the two outgoing particles are likely to be closer together than for e^- impact ionization, and the theoretical description of the process is expected to be very sensitive to the details of the approximation employed. This process is also interesting because of the absence of the exchange interaction and the possibility of the formation of the electron-positron bound-state, positronium (Ps), with a threshold energy 6.8 eV below the threshold for direct ionization (E_i). Experimental data had suggested that positron and electron impact might result in the same near-threshold energy dependence of the single ionization cross sections [13,14]. However, the accuracy of these data was rather poor. Experimental investigations of near-threshold direct ionization by positron impact are hindered by the comparatively low beam intensities and poor energy resolutions. Ps formation, which dominates ion production near E_i, may introduce an additional complication. In the present work, the cross sections for single direct ionization by positron impact have been investigated in detail within the first few eV above threshold for the first time and, in contrast to previous surmises, significant differences are observed from the electron impact case. The measurements have been made with an energy resolution of around 0.5 eV and the mean beam energy has been calibrated by determining the thresholds for Ps formation in different gases. The background contributions to the ion signal, arising, for example, from Ps formation, have been measured directly and subtracted from the data.

By considering collision processes which result in two particles in the final state, Wigner [15] showed that the near-threshold energy dependence of the associated cross section is dominated by the long range interaction of the product particles. Wannier [4] extended these ideas to the case of three quasistationary charged particles, as might arise near the threshold for electron impact ionization or double photodetachment. He argued that for impact energies (E) just above E_i, the energy dependence of the cross section for double e^- escape from a singly charged positive ion is purely dependent on the asymptotic configuration of the final state and, using classical arguments, derived the following expression for the cross section (Q_i^-) for single ionization by e^- impact of a neutral atom:

$$Q_i^- \propto (E')^n, \tag{1}$$

where $E' = E - E_i$ and $n = 1.127$.

Considerable experimental and theoretical effort in the study of this phenomenon has ensued [16]. Much experimental support, e.g. [17,18], has been found for the power law expressed by Eq. (1) which has also been rederived semiclassically and quantum mechanically [19–21]. However, recent experiments with spin-tagged electrons incident on atomic hydrogen [22] and a reexamination of photodetachment cross sections [23] have produced evidence of structure in Q_i^- which is inconsistent with the Wannier theory. An alternative model has been proposed by Temkin [9–11]. Unlike in the Wannier description, here the electrons are not equidistant from the ion and the escape is determined, at threshold, by events in which the inner electron sees the charge of the ion directly, while the other sees the Coulomb dipole (CD) potential produced by the ion and the inner electron. Both the Wannier-type and CD descriptions have been applied in the case of positron and electron projectiles and these and other theoretical results are given in Table I.

In the present work, a 100 mCi ^{58}Co β^+ emitter was used in conjunction with a W-mesh moderator and a retarding field anlayzer to produce a beam of around 5×10^3 e^+ s^{-1} with a measured longitudinal energy spread, in the magnetic field used to confine the beam, of 0.5 eV FWHM. This energy spread is an upper limit on the true energy spread due to the angular divergence of the

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TABLE I. Some of the available theoretical results for the near-threshold energy dependence of the $e^{\pm}$ impact ionization cross sections. C and α are quantities related to the dipole moment created by the ion and the ejected electron; μ is a constant of integration. These quantities are discussed in detail in [10].

Theory	Prediction
Wannier [4]	$Q_i^-(E') \propto (E')^{1.127}$
Peterkop [19,20]	
Rau [21]	
Klar [5,6]	$Q_i^+(E') \propto (E')^{2.651}$
Temkin [9–11]	$Q_i^{\pm}(E') \propto E'(\ln E')^{-2} \times [1 + C\sin(\alpha \ln E' + \mu)]$
Geltman [12]	$Q_i^-(E') \propto E'$ $Q_i^+(E') \propto \int_0^{E'} \exp[-\pi(2/x)^{1/2}]\,dx$

beam and instrumental resolution. The apparatus in and around the interaction region is presented schematically in Fig. 1. The e^+ beam was crossed with a gas jet and a pulsed electric field was used to extract the ions from the interaction region. The ion-extraction field was triggered by the detection of e^+ at the end of the flight path and was pulsed on, therefore, after the associated collisions. In this way, perturbations during a collision were minimized. Ions of the desired charge-to-mass ratio were selected by measuring their flight times. The mean beam energy (E) was augmented in 0.5 eV steps by means of a ramp generator which supplied, in synchronism, the advance pulse to a multichannel scaler (MCS) storing the number of positron-ion coincidences. If this number is divided, after background subtraction, by the incident beam intensity (also measured versus E), an ion yield is obtained as a function of the incident energy. This yield is directly proportional to the single ionization cross section by e^+ impact (Q_i^+).

An investigation of the near-threshold behavior of Q_i^+ in this manner requires (i) the accurate determination of the background on the ion coincidence signal, (ii) the efficiencies for ion detection and scattered e^+ transport to be energy independent, and (iii) a careful calibration of the projectile incident energy. By measuring ion-e^+ coincidences, ions resulting from Ps formation (the dominant ionization process near E_i) are largely undetected. However, random coincidences between ions and uncorrelated e^+ result in a background which can be measured by preventing the e^+ which have produced an ion (and have hence lost E_i which is 24.58 and 15.45 eV for He and H_2, respectively) from reaching the detector. This was done by applying a retarding potential $(V_{\rm ret})$ to the grids $g1$ and $g2$, just sufficient to prevent all e^+ that have created an ion from reaching the MCP. These grids were grounded for measurements of the gross signal. A slight disparity between e^+ count rates for each retarder state arose from the failure to detect those e^+ which are scattered (either elastically or after target excitation) at angles such that their longitudinal velocity is insufficient to overcome the potential barrier set by $V_{\rm ret}$. Since the background was proportional to the ion extractor pulse rate, this disparity led to a slight underestimate of the true background and was corrected by normalizing the background to the ratio between the pulse rates for each retarder state. Elastically scattered e^+ repelled by $V_{\rm ret}$ could conceivably traverse the interaction region a second time and create an ion, leading to an overestimate of the background. However, even assuming isotropic elastic scattering, the probability of such an event is estimated to be $<0.1\%$. Grids $g1/g2$ were switched between 0 V and $V_{\rm ret}$ states at the end of each pass of the MCS. Thus signal and background were measured alternately, reducing the effects of instrumental drift and source decay, hence allowing long data acquisition times.

The 26 mm diameter MCP was large enough to ensure that, for the impact energies studied here, all scattered e^+ could impinge on its active area so that the scattered e^+ detection efficiency was not dependent on energy in the range of interest here. An energy independent ion detection efficiency relies on detecting all e^+ before an ion can drift out of the volume from which it can be extracted and detected. By definition, in near-threshold ionization, the e^+ of interest survive with little kinetic energy and may also be backscattered. With the aid of computer simulations of the e^+ trajectories in the system, a weak electrostatic field penetrating the interaction region was devised to accelerate the quasistationary e^+ while introducing a negligible perturbation to the incident beam energy [24]. This field was generated by the retarding field analyzer and the e^+ accelerator tube R2, shown in Fig. 1.

Considerable effort has been expended in trying to verify the effect of such a penetration field experimentally. The ion yield was measured as a function of voltage on R2 and it was found that, at an incident energy 3 eV above E_i, applying -200 and -300 V to R2 resulted in a 2.0 ± 1.0 factor increase in the yield over the field-free case, while the single ion rates remained independent of this voltage. With higher potentials applied to R2, beam focusing effects were observed and so measurements were performed with R2 at -300 V.

The incident e^+ energy was determined by measuring the onset of the positronium formation cross section $(Q_{\rm Ps})$ for a selection of gases by randomly triggering the ion extractor with a pulse generator. Below E_i, all ionization is the result of Ps formation and so, in this case, the ion yield is proportional to $Q_{\rm Ps}$. It has been shown [25]

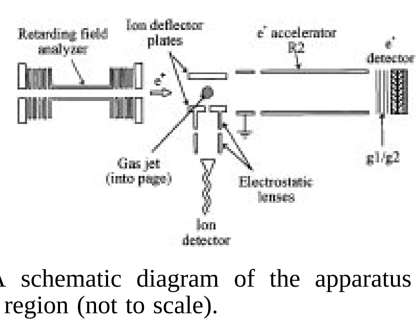

FIG. 1. A schematic diagram of the apparatus around the interaction region (not to scale).

that for Ne, Ar, Kr, and Xe, Q_{Ps} has a predominantly s-wave energy dependence for a few eV above threshold. Therefore the Ps yields for Ar, Kr, and Xe determined with the present system have been fitted by this form, using a shift on the apparent incident energy, arising from the e^+ work function of the moderator and contact potential effects, as one of the fitting parameters. This allowed the determination of E to within 0.1 eV.

The present values of Q_i^+ for He and H_2 are shown in Figs. 2(a) and 2(b), respectively, along with those obtained by other workers [13,14,26,27]. Also shown are the values of Q_i^- for theses gases [28,29]. The ion yields were converted into absolute cross sections using a target dependent normalization constant, obtained by fitting ion yields to Q_i^- [30] over the range of energies from 600 to 1000 eV. At these energies the ion yields were found to have almost the same energy dependencies as Q_i^-, and it was assumed that the cross sections had merged.

For He the present values of Q_i^+ are, at all energies presented here, smaller than those obtained by Knudsen *et al.* [13] (e.g., by 25% at 32 eV), Fromme *et al.* [26] (by 50% at 31 eV), and Sueoka *et al.* [14] (by 70% at 30.6 eV), but are larger than those obtained by Jacobsen *et al.* [30] (by around 27% at 30 eV). For H_2, the present data are in fair accord with those of Refs. [13,14] above 20 eV but, as in the case of He, approach zero faster with decreasing impact energy. The present results for H_2 are, however, around 50% greater than those obtained by Jacobsen *et al.* [31] at 28.2 eV. In both gases the present values of Q_i^+ are significantly smaller than Q_i^- at low energies where Q_i^+ and Q_i^- have significantly different energy dependencies. This may be due to the importance of Ps formation in this energy range. In the case of inner shell ionization [32], differences observed in the magnitude of near-threshold cross sections for e^- and e^+ impact have been attributed primarily to the acceleration or deceleration effects on each projectile in the Coulomb field of the nucleus.

In Figs. 3(a) and 3(b) the cross sections are plotted against E' on logarithmic axes. The data have been

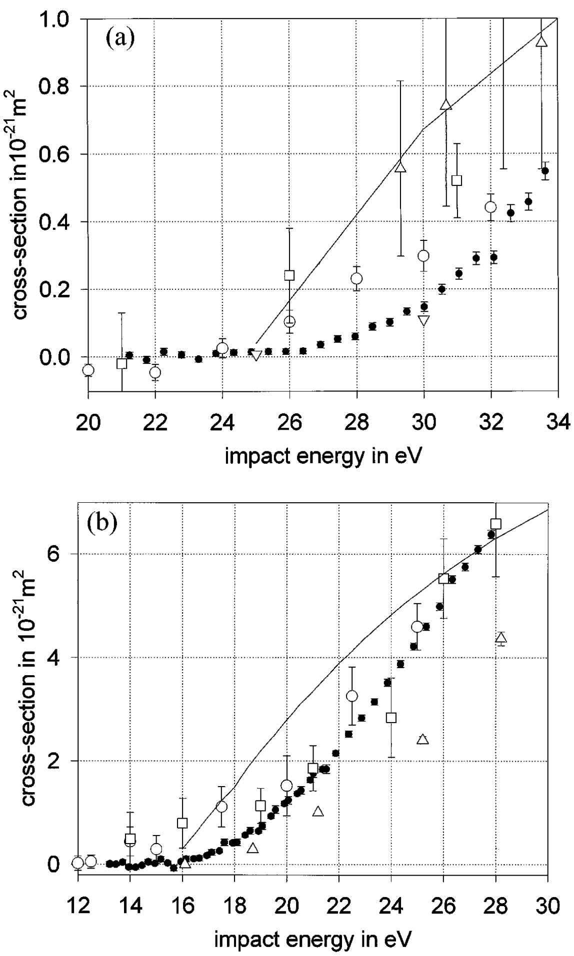

FIG. 2. (a) Q_i^+ for He: filled circles, the present data; open circles [13]; open squares [26], open upward pointing triangles [14]; open downward pointing triangles [30]. Q_i^- for He [28], solid line. (b) Q_i^+ for H_2: filled circles, the present data; open circles [13]; open squares [26], open triangles [31]. Q_i^- for H_2 [27], solid line.

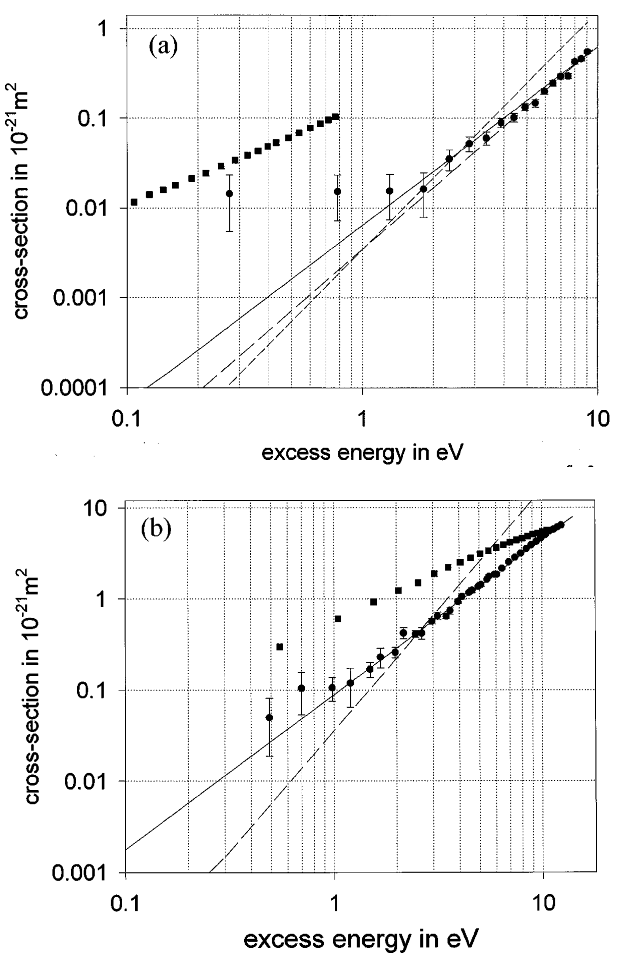

FIG. 3 (a) The present data for He, filled circles. Least squares fits to the data (see text) with $n = 1.99$, solid line; $n = 2.27$, long dashed line; and $n = 2.65$, short dashed line. Q_i^- [17], solid squares. (b) The present data for H_2, filled circles. Least squares fits to the data (see text) with $n = 1.70$, solid line; $n = 2.65$, dashed line. Q_i^- [27], solid squares.

least squares fitted by Eq. (1) over two energy ranges: (i) from $1 < E' < 3$ eV, the near threshold region, where the Wannier theory is expected to be valid [5]; and (ii) for $E' > 3$ eV, where the data may be qualitatively compared with the predictions of a CTMC calculation [33] for H. The points below 1 eV were not used in the near threshold fit because of the effects of the finite beam energy spread on the measured energy dependence of Q_i^+. To investigate the possibility of a residual background on the data, the mean value of the data below threshold was calculated and found to be zero within statistical uncertainties. By performing a least squares fit to the near threshold data, the values obtained for n in Eq. (1) are 1.99 ± 0.19 and 1.70 ± 0.11 for He and H_2, respectively. The uncertainties are those arising from the fitting procedure and the error in the beam energy calibration. Within the errors these values are the same, and qualitatively agree with the extension of the Wannier theory to e^+ impact [5–8] in that n is larger than for e^-, but quantitatively disagree with the expected value of 2.65. The discrepancy may indicate that the range of validity of Eq. (1) is smaller than expected.

Marchand *et al.* [17] found that for single ionization by e^- impact the exponent in Eq. (1) decreased from 1.16 ± 0.03 for $0.2 < E' < 0.8$ eV to 1.02 if the fit was extended up to $E' = 12$ eV. Physically, this is believed to arise from a weakening of the e^--e^- correlation in the final state. When the fit to the present data is performed for higher energies, the exponent values obtained are 2.27 ± 0.08 and 1.71 ± 0.03 for He and H_2, respectively. The value obtained for H_2 is the same as for the near threshold fit, however, for He the value is slightly higher. A CTMC calculation [33] predicts that Q_i^+ follows a power law energy dependence up to 9 eV above threshold and the fact that the data can be fitted by a power law reasonably well in a similar energy range is in qualitative agreement with this calculation, although the value of n was expected to be 3–4, for single ionization of H^0. No comparison is made here with the Coulomb-dipole theory [9–11] since its range of validity is expected to be confined to a much smaller range of energies ($E' <$ 0.1 eV) [11] than investigated in the present work.

In conclusion, the cross sections for direct ionization of He and H_2 by e^+ impact have been measured in the first few eV above threshold for the first time. The results show that Q_i^+ increases from threshold less rapidly than Q_i^- and reveal a difference in the energy dependencies of Q_i^- and Q_i^+. The results contradict previous tentative experimental conclusions [13,14] that the two cross sections may exhibit a similar energy dependence close to threshold and qualitatively agree with Wannier-type theories which predict a larger exponent in the case of e^+. Work is continuing to probe in greater detail the first few eV above threshold.

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