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Mechanisms for Electron Production in 30-MeV $O^{n+} + O_2$ Collisions*

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Absolute cross sections for electron emission in the complete energy and angular ranges were measured for 30-MeV $O^{n+} + O_2$ collisions at incident charge states of $n = 4$ to 8. Rises in inner- and outer-shell ionization of the target are studied for increasing n. Electrons ejected from the outer shell of the projectile are found to be very intense at forward emission angles θ. Auger electrons from the projectile are observed at $\theta < 42°$ for n as large as 6.

Most previous measurements of electron production in ion-atom collisions have been made with projectile energies lower than a few MeV; for recent progress in this field see current reviews.[1,2] Only recently, Burch and co-workers[3-5] and Matthews and co-workers[6] using ions from tandem Van de Graaff accelerators reported on electron production in experiments with projectiles having energies an order of magnitude higher than previously used. In these experiments, however, electrons have been measured only at fixed backward angles with respect to the incident beam, and only certain fractions of the electron spectra (target Auger peak[3,5,6] and projectile "electron-loss" peak[4]) have been detected. Our purpose in this work is to study the overall angular and energy distributions of secondary electrons produced by energetic heavy ions with a variety of incident charge states. This is the first such comprehensive investigation for high-energy collisions and it is made to obtain a general picture of ionization mechanisms with ions supplied from high-energy accelerators.

We report absolute cross sections for electrons ejected in 30-MeV $O^{n+} + O_2$ collisions with projectile charge states of n from 4 to 8. Measurements were made at forward observation angles of 25 to 90°; the data do not substantially change in the range of backward angles. The measured electron spectra indicate pronounced structures, each of which can be attributed to certain excitation and de-excitation processes in the target or the projectile atom. It is found that most of the spectral structures are strong only at forward electron-ejection angles. In particular, at small angles outer-shell electrons emitted from the projectile are found to dominate the electron spectra. Furthermore, Auger electrons ejected from the 30-MeV projectile can be observed only at angles smaller than 42°. At 25°, projectile Auger electrons are found for projectile charge states as high as 6, indicating the presence of collision processes such as simultaneous vacancy creation in the inner shell and transfer of two electrons to

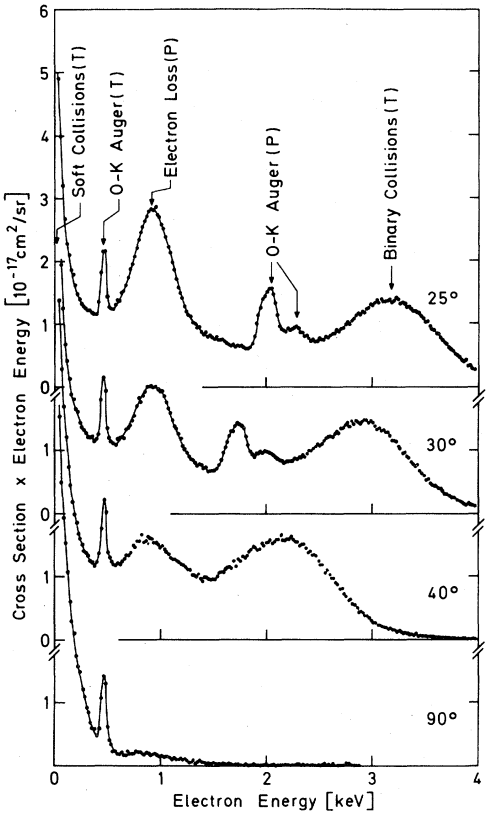

FIG. 1. Cross section times electron energy for electron production in 30-MeV $O^{5+} + O_2$ collisions at different electron observation angles.

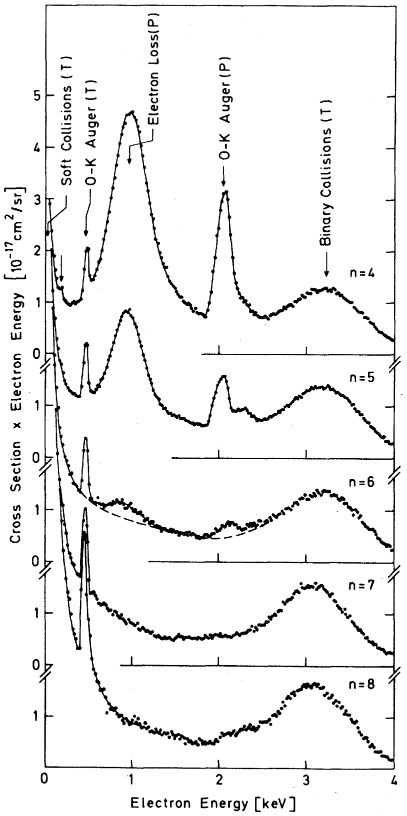

FIG. 2. Cross section times electron energy for electron production in 30-MeV $O^{n+} + O_2$ collisions at an electron observation angle of 25° for different projectile charge states n.

outer shells of the projectile.

The measurements were made using the crossed-beam apparatus of the Hahn-Meitner-Institut Berlin which was temporarily transported to the FN tandem accelerator laboratory of the University of Washington. The apparatus has been described in detail previously.[7] Electrons produced in ion-atom collisions were analyzed by a parallel-plate electrostatic spectrometer with an energy resolution of 2.6% full width at half-maximum. The spectrometer efficiency and its energy dependence were known in the studied electron-energy range,[7] so that absolute cross sections for electron production could be determined. Low pressures were maintained in the system to provide single-collision conditions. Between the charge-state analyzing magnet and the gas target (of ~3 mm thickness) the ion beam traversed a 10-m beam tube and a 30-cm section of the scattering chamber. The pressures in the beam tube, the chamber, and the target were 5×10^{-7}, 5×10^{-5}, and $\sim3\times10^{-3}$ Torr, respectively. Assuming an upper-limit value[8] of 10^{-16} cm^2 for the charge-exchange cross section, it was calculated that less than 1% of the incident particles underwent charge-exchange collisions.

In Figs. 1 and 2 experimental results are given for different observation angles and for several charge states of the incident ion, respectively. The electron spectra show several peaks which are discussed individually below. In Table I are given cross sections obtained by integration of the Auger peaks. Total cross sections for Auger

TABLE I. Total cross section per atom (in units of 10^{-18} cm^2) for Auger-electron ejection from the target T and the projectile P in 30-MeV $O^{n+} + O_2$ collisions as a function of the projectile charge state n.

	4	5	6	7	8
T	6.4 ±1.5	7.4 ±1.8	8.8 ±2.3	11.4 ±2.6	17.5 ±3.9
P	6.3 ±1.5	2.7 ±0.6	0.72 ±0.18	•••	•••

electron ejection from the projectile and the target were calculated assuming isotropic electron emission in the rest frame of the corresponding particles.

Soft and binary collision peaks.—The peaks labeled "Soft Collisions (T)" and "Binary Collisions (T)" are due to electrons produced by Coulomb interaction of the incident (screened) nucleus with, primarily, outer-shell electrons of the target. Similar peaks have previously been studied in low-energy collisions with light-ion impact; see for instance the spectra[7,9] obtained by H^+ incident on He. In the theoretical description based on the Born approximation, "soft" and "binary" collisions correspond, respectively, to the minimum and maximum momentum transfer from projectile to the target atom. The soft-collision peak is nearly isotropic in intensity and position, whereas the binary-collision peak is strongly shifted to lower energies with increasing observation angle and vanishes at angles larger than 90°. Figure 2 shows the projectile-charge dependence of the peak intensities. It is found that for charge states of 4 to 8 the soft-collision peak (at 40 eV) and the binary-collision peak (at its maximum) increase by factors of 5.2 and 1.25, respectively. These numbers show that in the case of soft collisions the screening effect of the projectile electrons on the incident nucleus is considerably larger than in the case of hard or binary collisions.

Electron loss peak.—The peak labeled "Electron Loss (P)" represents electrons ejected from the projectile by elastic scattering from the screened Coulomb field of the target. Such electrons have recently been observed by Wilson and Toburen[10] and Burch, Wieman, and Ingalls[4] who have also given a binary-encounter description of the electron-loss process. The centroid energy of the peak corresponds to an electron velocity equal to the projectile velocity. Using the formulas in Ref. 4 it can be shown that the base width of the electron-loss peak is given in first order by $4(E_B E_i)^{1/2}$, where E_B is the binding energy of the "lost" electron and E_i is its mean ejection energy. In high-energy (30-MeV) collisions the electron-loss peak was previously observed[4] only at 90° where its intensity is relatively small (Fig. 1). The present results, however, indicate that the electron-loss peak is very intense in the spectra measured at forward angles.

From the base-width formula given above, it follows that the observed electron-loss peak is produced only by outer-shell electrons of the projectile. (Electrons originating from the projectile K shell are hardly seen as they are too much spread out over the spectrum.) Indeed, integration of the present electron spectra shows that the studied peak for O^{4+} impact is twice as large as the peak for O^{5+}. However, for O^{6+} impact the intensity of the electron-loss peak is still considerable, i.e., 0.12 of that for O^{5+}. This intensity is probably too large to be due to an O^{5+} contamination in the O^{6+} beam. It is possible that a contamination of O^{6+} ions excited to metastable states partly produces the observed intensity.

Target Auger peak.—The peak labeled "O-K Auger (T)" is produced by Auger electrons following vacancy creation in the K shell of the target by the incident (screened) nucleus. Recently, Burch *et al.*[5] have shown for high-energy collisions that Auger-electron measurements are appropriate to study the incident charge-state dependence of inner-shell vacancy production.

The numbers in Table I show that the Auger-electron production cross section for the target increases by a factor of 2.8 as the projectile charge state increases from 4 to 8. It should be noted that the projectile velocity is slightly larger than the velocity of the oxygen K-shell electron; hence, the inner-shell ionization of the target is expected to take place primarily via a direct Coulomb excitation process. The factor-2.8 rise of the Auger-electron production cross section is intermediate between the factor-1.28 and -5.2 rise in the intensities of the binary-collision and soft-collision peaks, respectively. It appears reasonable, as in the case of outer-shell ionization, to explain the variation of the target K-shell ionization primarily by screening effects of the projectile nuclear charge.[5]

Projectile Auger peak.—The peak labeled by "O-K Auger (P)" is produced by Auger electrons ejected from the moving projectile after the collision. Previously, projectile Auger electrons have been measured in gas-target experiments only at relatively small ion energies, below about 1 MeV; see Refs. 1 and 2. For 30-MeV oxygen large shifts of the projectile Auger peak appear as a result of kinematic (Doppler) effects. Projectile Auger electrons are visible only at angles smaller than 42° (Fig. 1). In this angular range the peak appears twice in the spectrum, i.e., at 180 and 2050 eV for 25° (note also the unlabeled arrow above the O^{4+} spectrum in Fig. 2). The appearance of two projectile Auger peaks in the spectrum is well understood in terms of different velocity vector diagrams. Furthermore, at the high-energy side, the Auger peak shows a shoulder which might be attributed to double K-shell ionization or electron excitation to upper bound states.

For O^{4+} the centroid energy of the Auger electrons in the projectile rest frame was calculated to be 420 eV which is considerably smaller than the centroid energy (470 eV) of the target Auger electrons. Auger peaks are shifted to lower energies as an increasing number of outer-shell electrons are missing.[1,2] This shows that the precollision difference in the charge states of the two collision partners is partly preserved in the K-shell ionization collision. Despite this charge-state difference, the Auger-electron production cross sections are found to be equal for projectile and target in $O^{4+}+O_2$ collisions (Table I).

For O^{5+} impact the production of projectile Auger electrons needs the simultaneous vacancy creation in the inner shell and the transfer of an electron to an outer shell of the projectile. (Auger transitions require at least two electrons in outer shells.) This transfer can take place by K- to L-shell electron excitation in the projectile or by capture of an electron from the target. The relatively strong Auger-electron intensity for O^{5+} indicates a rather large probability for this process. In the case of O^{6+} impact two electrons must be transferred to the projectile outer shells in addition to the inner-shell vacancy production. It is seen that this process is still present, as the intensity of the projectile Auger peak for O^{6+} is larger than expected from a possible O^{5+} contamination of the O^{6+} beam. The intensity ratio of the projectile Auger peaks for O^{6+} and O^{5+} is 0.27 (see Table I), whereas the same ratio for the electron-loss peaks is 0.12 which gives an upper limit for possible beam contamination.

In summary we have shown by using electron spectroscopy, primarily at forward observation angles, that a variety of identifiable mechanisms contribute to the ionization process in energetic heavy-ion–atom collisions. Strong features were observed in the electron spectra and attempts were made to explain the spectral structures qualitatively in terms of simple ionization models.

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