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Origin of cusp electrons in slow ($v \sim 0.4$ a.u.) O^{6+} + He collisions

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Continuum electron emission along the beam direction has been investigated in collisions of 60-keV O^{6+} ions with He. It is found that electron capture to the continuum is nearly always accompanied by bound-state capture suggesting that "cusp" electrons originate in a two-electron process in these slow collisions.

Recently, evidence was found for two-electron transfer with high probability for nonequivalent electron configurations in 60-keV O^{6+} + He collisions.[1,2] In these works, the intensity of Coster-Kronig electrons emitted from the deexcitation of the doubly excited configurations $1s^2 2pnl$ ($n > 5$) formed in the capture process was found to be about 30% of the Auger electron intensity resulting from the doubly excited configurations $1s^2 3l3l$. On the basis of potential-energy curve diagrams it was argued that the nonequivalent configurations populated in the collision interaction and leading to Coster-Kronig transitions were formed via a correlated two-electron capture mechanism, whereas equivalent configurations resulting in L-Auger transitions arose mainly from independent capture events.

Measurements by other investigators,[3-5] however, have questioned both the magnitude and the proposed origin of the nonequivalent two-electron capture mechanism, claiming that its contribution was not more than about 10% of that due to equivalent capture events. More recently, new measurements[6] (to be discused below) show general agreement with the earlier measurements of Stolterfoht and co-workers[1] for the magnitude of the emitted electron intensity from Coster-Kronig decays relative to the intensity from Auger decays. In any event, based on these studies, it appears that two-electron capture to bound nonequivalent configurations is about 10%–30% of the double capture to bound equivalent configurations, although the mechanism by which the former process manifests itself has not yet been resolved.

It is worth noting that the studies to date[1-6] for these slow (~0.4 a.u.) collisions have relied upon the formation of doubly excited states in order to observe both the equivalent and nonequivalent double-capture processes. This means that important ground-state, singly excited,[7] and continuum double-capture contributions may be overlooked, e.g., the configurations $(2s)^2$, $(2snl)$, and $2s\epsilon l$, where ϵ represents a continuum state. Thus, double capture can involve simultaneous bound- and continuum-state capture (and double ground-state capture) in addition to capture to "bound" doubly excited states.

At higher velocities (≥ 0.1 MeV/u), studies[8-10] have shown that continuum capture accompanied by bound-state capture can contribute substantially to the total cusp-electron production. In two of these works[8,10] it was concluded that electron correlation played a role in the two-electron transfer process. There is no *a priori* reason to believe, however, that similar results should be obtained at the comparatively low velocities considered in the present work. On the contrary, the results presented here differ in several important ways from the earlier studies.[8-10]

In this Rapid Communication we show that the continuum capture (i.e., cusp electron production) in 60-keV O^{6+} + He collisions is nearly *always* accompanied by bound-state capture indicating that continuum capture originates in a two-electron process. Since this particular nonequivalent double-capture contribution is in addition to that leading to the Coster-Kronig transitions observed in Refs. 1 and 2, the present results suggest that the nonequivalent capture process is considerably more important in these collisions than had been previously believed, i.e., greater than the 30% in comparison to equivalent capture found in Ref. 1.

The experimental work was conducted at Lawrence

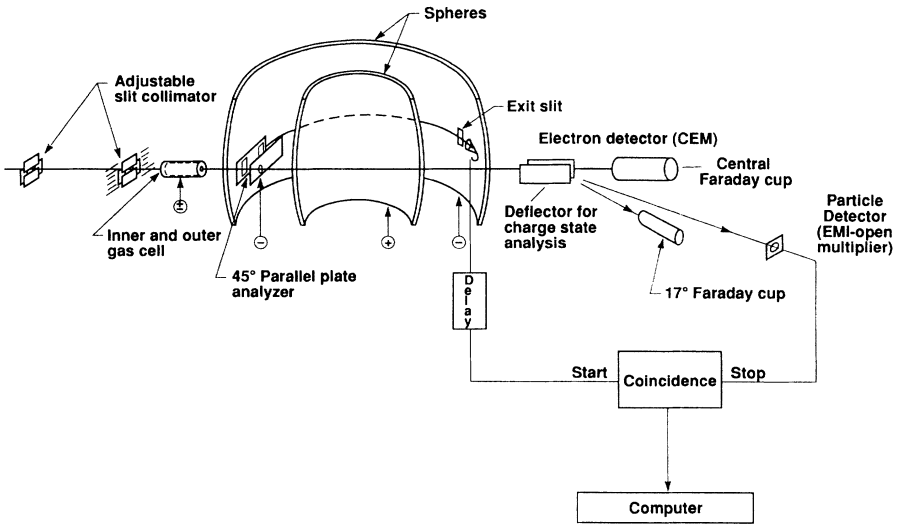

FIG. 1. Schematic of the experimental setup for measuring coincidences between continuum electrons and specific emerging ionic charge states.

Berkeley Laboratory using the electron cyclotron resonance (ECR) ion source at the 88-in. Cyclotron Facility. A schematic of the apparatus is shown in Fig. 1; a similar setup has been previously discussed.[11] Incident oxygen ions in charge state $q=6+$ were extracted from the source and the ion beam was collimated to a size of about 2 mm^2 diameter by two sets of adjustable apertures located 1.5 m apart. The ions passed through a differentially pumped gas cell after which they were electrostatically analyzed in order to separate the charge states. The emerging ions were then collected in a Faraday cup or were detected with an electron multiplier tube. Electrons emitted at 0° (i.e., along the beam direction) from the interaction region were deflected 90° out of the beam by a 45° parallel-plate analyzer and then energy analyzed in a hemispherical electron analyzer and detected with a channeltron located at the exit slit.

The electrons associated with capture to continuum states have laboratory electron energies corresponding closely to the beam velocity. Therefore for 60-keV O^{6+} ions these continuum electrons have laboratory energies of about 2 eV. The gas cell was located inside a second cell of larger diameter (see Fig. 1) at ground potential permitting the inner cell to be biased. The inner cell was biased to -40 V to accelerate the electrons out of the target region and hence minimize the disturbance of the electrons due to spurious instrumental effects. This same technique and voltage were used in Ref. 1.

Coincidences between continuum electrons emitted along the beam direction (i.e., at 0°) and emerging ions were recorded with a time-to-amplitude converter, the time resolution for the measurements being about 100 ns. In all of the measurements, the time resolution was sufficient to give a well-defined peak from which random coincidences could be subtracted. Coincidence yields for outgoing O^{5+} and O^{6+}, as well as the total continuum electron emission yields associated with each of these coincidence yields, were measured as a function of the pressure in the gas cell to check for linearity and to ensure single-collision conditions. The pressure in the gas cell was measured with a capacitance manometer. In all cases the net electron yield for zero gas pressure was negligible. To conduct the coincidence measurements for $q=6+$ it was necessary to attenuate the incident beam by a factor of about 100 so that the electron multiplier was not saturated by an excessive particle flux.

Spectra taken at 0° for O^{5+} and O^{6+} ions coincident with continuum electron emission, and the total "singles" continuum electron yields corresponding to each of these coincidence spectra are shown in Figs. 2 and 3. Backgrounds due to random coincidences have been subtracted channel by channel from the two coincidence spectra giv-

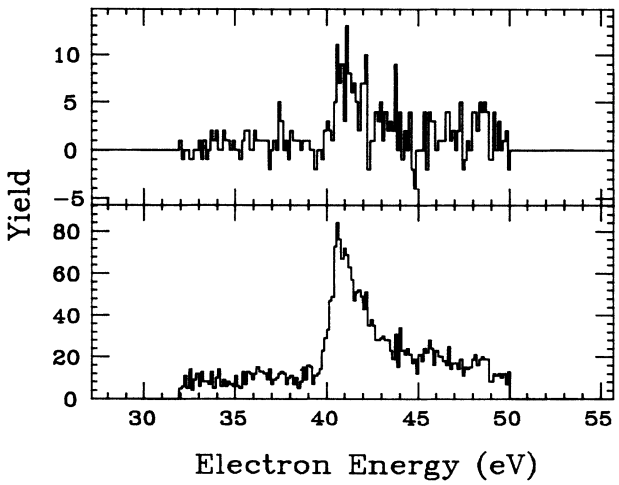

FIG. 2. Spectra showing continuum-electron emission coincident with emerging O^{5+} ions (upper part), and the corresponding total singles continuum electron emission (lower part) for 60-keV O^{6+} + He collisions. The coincidence spectrum has been corrected channel by channel for the background due to random coincidences. The abscissa gives the electron energies in the laboratory frame.

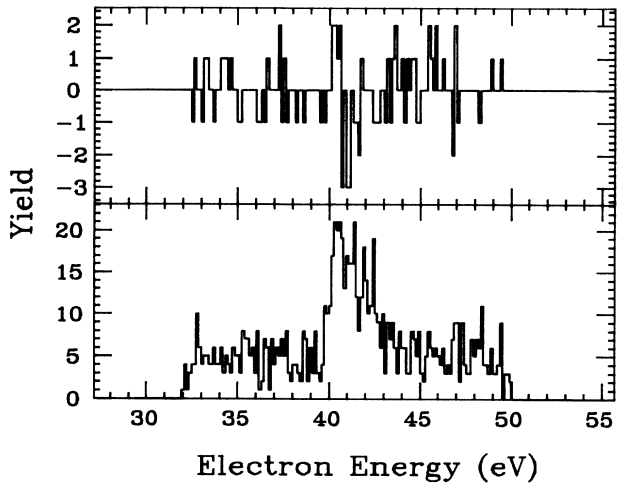

FIG. 3. Same as Fig. 2 except the upper coincidence spectrum is for continuum electron emission coincident with emerging O^{6+} ions.

ing rise to negative values in some channels. Comparison of the coincidence spectra shows that only for emerging O^{5+} is there a net positive yield of true coincidences remaining after the background subtraction. The spectra of Figs. 2 and 3 are typical of spectra taken at different times under varying conditions and the essential findings were always the same.

The experimental setup also allowed high-resolution singles measurements to be conducted when the coincidence measurements were not being done. The electron spectrum resulting from O^{6+} on He following two-electron capture into doubly excited bound states was measured[6] with an energy resolution of 0.2% [full width at half maximum (FWHM)] as shown in Fig. 4. The spectrum shows lines due to Coster-Kronig transitions as well as lines due to L-Auger transitions. The intensity ratio between the two different line groups agrees well with the previously reported ratio of Stolterfoht and coworkers,[1] indicating that about 30% of the two-electron capture to bound doubly excited states results in non-

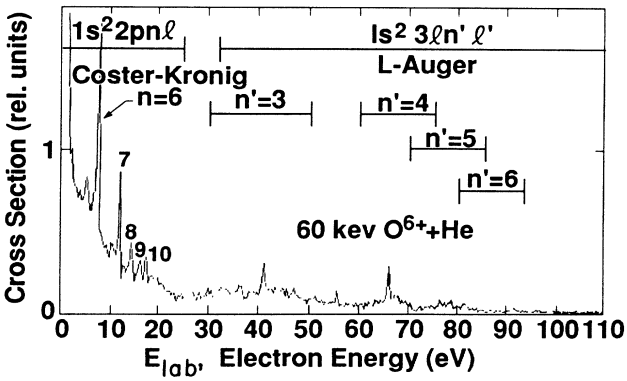

FIG. 4. High-resolution electron spectrum from 60-keV O^{6+} ion impact on He. The spectrum is displayed as a function of the laboratory electron energy.

equivalent electron capture.

It is emphasized that the spectrum for continuum electrons coincident with emerging O^{5+} (Fig. 2) results from collisions in which one electron is transferred to a projectile bound state (electron capture) while an additional electron is lost from the target. Hence, the peak in the O^{5+} coincidence spectrum represents principally those events in which continuum capture is accompanied by bound-state capture, i.e., a two-electron-capture event. Electrons from Coster-Kronig or Auger decays of doubly excited O^{4+}, which would appear to the right-hand side of the peak in Fig. 2, are not strongly evident although there is an indication of a nonzero electron contribution in this region.

The coincidence spectrum for O^{6+} (Fig. 3) represents those events in which a continuum electron is detected *without* an accompanying bound-state capture, i.e., a one-electron-capture event into the continuum. This spectrum is qualitatively and quantitatively different from the coincidence spectrum of Fig. 2 in that there is essentially no net electron yield after background subtraction, indicating that continuum-electron capture does not occur by itself in these collisions. Since bound-state capture is expected to occur in relatively small impact-parameter collisions compared to continuum capture, these results imply that nonequivalent two-electron capture occurs only for small-impact parameters. Evidence for such an effect has been observed in higher-energy 0.53-MeV/u F^{9+}+Ne collisions[12] although these higher-energy measurements do not necessarily have a direct bearing on the present results. Additionally, evidence for the increasing importance of continuum capture accompanied by bound-state capture for decreasing velocity is found by Köver *et al.*[13] in 50–150-keV/u He^{+}+He and Ar collisions.

It is noted that the sum of the electron yields in the two coincidence spectra (contributions from the other outgoing oxygen charge states are negligible) do not add up to the total singles continuum electron yield. This is because the efficiency of the electron multiplier tube used for outgoing particle detection is less than unity. This efficiency can be determined from the ratio of the measured singles yields accompanying the 5+ and 6+ coincidence measurements, respectively, since the total electron yield must be the same in either case. This ratio gives an efficiency value of $\sim$25% for the electron multiplier which, in turn, accounts for greater than 85% of the total electron yield in the O^{5+} coincidence channel. Since there is virtually no net yield in the O^{6+} coincidence channel, the remaining discrepancy can be attributed to the uncertainty ($\pm$10%) in determining the electron multiplier efficiency or to a small ($<$5%) contribution to the total electron yield from slit scattering.

Thus the results presented here indicate that continuum-electron capture is nearly always accompanied by bound-state capture in 60-keV O^{6+}+He collisions suggesting that cusp electrons have their origin in a two-electron process for these slow ($v\sim$0.4 a.u.) collisions. In order to understand the mechanism responsible for this highly nonequivalent two-electron-capture process, it is necessary, in general, to consider both independent-particle interactions and electron correlation. Although a

fully quantitative analysis based on the above results is not possible, a relative measure of the independent and correlation contributions may be obtained from the method given in Ref. 10. In that work, the following relationship for *independent* capture events is obtained:

$$\frac{\sigma_{b+c}}{\sigma_c} \simeq \frac{2\sigma_{2b}}{\sigma_{1b}}, \tag{1}$$

where σ_{1b} and σ_{2b} are the total cross sections for single and double bound-state capture, respectively, σ_c is the cross section for continuum capture, and σ_{b+c} is the cross section for combined bound-state and continuum capture. The cross sections[14] for σ_{2b} and σ_{1b} are 1.6×10^{-16} cm^2 and 13×10^{-16} cm^2, respectively, giving $2\sigma_{2b}/\sigma_{1b}=0.25$, while a *lower* limit for the ratio σ_{b+c}/σ_c from this work is $0.85/0.15=5.7$. Then, $\sigma_{b+c}/\sigma_c \gg 2\sigma_{2b}/\sigma_{1b}$, indicating that the combined bound state and continuum capture is significantly larger than expected from independent particle interactions. Thus, this comparison would suggest that electron correlation may play a significant role in two-electron capture to highly nonequivalent configurations.

Finally, since the present double-capture events involving the continuum are in addition to the nonequivalent capture to bound doubly excited states observed in Refs. 1 and 2, it would appear that the nonequivalent two-electron-capture process is considerably more important in the dynamics of these collisions than previously believed. However, the extent of electron correlation in this two-electron transfer process must be further quantified. It is clear that additional studies (with fully stripped ions and other targets perhaps) of nonequivalent two-electron capture are needed to understand the mechanisms for cusp-electron production at low velocities.

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