Electron loss and transfer for 20–110-keV iodine–rare-gas collisions

B. Hird, M. W. Orakzai, and F. Rahman*
Ottawa-Carleton Institute for Physics, Ottawa University Campus, Ottawa, Ontario, Canada K1N 6N5
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Atomic cross sections have been measured for the loss and transfer of an electron during a collision between a neutral iodine atom and a rare-gas atom. The neutral iodine beam, with energy between 20 to 110 keV, was unlikely to contain a significant mixture of metastable-state atoms because it was produced by neutralizing a negative-iodine-ion beam. The σ_{0+} cross section is largest for the argon and krypton targets, not for xenon, as might have been expected. The σ_{0-} cross section is very small for the light targets and only becomes appreciable for xenon at the highest energy used.

I. INTRODUCTION

Energetic collisions between atoms, in which an electron is lost or transferred, have not been extensively measured in the 100-keV energy range because of the difficulty of creating an atomic beam which is in a well-defined atomic state. The technique of producing the atomic beam by electron detachment from a negative-ion beam in a low-pressure gas has been shown to populate mainly the ground-state doublet states in atomic beams of chlorine[1] and fluorine.[2] We report measurements using the same technique to produce a fast neutral iodine beam.

Among the low-lying excited states of an iodine atom, the ^4P and the $^4P^o$ states have sufficiently different structures from the $^2P^o$ ground-state doublet that they are likely to have lifetimes long enough to survive the 1-μs flight time between the neutralizing and the ionizing regions of the apparatus. Since the results of a cross-section measurement are a weighted average of the values for each atomic state of the beam, it is important to avoid producing an unknown fraction of the atoms in these metastable quartet states. In contrast, the cross sections for the ground-states doublet states are likely to be very similar because of their similar atomic structure, and energy, so that the relative mixture of these doublet states in the neutral beam is unimportant.

The justification for neglecting the quartet states is as follows. Simple direct detachment, in which the valence electron is removed, leaving the neutral core, produces only the ground-state doublet, since these states are the parents of the stable I^- negative ion. However, it has been established that excitation of I^- also occurs in I^-–rare-gas collisions at a few keV collision energy.[3] These excited negative-ion states are identified by discrete resonances in the emitted electron spectrum. The strongest resonance, at an excitation of 6.41 eV, has been assigned a structure $5s^25p^4(^3P)6s^2$, and has as its parent the ^4P metastable state. However, this parent is at a higher energy so that autodetachment is only possible to the ground-state doublet. In a similar way the $5s^25p^4(^3P)6s6p$ negative-ion resonance is at a lower energy than its parent, which is the metastable $^4P^0$ state, so that the excited negative ion, which may be created by a gas collision, again does not decay to a metastable atomic state. Thus little metastable atom production is expected from negative ion–rare-gas atomic collisions.

The only previously reported electron loss and transfer cross sections for iodine–rare-gas collisions are the data of Layton and Fite[4] for argon between 45 and 75 keV.

II. METHOD

The experiment method has been described previously.[1] A conventional rf ion source, to which a side tube containing a small crystal of iodine had been connected, produced negative-iodine-ions by electron capture collisions in the exit canal. The rf discharge was run on argon gas, but this element has no stable negative ions, so it does not contribute to the beam.

The negative ions were accelerated, magnetically analyzed, and focused so as to pass through two consecutive differentially pumped gas cells. These cells were mechanically constructed so that the four apertures defining their vacuum-gas boundaries were accurately aligned with each other.

The first gas cell, which neutralized the negative-ion beam, had a length of 10 cm with a 0.8-mm entrance aperture, and a 0.6-mm exit aperture. The argon gas pressure inside was optimized so as to convert about 60% of the negative ions to neutral ions. A transverse-electric field, applied to the 15-cm-long vacuum region between the two gas cells, deflected all charged ions which emerged from the first cell away from the 0.4-mm entrance aperture of the second cell.

The 4.94-cm length of the second cell, in which the cross sections were measured, was chosen to maintain approximately single-collision conditions when using gas pressures in the range from the background pressure of 10^{-6} Torr up to 10^{-3} Torr. A 1.5-mm exit aperture was made large enough to allow ions which had been created by gas scattering to escape if they were within 2° of the neutral beam direction.

Beyond the second cell another transverse-electric field separated the charge states sufficiently that the negative-, neutral, and positive-charged iodine particles were each directed to the center of one of three side-by-side channel electron multipliers. Figure 1 shows the mechanical layout of the apparatus.

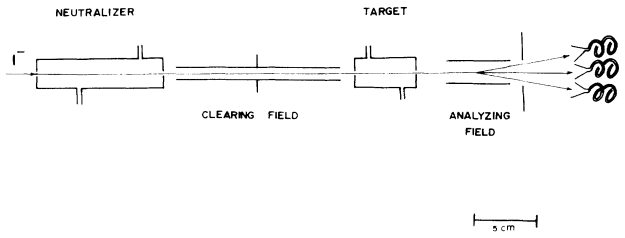

FIG. 1. The target geometry, showing the neutralizer gas cell, followed by a clearing field and the target gas cell. The positive, neutral, and negative iodine particles which emerge from the target are separated and counted individually.

The cross section σ_{0-} for fast negative-ion and the cross section σ_{0+} for fast positive-ion production was calculated from measurements of the relative numbers of counts in the three channel multipliers as a function of the gas pressure in the second cell. The channel multipliers were operated digitally, and with sufficient gain and at low enough counting rates ($<10^3$ Hz) to have effectively 100% detection efficiency.[5] Thus it could be assumed that the ratio of the numbers of counts was the ratio of the particles striking the respective channeltron cones. The gas in the two cells was supplied through thermal mechanical leaks, and measured through separate connections, by capacitance nanometers. The pressures in the two gas cells were found to be independent of each other, over the range used, thus establishing that there was negligible contamination of the second cell by gas from the first.

The value of the cross section was calculated using a power-series expansion of the charge-particle populations as a function of target pressure. To second order, equivalent to considering single and double collisions of the same particle in its traversal of the target gas, the cross section σ_{0+} for ionization of the iodine neutral atoms is given by

$$T\sigma_{0+}=\frac{N^+/N^0}{1+N^+/2N^0}\times\left[1+\frac{1}{2}\left[\sigma_{+0}+\sigma_{+-}+\sigma_{+2}-\sigma_{0-}-\sigma_{02}-\frac{\sigma_{0-}\sigma_{-+}+\sigma_{02}\sigma_{2+}}{\sigma_{0+}}\right]T\right],$$

where T, the target thickness, is the product of the target-gas atomic density and its effective length. The ratio of the positive ion to the neutral counts over the same time interval is given by N^+/N^0. The notation for the cross sections is that the first suffix is the initial fast particle charge, and the second suffix is its final charge. A similar formula, but with the + and − signs interchanged, was used to calculate the σ_{0-} cross section.

The method of analysis was to make a linear least-squares fit to a graph of the right-hand side of the equation, plotted as a function of target-gas pressure. The gradient of this fit then gave the cross-section value when multiplied by the appropriate factor to convert gas pressure to target thickness T.

The upper limit on the target gas pressure was set by the requirement that the correction term in the large parentheses should be limited to a few percent. Such a limit was necessary because only double collisions are included in the correction term, and because some of the cross sections in the correction term are incompletely known. The only values available are the cross sections σ_{-0} and σ_{-+}, measured by Hird and Rahman[6] for all the targets and by Lichtenberg *et al.*[7] for He and Ar. There are data for σ_{+2} and σ_{+0} in our energy range by Fedorenko,[8] but for the Ne and Ar targets only. The other cross sections were obtained by extrapolation. The Fedorenko data were scaled to the heavier targets in the inverse ratios of the target ionization potentials. The Ar and Ne σ_{+2} data, with a Xe^+ beam of Brackman and Fite,[9] were extrapolated in this way to an I^+ beam and to heavier targets except that a maximum of 6×10^{-16} cm^2 was assumed, since all known σ_{+2} cross section seem to peak at about this value. The cross sections σ_{+-} and σ_{02} were neglected, assuming that such double-transfer cross sections are relatively small. The σ_{0+} cross section, which is being calculated, itself appears in the correction

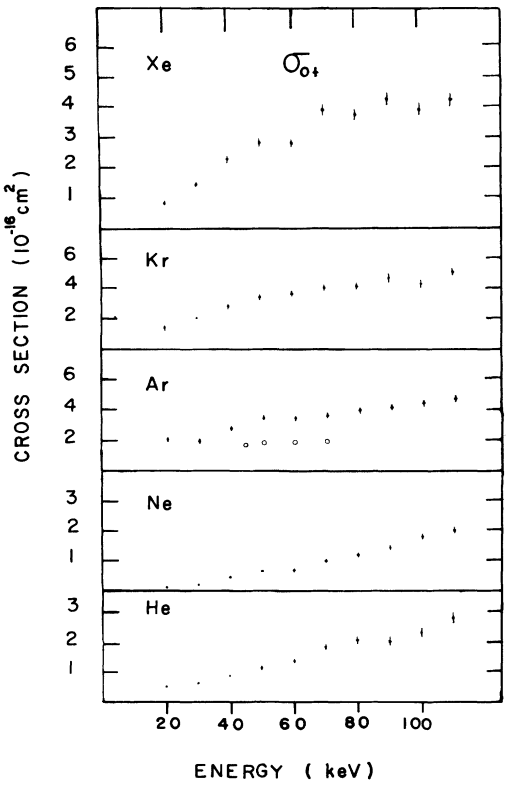

FIG. 2. The cross section σ_{0+} for the loss of an electron by an iodine atom in a single collision with a rare-gas atom. The present measurements are shown with error bars. The open circles are the data of Layton *et al.* (Ref. 4).

TABLE I. Cross sections for the electron loss of an iodine atom in a collision with a rare-gas atom σ_{0+}, and for the transfer of an electron from a rare-gas atom to an iodine atom σ_{0-}.

Energy (keV)	He	Ne	Ar	Kr	Xe
			$\sigma_{0+}(10^{-16}$ cm$^2)$		
20	0.55±0.03	0.12±0.02	2.10±0.11	1.38±0.10	0.85±0.05
30	0.66±0.04	0.21±0.03	1.99±0.11	2.04±0.11	1.47±0.09
40	0.90±0.05	0.46±0.04	2.84±0.15	2.82±0.15	2.29±0.12
50	1.17±0.06	0.65±0.04	3.52±0.18	3.46±0.18	2.84±0.15
60	1.41±0.08	0.69±0.04	3.50±0.18	3.67±0.19	2.83±0.15
70	1.87±0.10	0.98±0.06	3.69±0.19	4.03±0.21	3.92±0.21
80	2.10±0.11	1.19±0.07	4.02±0.21	4.16±0.21	3.74±0.22
90	2.04±0.11	1.43±0.09	4.25±0.22	4.63±0.24	4.26±0.23
100	2.34±0.12	1.77±0.10	4.47±0.23	4.28±0.23	3.91±0.22
110	2.77±0.14	1.99±0.11	4.79±0.25	5.08±0.26	4.22±0.24
			$\sigma_{0-}(10^{-16}$ cm$^2)$		
20					0.03±0.01
30					0.08±0.02
40					0.10±0.01
50					0.18±0.02
60			0.02±0.01	0.03±0.01	0.30±0.03
70			0.03±0.01	0.05±0.01	0.53±0.04
80			0.02±0.01	0.08±0.01	0.64±0.04
90			0.03±0.01	0.11±0.02	0.99±0.06
100		0.04±0.01	0.03±0.01	0.16±0.02	1.11±0.07
110	0.03±0.01	0.03±0.01	0.07±0.01	0.23±0.02	1.40±0.08

term. It was obtained using an itinerative procedure in which the correction term was first neglected.

To estimate of the importance of the correction term, the calculations were repeated without it. If the difference was more than about 7%, or 10^{-18} cm^2 for the small value cross sections, then the highest pressure data were omitted and the calculation repeated until the correction term was small enough.

The daily reproducibility of the data was found to be about 5%. This was the order of the sum of the errors from counting statistics, the pressure calibration, and the target length determination.

III. RESULTS AND DISCUSSION

A. Fast positive-ion creation

The positive-ion cross-section results are shown in Fig. 2 and in Table I.

The dependence on target mass in previous σ_{0+} measurements with chlorine[1] and fluorine[2] beams was explained in terms of the relative ionization potentials of the projectile and the target. The cross section for the fluorine beam was found to decrease as the target mass increased from He to Xe, whereas the chlorine cross section increased from He to Ar and then decreased for Kr and Xe. This was explained by the increase in the importance of target ionization in the heavier rare gases, with a smaller effect for chlorine because it has a lower ionization potential than fluorine. If this explanation is valid, then there should be even less target ionization with the iodine beam since it has a lower ionization potential than all the rare gases. It would thus be expected that the cross section would increase with target mass and be largest for Xe. However, the trend in the cross sections is very similar to that of chlorine, with the largest cross section for Ar and Kr, not Xe.

It is likely that the maximum in the σ_{0+} cross section

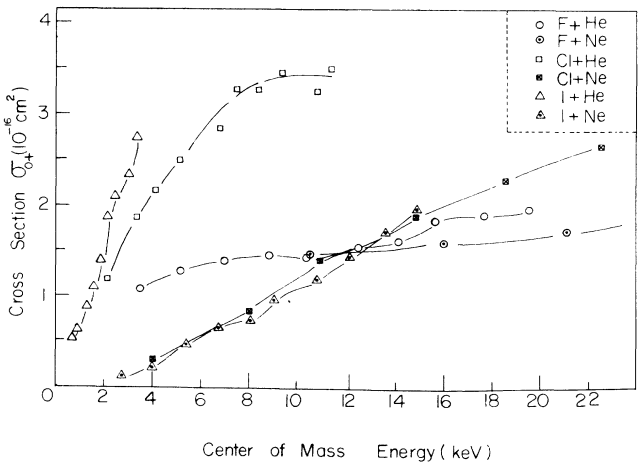

FIG. 3. A comparison of the σ_{0+} cross sections for chlorine (Ref. 1), fluorine (Ref. 2), and iodine in helium and neon targets, plotted in the center-of-mass system. The lines have no theoretical significance and are merely to guide the eye.

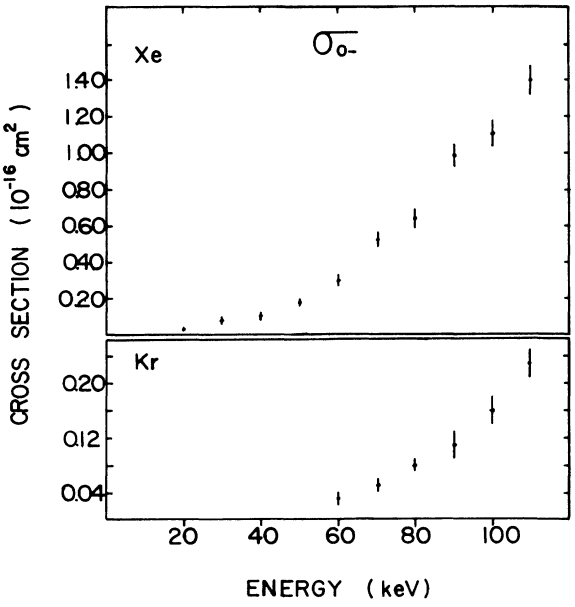

FIG. 4. The cross section σ_{0-} for transfer of an electron to an iodine atom in a single collision with a rare-gas atom.

occurs at higher energies than these measurements for all the target gases. Maxima were observed in the previous measurements with fluorine and chlorine beams, but the center-of-mass energies are lower for the iodine–rare-gas measurements. Figure 3 shows the present σ_{0+} data and the previous fluorine and chlorine data plotted in the center-of-mass system for the helium and neon targets, where target ionization can be neglected. Some striking similarities and differences appear. The iodine and chlorine data are very similar for the same target, but very different between He and Ne. On the other hand, the fluorine-He data are very similar to the fluorine-Ne data, but quite different from the chlorine and iodine data. This suggests fluorine is ionized by a different collision mechanism than chlorine or iodine. It would be interesting to determine the same cross sections with a bromine beam to find whether they follow the fluorine or the chlorine and iodine trends.

B. Fast negative-ion creation

The σ_{0-} cross sections are shown in Fig. 4, and in Table I. The cross section is too small to measure over most of our energy range for the helium and the neon targets. These cross sections have an upper limit 2×10^{-18} cm^2. However, it grows rapidly with energy for krypton and xenon. The states involved in the collision process are well defined, since the electron which is attached to the atom must come from the valence shell of the rare-gas atom. The energy defect for this collision process thus equals the difference of the electron affinity of iodine and the ionization potential of the rare-gas target. It may be possible to fit the cross section if the correlation diagrams for these states of the (I^o–rare gas) molecules were available.

*Permanent address: Physics Department, University of Peshawar, Peshawar, Pakistan.

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