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Ionization in Low-Energy Atomic Collisions of Neon with Neon and Krypton with Krypton*

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Neutral atomic beams of neon and krypton have been used to measure the total-ionization cross section for symmetric collisions as a function of energy. The beams were produced by symmetric charge transfer of ions produced in an electron-impact ion source with low-energy electrons. Beam energies ranged from below the ionization thresholds to 2000 eV for neon and to 1000 eV for krypton. Neutral-beam intensities were determined by the measurement of slow- and scattered-ion currents generated in the charge-transfer cell. It is found that the Ne-Ne ionization cross section is a rather smoothly varying function of energy, while that for Kr-Kr collisions exhibits structure. The two cross sections become equal at approximately 130 eV incident energy, above which the Kr-Kr cross section remains below that for Ne-Ne. Results are compared with those by Flaks at higher energies, and those by Bussmann and Rostagni at intermediate energies.

I. INTRODUCTION

In this paper we report measurements of the total-ionization cross sections for collisions between neon atoms and between krypton atoms. The neutral beams, ranging in energy from about 20 eV to 1000 eV, were formed by symmetric charge transfer, as described in previous work.[1-5] Neon- and krypton-gas thin targets were established in the region of a guarded parallel-plate ionization chamber. The total negative charge resulting from ionizing collisions was measured, along with target pressure and incident-beam intensity. From these quantities and the current-collector length, the absolute ionization cross section can be determined. It is necessary, especially at the lower beam energies, to account for secondary electrons produced on the electrode surfaces.[2]

Data were obtained in some cases over very closely spaced energy intervals to determine whether structure exists in the cross section, as was found for the case of argon-atom collisions.[5]

II. NEUTRAL BEAM FORMATION

As in earlier work, an electron-impact ion source was utilized to produce the ions, which were then electrostatically accelerated and focused. The ionizing electron energy was maintained at values below those required to produce metastable states. The energy spread of the ion beam is less than 0.5 eV at half-maximum. Both gases used in the experiment were Matheson Company Research Grade, with listed minimum purities of 99.995%. Because of the magnitude of the symmetric-resonance charge-transfer cross section, the purity of the neutral beam should be greater than that of the ion beam, with more than 99% of the krypton or neon atoms in the ground electronic state.

The ion source, lenses, and charge-transfer cell are described in detail elsewhere.[1,2] Briefly, the neutral-beam intensity is established by the measurement of both slow- and scattered-ion currents in the charge-transfer cell. This cell consists of a cylindrical grid held at ground potential and surrounded by a cylindrical cup whose potential may be varied from − 1.5 V to + 45 V with respect to ground. Generally, a cup potential of 4.8 V was utilized to collect the slow-ion current. While higher voltages were frequently required to achieve saturation, leakage of the retarding field can affect the beam energy. Therefore, when lower values were used, corrections to the measured cross sections (typically 5–10%) were made for incomplete slow-ion collection. Outside the cup, a repeller and collector arrangement was used to remove the ions from the beam. The portion of the beam neutralized was approximately 15%. With a well-focused ion beam, the neutral-beam intensity is closely equal to the slow-ion current. In practice, the scattered-ion current i_2 is measured, along with the slow-ion current i_3 and the fast primary current i_1 to the collector. The neutral-beam intensity is given by

$$B = i_3/(1 + i_2/i_1) . \tag{1}$$

The current i_1 is not affected by secondaries arising from the collector.[1]

For the case of krypton, pressure measurements were made in the charge-transfer cell in order to determine the charge-transfer cross sections. These measurements were made with an MKS Baratron capacitance manometer which was utilized for ionization target-pressure determinations as well. Ratios between the Baratron readings and McLeod gauge readings were in good agreement with those reported by Utterback and Griffith,[6] after allowing for mercury capillary depression. The resulting charge-transfer cross sections are in good agreement with those reported for $Kr^+ + Kr$ by Hasted,[7] and averaged about 20% larger than the theoretical calculations by Rapp and Francis.[8] For the case of neon, slow-ion current measurements were again made as a function of the cup potential in order to establish the correction for incomplete slow-in collection. Furthermore, because slow neon ions are efficient producers of secondary electrons from metallic surfaces, a 7% reduction of neutral beam intensity was made to account for secondaries ejected from the grid in the charge-transfer cell. This value for the secondary-electron emission coefficient was determined in the manner described previously,[1] and

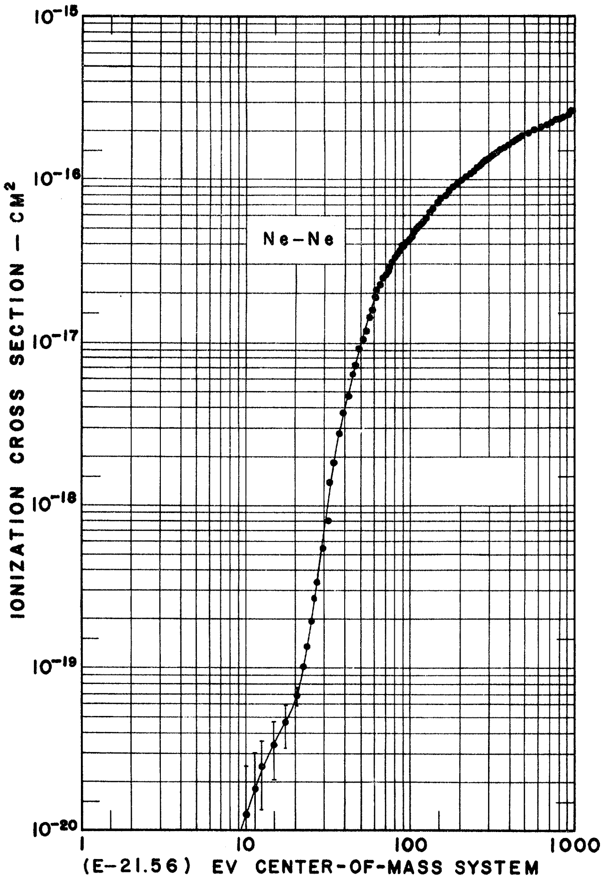

FIG. 1. Ne-Ne ionization cross section.

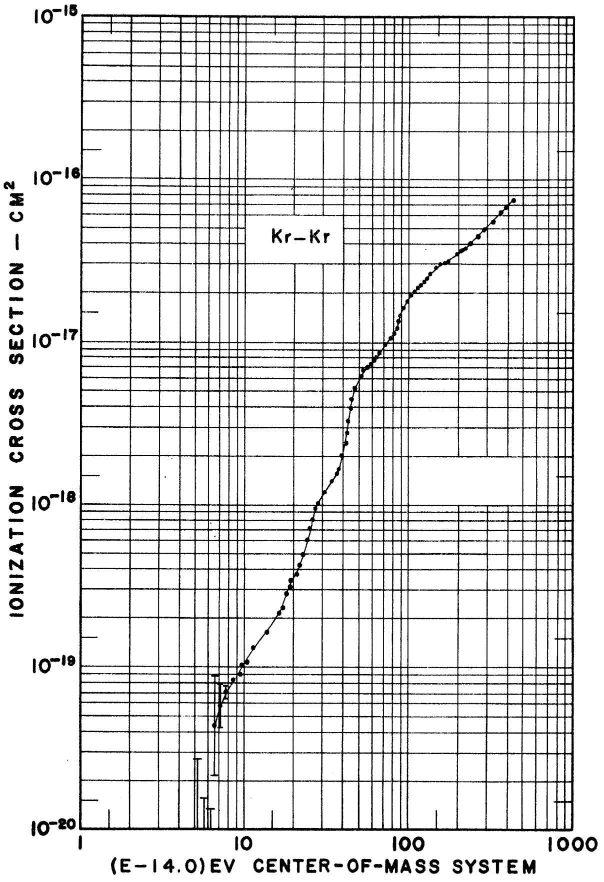

FIG. 2. Kr-Kr ionization cross section.

represents an extrapolation from measurements made with the ion beam incident on a gold foil down to 50 eV. (Electrodes in the neutralization chamber are all gold plated.)

An additional correction to the neutral-beam intensity arises from the occurrence of further neutralization at the ends of the charge-transfer cell. This correction, while difficult to establish exactly, is taken to be 10%. A comparison of the secondary-electron emission coefficients γ^+ and γ^0 for 1000 eV ions and neutrals, respectively, generally shows that γ^0 is greater by about 20%. While most of this difference could be real,[9] the 10% increase in B represents a compromise. The over-all uncertainty in the intensity is taken to be ±20%, and represents the largest uncertainty in the measured cross sections, except at energies near threshold.

III. IONIZATION MEASUREMENTS

Mercury diffusion pumps were used throughout the system. Background pressure was about $2\times10^{-}$ Torr. The parallel-plate electrode arrangement for the ionization chamber was the same as that described previously.[2] A collecting potential of 1500 V was sufficient to collect essentially all the electrons. A potential difference of 390 V was maintained between the secondary-electron suppressing grid and back plate. With this arrangement, it was unnecessary to correct the ionization current for saturation. At lower beam energies, it was necessary to reduce the collecting and suppressing voltages in order to reduce background noise. Saturation corrections of about 15% were then required. Measurements were also performed, as before, with the grid potential equal to that of the back plate to permit a measurement of the total secondary-electron current. The procedure is outlined in Ref. 2. The resultant cross sections are obtained from the equation

$$\sigma = 3.05\times10^{-14}(i/PB)\ \mathrm{cm}^2 ,$$

where i is the negative collector current in amperes corrected for secondary electrons from the grid and for background, P is the target pressure in units of 10^{-4} Torr and B is the neutral-beam equivalent current. σ represents the ionization of both the target and the projectile.

Results are shown in Figs. 1 and 2, where the ionization cross section is plotted as a function of the center-of-mass energy in excess of the ionization potential. Thus the symbol E on the abscissa represents half the beam energy. For the case of neon, Fig. 1, uncertainties in the measured ionization current became very large at beam energies below about 80 eV, owing mostly to the large secondary-electron current correction.

For krypton, Fig. 2, this correction was smaller, and measurements at beam energies down to about 45 eV are fairly reliable (±20%).

DISCUSSION

There have been no attempts to predict the total-ionization cross sections for these atoms, so that no comparison with theory is possible. It is rather striking, however, to note the contrast between the two curves: while the Kr-Kr cross section is somewhat undulatory in its increase with energy, the Ne-Ne ionization is a rather smoothly increasing function of available energy except at the lower end. The neon curve suggests an upswing in the cross section at about 21 eV excess c.m. energy, which corresponds to the threshold for ionization of the second neon atom. A similar increase is suggested in krypton at about 15 eV, though not as pronounced. Published data for argon,[5] as well as work currently in progress, indicate a very distinct rise in ionization in the neighborhood of 15 eV excess energy for Ar-Ar collisions, corresponding closely to the ionization energy of the second argon atom.

In Fig. 3 we compare the results of our measurements with those of other investigators. Rostagni's data[10] for Ne-Ne collisions, shown as curve C, are in fairly good agreement over the interval of overlap. The results of Bussmann,[11] which differ from earlier published values by Fetz and Bussmann,[12] are also shown. The present results agree well with his, except at the lower energies. Cross sections reported by Flaks[13] for higher energies (curve F) would have to be raised about 40% to match up well. Bussman's data are shown in Ref. 11 only as lines, and it is not possible to ascertain whether the actual data suggest any of the structure we have observed in krypton. However, the two experiments are in fair agreement in regard to magnitude. Flaks's data for krypton appear to be rather high by comparison. One notes, in fact, that his cross sections for krypton lie above those for neon, while we find just the opposite. Perhaps the two curves cross again above 1000 eV.

In forming the neutral atomic beams, the possibility arises that some of the beam is in a metastable state. Evidence of this effect for helium and argon has been found for symmetric charge transfer at energies only slightly above threshold for the respective metastable.[14,15] However, the cross sections for metastable production are quite small. In the case of argon, the form of the ionization cross section has been found to be largely independent of neutralizing gas, even when H_2 is used. The concentration of metastables in the present work, if consistent with helium and argon, is expected to be no more than a few tenths of a percent at beam energies of about 50 eV and no more than a few percent at 1000 eV.

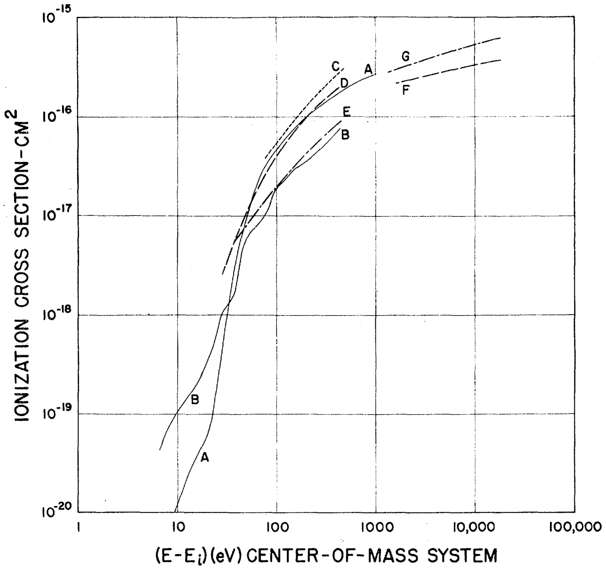

FIG. 3. Comparison with other investigators. Curves A and B: present results for Ne and Kr; curve C: Ref. 10, Ne; curves D, E: Ref. 11, Ne and Kr, respectively; curves F, G: Ref. 13, Ne and Kr, respectively.

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