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Recoil Ions from Close 20-keV H^+ Collisions with O_2, CO, CO_2, and Ne

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Recoil ions ejected at 70° from 20-keV proton collisions with O_2, CO, CO_2, and Ne were analyzed by an electrostatic analyzer. For the molecular targets, only singly ionized ions of oxygen or carbon were detected while in the spectrum of neon ions, Ne^+ and Ne^{2+} were both observed. The absence of O_2^+, CO^+, and CO_2^+ is due to the fact that the recoil ions detected in this experiment result only from very close collisions with one of the atoms in the molecule resulting in dissociation. A possible explanation for the absence of O^{2+} and C^{2+} peaks based on the molecular nature of the targets is proposed.

INTRODUCTION

In a recent paper,[1] we presented recoil-ion spectra from very-small-impact-parameter collisions of protons with argon and krypton target atoms. Recoils from such close collisions were selected by observation of ions ejected only at relatively large angles away from 90°, in that case at 50° and 70° relative to the beam direction. For such collisions, the production of multiply charged ions was found to be greater than for more distant collisions. In the present work we have applied this technique to the molecular targets O_2, CO, and CO_2. Since comparison to the Ar and Kr work may be somewhat misleading because of the different numbers of electron shells involved, we also present a spectrum using neon as a target atom which has the same number of atomic shells.

Browning and Gilbody[2] have studied the fragmentation of O_2 and CO, along with other targets, under 5—45-keV proton bombardment by collecting all slow ions with a large electric field and analyzing them with a mass spectrometer. In their experiment, collisions at all impact parameters capable of producing ions contributed to the spectrum. However, since distant collisions were more probable, they were the dominant ones.

EXPERIMENTAL RESULTS

The experimental method and apparatus have been described previously.[1] When target-gas pressures of 0.3 and 0.6 milliTorr were used in the present measurements, the results were the same within statistical fluctuations. The effective path length for the recoil ions from collision center to detector was 5 cm at the target-gas pressure. Two runs were averaged for the O_2 data and four runs each were made for CO and CO_2.

Figure 1 shows the spectra along with Gaussian curves fitted to each of the peaks. Most of the signal between 200 and 400 V for the molecular gases is due to reflections of ions from the field-straightener plates in the parallel-plate analyzer. The expected positions of the O^+ and C^+ peaks calculated for 20-keV elastic collisions are 518 and 664 V, respectively. Prominent peaks appear in the spectra at energies that agree with these values within 2%. This is consistent with the uncertainty of the energy scales for the beam and the recoil-ion analyzer. Peaks for O^{2+} and C^{2+}, if present, should have come at half these values or 259 and 332 eV. However, no trace of these peaks is seen, although in the comparison case the Ne^{2+} peak shows up clearly. Likewise, the O_2^+, CO^+ and CO_2^+ peaks which should come at 275, 312, and 203 V are not present. In the experiment of Browning and Gilbody[2] the O_2^+ cross section is actually larger than that for O^+, and the CO^+ cross section is nearly four times as large at 20 keV as that for C^+.

The absence of molecular ions in the spectrum is a consequence of the fact that recoil ions ejected with energies of hundreds of eV and at angles as much as 20° away from 90°, as in this experiment, result only from collisions in which the projectile comes very close to the nucleus of

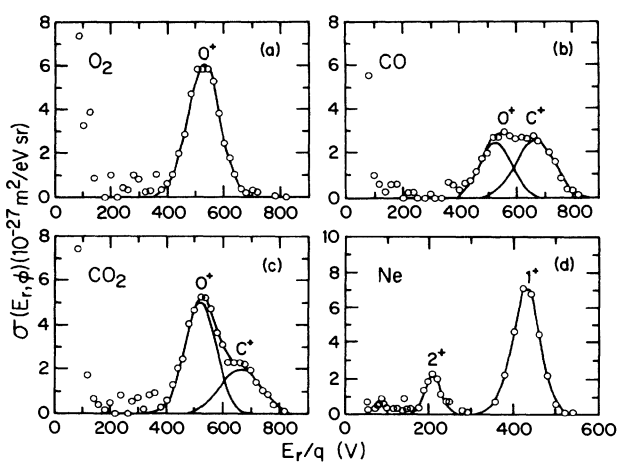

FIG. 1. Recoil-ion spectra at 70° for 20-keV proton collisions on various targets. The abscissa is the recoil energy per unit charge of the ions and is measured in volts. The ordinate is the differential cross section. (a) Oxygen, (b) carbon monoxide, (c) carbon dioxide, and (d) neon.

TABLE I. Differential cross sections for recoil ions in units of 10^{-25} m^2/sr.

Target	O_2	CO	CO	CO_2	CO_2	Ne	Ne
Ion	O^+	O^+	C^+	O^+	C^+	Ne^+	Ne^{2+}
Expt.	9.8	3.7	4.8	7.5	3.8	6.6	0.95
Theor.[a]	30	30	19.6	30	19.6	43	
Ionization efficiency	0.33	0.12	0.24	0.25	0.19	0.18[b]	

[a]Theoretical calculation of the elastic cross section.
[b]Calculated from the sum over the charge states.

one atom of the molecule. Calculations of the scattering integrals for O_2 using a screened Coulomb potential indicate that for recoils ejected at 70° the impact parameter is only 0.82 pm and the corresponding distance of closest approach is 1.2 pm. This is considerably smaller than the K-shell radius of oxygen which is 6.9 pm and much smaller than the interatomic distance of the atoms which is about 160 pm. Therefore the collisions isolated for study here are essentially binary collisions between the projectile and a single atom. Such hard collisions would be expected to result in the breakup of the molecular target with a probability close to 100%. It is not as clear, however, why multiply charged oxygen and carbon ions are not present. In the work on argon and krypton[1] the ratio $\sigma(2+)/\sigma(1+)$ was approximately 1. For neon, this ratio is 15%. But in the present data there is no detectable C^{2+} or O^{2+}. Our measurements give an upper limit to this ratio of 2.5%. In Browning and Gilbody's data[2] the C^{2+} production is about 4% of the C^+ production.

A possible explanation of the difference between the $2+$ ion production in O_2, CO, and CO_2, on the one hand, and Ne on the other has to do with the molecular nature of the targets. There are several possible mechanisms for producing doubly charged target ions. These are direct two-electron ejection, two-electron capture, simultaneous capture and electron ejection, and K Auger emission. In each case, the process of removing the electrons takes place so quickly that the relatively slow moving recoil ion does not completely escape from the molecule until well after the ionization process is complete. Therefore, if a doubly charged ion were produced, it would be likely to capture an electron as it emerged through the molecular charge cloud. To put it another way, the faster electrons tend to arrange themselves after the collision so as to equalize the charges on the separating fragments.

In the previous paper[1] we compared the production of multiple ions in a zero-impact parameter collision with those resulting from all possible impact parameters. We can extend that comparison to neon with the present data. The fraction of the total ionization which is due to multiple ionization is given by the quantity $\sum_{n>2} n\sigma(n+)/\sum_{n>1} n\sigma(n+)$. This can be calculated from the data of DuBois *et al.*[3] which includes all impact parameters. The values of this fraction for their 25-keV data on neon, argon, and krypton are 4.4%, 35%, and 41%, respectively. The corresponding numbers for the present 20-keV zero-impact-parameter data are 22%, 74%, and 71%. The greater multiple ionization in close collisions is obvious and is especially striking in the case of neon.

The singly differential cross sections were determined from the present data by calculating the areas under the Gaussian curves and are given in Table I. Theoretical values of the elastic cross sections were calculated from classical scattering integrals assuming a screened Coulomb potential and are also listed in the table. The ratio of the experimental value (the sum of the experimental values in the case of neon) to the total theoretical values gives the ionization efficiency for these collisions. The values of the ionization efficiency obtained for the molecular targets (19—33 %) are unexpectedly small; considerably smaller even than those determined[1] for argon and krypton.

The linewidths of the lines in the CO and CO_2 spectra were 25% and the line in the O_2 spectrum about 28%. These widths are somewhat greater than for neon which is 18% and for argon and krypton[1] which were 16% and 19%, respectively. The greater widths for the molecular gases is expected because of the dissociation energy. Combining the expected widths due to the thermal energy, the dissociation energy, the energy resolution of the analyzer, and the angular spread of the projectile beam and the recoil ions, we can, as in the previous work,[1] account for a large fraction (55—80 %) of the measured widths. The remainder may result from variations in the energy loss due, e.g., to excitation.

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