Charge-changing cross sections for Pb and Xe ions at velocities up to 4×10^9 cm/sec

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We have made a comprehensive study of charge-changing cross sections in N_2 of Pb and Xe ions at velocities near 4×10^9 cm/sec. We determine the velocity, ionization state, and Z dependence of the capture and ionization cross sections and make an extensive comparison with theory.

Capture or loss of an electron by a fast very heavy complex ion colliding with an atom is one of the more refractory problems in atomic collisions.[1,2] For very heavy ions at velocities $\geqslant 10^9$ cm/sec only a small amount of experimental information is available.[3,4] Also, there is a general perception that theoretical models used for lighter and simpler ions may be inadequate.[2]

In this Communication we present the first comprehensive study of charge-changing collisions of very heavy ions at velocities above 10^9 cm/sec. From experimental measurements of Pb ($Z=82$) and Xe ($Z=54$) ions in N_2 at velocities (relative to the speed of light) of $\beta = v/c = 0.134$ and $\beta = 0.099$, and Xe at $\beta = 0.072$ we extract a total of 178 cross sections. We determine the velocity, ion charge, and nuclear charge dependence of these cross sections. In comparison with theory, we find several simple models which adequately describe our results.

The apparatus and experimental methods used are similar to those described in Refs. 2 and 5. In our experiment, the incident ionization states are obtained by magnetically separating a beam of ions accelerated at the Lawrence Berkeley Laboratory's Super-HILAC. These ions then pass through a differentially pumped 24-cm-long chamber containing nitrogen gas at a maximum pressure of 1.0 Torr. The final ionization states are analyzed in a second electromagnet and are detected by a position-sensitive gas-filled proportional counter. The raw data collected are the relative number of ions striking the detector at the locations corresponding to the different ionization states as a function of the pressure in the charge-exchange chamber.

Cross sections [Figs. 1(a) and 1(b)] were fitted to the data by the least-squares method using a computer code developed by Betz.[4,5] Satisfactory fits could be obtained only by including cross sections for the loss of two or more electrons. The sum of the multiple-loss cross sections here averages about 15% of the one-electron-loss cross section. For most ionization states, cross sections were found by fitting data from two or three different incident ionization states. The variation in a cross section when fitted to data from three different incident ionization states is the basis of our fitting error. We find a (one standard deviation) fitting error of 14% for the capture cross section and 26% for the loss cross section. These errors are shown as error bars in the lower left of Figs. 1(a) and 1(b). The larger error in the single-electron-loss cross section is consistent with the larger number of degrees of freedom available when fitting to multiple cross sections. We estimate the systematic error, principally an uncertainty in the thickness of the gas target, to be 20%.

The velocity dependence of the capture cross sections σ_c is extracted by fitting the cross sections in Fig. 1(a) to $\sigma_c = A\beta^n$ where A is a constant and $\beta = v/c$. Between $\beta = 0.099$ and 0.134 we find, for Pb averaged over ionization states 34+ to 44+, that $n = -5.83$ (0.12); and for Xe 28+ to 43+, that $n = -5.8$ (0.3). From the Xe 27+ cross section measured at $\beta = 0.072$ and 0.099 we find $n = -5.9$.

We obtain the ionization-state dependence of the capture cross section by fitting to $\sigma_c = Aq^n$ where q is the ionization state. At $\beta = 0.134$ we find for Pb, that $n = 2.9$ (0.4), and for Xe, $n = 3.1$ (0.9). At $\beta = 0.099$, we find for Pb, that $n = 3.0$ (0.3), and for Xe, $n = 3.1$ (0.7); and at $\beta = 0.072$, we find for Xe, $n = 3.3$ (0.3).

The capture cross sections in Fig. 1(a) exhibit at most a weak dependence on the nuclear charge Z. For $\sigma_c = AZ^n$ we find at $\beta = 0.134$, that $n = 0.2$ (0.1), and at $\beta = 0.099$, $n = -0.2$ (0.2).

Experimental cross sections, and the Oppenheimer-Brinkman-Kramer (OBK) model have been used by several authors[1,2] to predict the velocity, ionization state, and Z dependence of the capture cross sections for high ionization states of very fast, very heavy ions. Janev and Hvelplund[1] propose $\sigma_c = Aq^3$, where q is the ionization state and A a constant, while Betz[2] suggests $\sigma_c = AZ^0q^2$ for $q \geqslant 20$ and $\beta \geqslant 0.03$: Our experiment is consistent with Z^0 but strongly favors q^3 over q^2. On the basis of the OBK

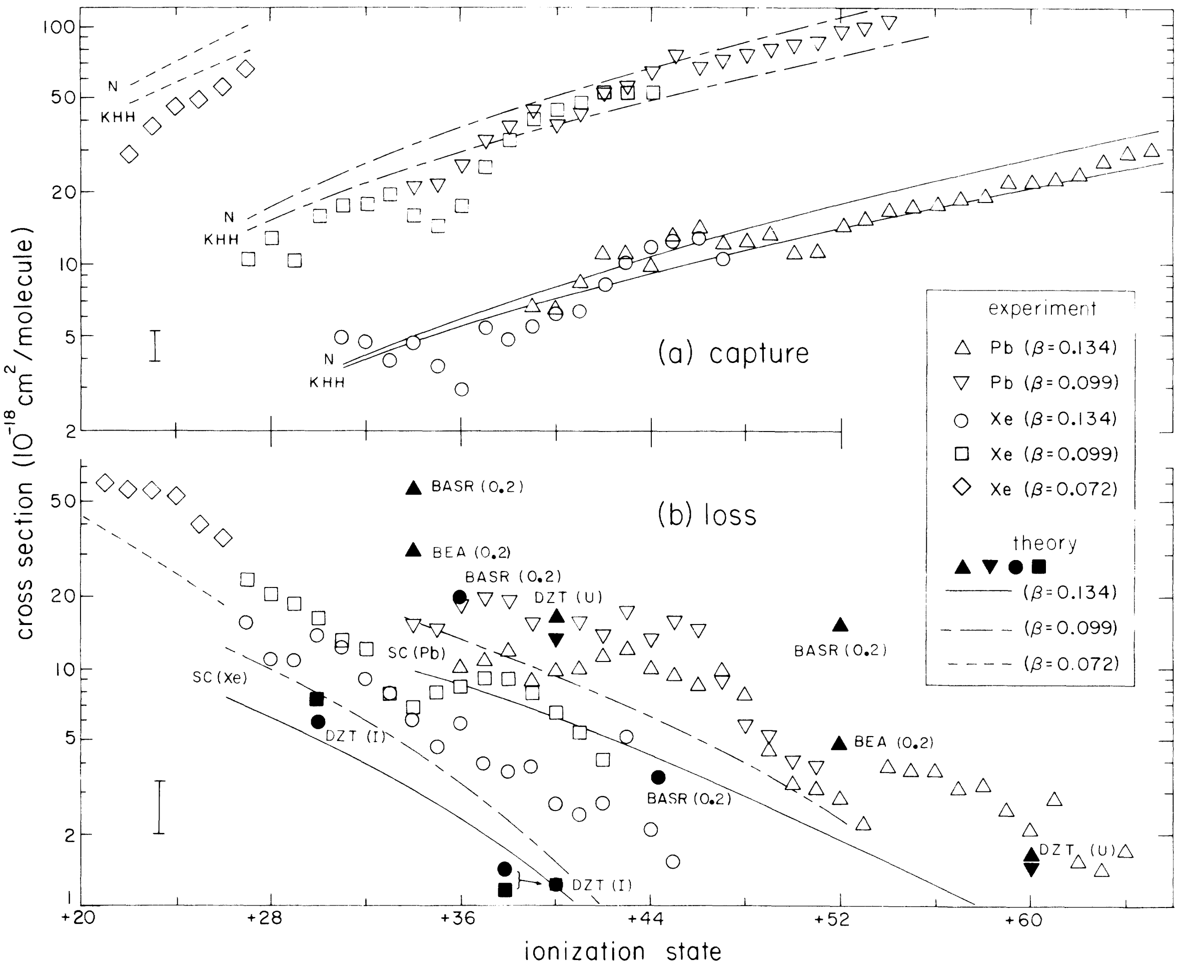

FIG. 1. (a) Capture and (b) single-electron-loss cross sections in N_2 as a function of the ionization state for Pb and Xe ions. Experiment is shown as open symbols, theory with the corresponding closed symbols and with broken and solid lines. In (a) KHH is Ref. 9, and N is Ref. 10. In (b) theory in closed symbols should be compared to experiment with corresponding open symbols. BASR (Refs. 11 and 12) and BEA (Ref. 13) were calculated for Hg ($Z=80$) and Xe at $\beta=0.2$ and DZT (Ref. 14) was calculated for U ($Z=92$) and I ($Z=53$) at $\beta=0.134$ and 0.099. SC is semiclassical (this work and Ref. 6).

model, both authors predict $\sigma_c = A\beta^{-12}$ in the high velocity limit. At $\beta=0.134$ we find no evidence of this velocity dependence.

Simple calculations based upon semiclassical models[6-10] have provided some accurate capture cross sections for lighter ions and lower velocities. However their validity for heavy ions at high velocity has been open to question.[2] The results of two semiclassical calculations multiplied by a factor of 2 to roughly account for molecular nitrogen, are plotted in Fig. 1(a). Knudsen, Haugen, and Hvelplund[9] (KHH) use a Lenz-Jensen statistical model for the target atom; while Nikolaev[10] (N) uses a treatment similar to Bohr.[6] Both models are in excellent agreement with this experiment.

We determine the velocity dependence of the loss cross sections σ_l between $\beta = v/c = 0.099$ and $\beta=0.134$ by fitting the cross sections in Fig. 1(b) to $\sigma_l = A\beta^n$ where A is a constant. We find, for Pb averaged over ionization states 36+ to 51+, that $n=-0.98$ (0.2), and for Xe 27+ to 42+, $n=-1.56$ (0.25). These values disagree with the β^{-2} dependence predicted for very fast collisions in a Born approximation,[11,12] and a binary encounter approximation calculation.[13]

The ionization state (q) dependence of the loss cross section σ_l is found by fitting to $\sigma_l = Aq^n$. From the data in Fig. 1(b), we find for Pb, $n=-3.8$ (0.4) at $\beta=0.134$ and $n=-3.3$ (0.6) at $\beta=0.099$. For Xe we find $n=-4.4$ (0.5), -3.3 (0.4), and -3.1 (0.7) at $\beta=0.134$, 0.099, and 0.072, respectively.

The Z dependence of the loss cross section is obtained by fitting to $\sigma_l = AZ^n$. We find, for ionization states 36+ to 42+, that $n = 2.6$ (0.3) for Xe-Pb at $\beta = 0.134$, and $n = 1.9$ (0.2) at $\beta = 0.099$.

To predict the loss cross sections of fast heavy ions in the velocity region $\beta \geqslant 0.2$ for heavy-ion fusion studies, Gillespie[11] and others[12] have used a Born approximation sum rule (BASR) and Yu[13] has used a binary encounter approximation (BEA). For accelerator design studies, Dmitriev, Zaikov, and Tashaev[14] (DZT) have developed a semiempirical model to predict cross sections over the region $\beta > 0.325/Z$. Loss cross sections calculated at $\beta = 0.2$ by the BASR[11,12] and BEA[13] for Hg 52+ and Hg 34+ ($Z = 80$), and the BASR[11] for Xe 36+ are indicated in Fig. 1(b). The BASR cross sections (at $\beta = 0.2$) are substantially larger than our experimental values (at $\beta = 0.134$). The BEA calculation is within a factor of 2–3. Correction for the difference in β would make the experimental disagreement with the BASR and BEA calculations larger. The DZT semiempirical values[14] [Fig. 1(b)] for U 60+ ($Z = 92$) and U 40+ at $\beta = 0.134$ and 0.099 are a good match to the experimental cross sections for Pb, while their values for I 40+ ($Z = 53$) and I 30+ at $\beta = 0.099$ and 0.072 underestimate our Xe cross sections by only a factor of 2.5.

Good agreement with all of our data is obtained with a semiclassical (SC) model. We start with Bohr's formula for the loss cross section, from Eq. 3.1.3 of Ref. 6:

$$\sigma_l = 2\pi a_0^2 Z_T^2 \left(\frac{\alpha}{\beta}\right)^2 \sum_j \left(\frac{1}{I_j} - \frac{1}{2\beta^2}\right) ,$$

where Z_T is the effective charge of the target, I_j is the binding energy (in units of the rest mass of the electron) of the jth electron in the ion, and the sum is over all electrons j for which $2\beta^2 > I_j$. However, instead of a statistical model for the electron binding energies used by Bohr and Lindhard (Ref. 8, p. 15), we use binding energies obtained from a relativistically corrected Hartree-Fock calculation.[15] We neglect excitation to autoionizing or metastable states. The single-electron-loss cross sections in N_2 obtained from the calculation are plotted in Fig. 1(b). The agreement with experiment is on average within a factor of 2, and better at the lower ionization states and lower Z.

The velocity dependence of the loss cross sections in the SC model is largely determined by the ratio of the projectile velocity β to the binding energy of its electrons I_j. When β is very large compared to I_j for most of the electrons in the ion, the velocity dependence can approach β^{-2}. However, at velocities (where the kinetic energy is) just above I_j of the most loosely bound electrons, the slope of σ_l vs β can become zero or assume positive values.

The loss cross sections for partially ionized Pb and U at velocities $\beta \geqslant 0.2$ are required for the use of fast heavy ions as igniters for pellet fusion. The cross sections are critical in determining the (vacuum) conditions for acceleration and final focusing of the ions in the reaction vessel,[16–18] and in determining the energy deposition in the pellet. Our SC calculation of the cross section for single-electron loss in N_2 for Pb 2+ at $\beta = 0.2$ yields a value of 1.4×10^{-16} cm^2/molecule.

In summary, from measured charge-changing cross sections of Pb and Xe in N_2 we find that in the region $\beta \approx 0.1$ the capture cross sections scale approximately as $Z^0 q^3 \beta^{-6}$ and are in good agreement with semiclassical models. We also find that the loss cross sections decrease more slowly than β^{-2} and are in disagreement with a Born-approximation calculation. Agreement, however, is good with the DZT semiempirical model and a Bohr semiclassical calculation.

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