Projectile $1s \rightarrow 2p$ Excitation Due to Electron-Electron Interaction in Collisions of O^{5+} and F^{6+} Ions with H_2 and He Targets

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Evidence is presented of an excitation process in ion-atom collisions analogous to electron-impact excitation in free-electron-ion collisions. The production of $1s2s2p\ ^4P$ projectile states excited in collisions of $(1s^22s)$ O^{5+} and F^{6+} with He and H_2 targets was found to increase with projectile energy above ~0.75 MeV/u, in agreement with an impulse-approximation treatment of $1s \rightarrow 2p$ electron-impact excitation of ions in collisions "quasifree" target electrons. Such ion-atom excitations could provide presently unavailable information about inner-shell electron-impact excitation.

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In energetic ion-atom collisions projectile inner-shell excitation is usually attributed to the Coulomb interaction between the target *nucleus* and the projectile electrons.[1] The projectile energy at threshold for such a direct electron-*nucleus* excitation (enE), K_0^{enE}, is equal to the required electron excitation energy ΔE. The excitation cross section, σ_{enE}, is expected to scale as $Z_t'^2$, where Z_t' is the effective target nuclear charge,[1] and reaches a maximum value at projectile velocities near the velocity of the excited electron. It remains rather constant upon further increase of the projectile energy.[2,3]

Projectile inner-shell excitation can also be attributed to the Coulomb interaction between target *electrons* and the projectile electron.[1,4-6] As seen from the projectile frame the target electrons are impinging on the projectile. For free electrons such an excitation process is known as electron-impact excitation (eIE). For bound electrons, as in the ion-atom collisions considered here, we refer to this process as electron-electron excitation (eeE). The projectile energy at threshold for eeE, K_0^{eeE}, is equal to $(M/m)\Delta E$, where M/m is the ratio of the projectile to electron masses. The cross section σ_{eeE} is smaller[1] than σ_{enE} by a factor of $1/Z_t'^2$, and is expected to exhibit the sharp threshold behavior of the underlying electron-impact excitation process. The observed threshold behavior of σ_{eeE} will be partially washed out by the target electron's orbital velocity distribution.

By detecting the emitted stabilizing x rays[2-4] or Auger electrons[7] with high resolution, information can be gained about the production of these excited projectile states. To date, no experiment has been able to distinguish eeE from enE, although the effects of the target electrons have been included in calculations in the form of an overall screening or antiscreening[8-10] of the target nucleus charge.

In this Letter, we present measurements in which we clearly observe the eeE process. These measurements consist of the observation of projectile $1s \rightarrow 2$ excitation in energetic 0.25-2-MeV/u collisions of Li-like $(1s^22s)$ O^{5+} and F^{6+} ions with H_2 and He targets. By using such low-Z targets enE is minimized. For these ions, the $1s \rightarrow 2p$ eIE threshold energy corresponds to an equivalent projectile energy of about 16.3 MeV for O^{5+} and 25.0 MeV for F^{6+}, respectively. Using high-resolution 0° Auger-electron spectroscopy,[11-14] the $1s2s2p\ ^4P$ projectile state was resolved and production cross sections were determined as a function of projectile energy. The $1s2s2p\ ^4P$ state cannot be produced by direct enE, since this would require a spin-flipping transition not possible for such low-Z ions. However, $1s \rightarrow 2p$ excitation can proceed to the ^4P state through eeE by the exchange[5] of the projectile electron with the exciting target electron. Thus, for the production of this state at collision energies above K_0^{eeE}, eeE should be distinguishable from enE.

In the present experiment, the production of the $^{16}O^{5+}$ and $^{19}F^{6+}$ $1s2s2p\ ^4P$ states above ~0.75 MeV/u was found to increase sharply with projectile energy, particularly for collisions with the H_2 target. The energy dependence of the thresholdlike behavior of the measured cross sections could be well described using calculated cross sections for eIE found in the literature, folded by the momentum distribution (Compton profile) of the target electrons. By accounting for the target electrons' "quasifree" nature in this way, we relate eIE, a free-electron-ion collision process, to that of eeE, an ion-atom collision process. This is analogous to the impulse-approximation treatment of resonance transfer excitation (RTE),[15] relating dielectronic recombination, another free-electron-ion collision process, to that of RTE occurring in ion-atom collisions. Our results constitute a direct measurement of $1s \rightarrow 2p$ excitation of an *ion* by an electron, information presently unavailable by existing electron-ion experiments.[16] Furthermore, eeE is a part of the more complex 2eTE process recently reported[17] in energetic $F^{8+} + H_2$ collisions. Thus, our direct observation of eeE further corroborates the evidence for 2eTE.

Doubly excited Li-like O^{5+} $(1s2s2l)$ and F^{6+}

$(1s2s2l)$ projectile (P) states were formed in a collision with a target T (He or H_2),

$$P(1s^2 2s) + T(1s) \rightarrow P(1s2s2l) + T$$
$$\hookrightarrow P(1s^2) + e^- \quad \text{(Auger decay channel)}.$$

The $1s2s2l$ autoionizing states can decay by ejecting an Auger electron which was detected with high resolution at 0° with respect to the beam direction.[11-14] The resulting target state was not determined. Experimental details have been reported[18-20] previously and are not presented here. The absolute efficiency for electron detection was determined by normalizing to previously measured Ne K-Auger cross sections[21] for 3-MeV p+Ne collisions, which we also measured in the same 0° geometry. In this Letter, we discuss only the production of the $1s2s2p\,^4P$ state for which the eeE process is best exemplified.[22]

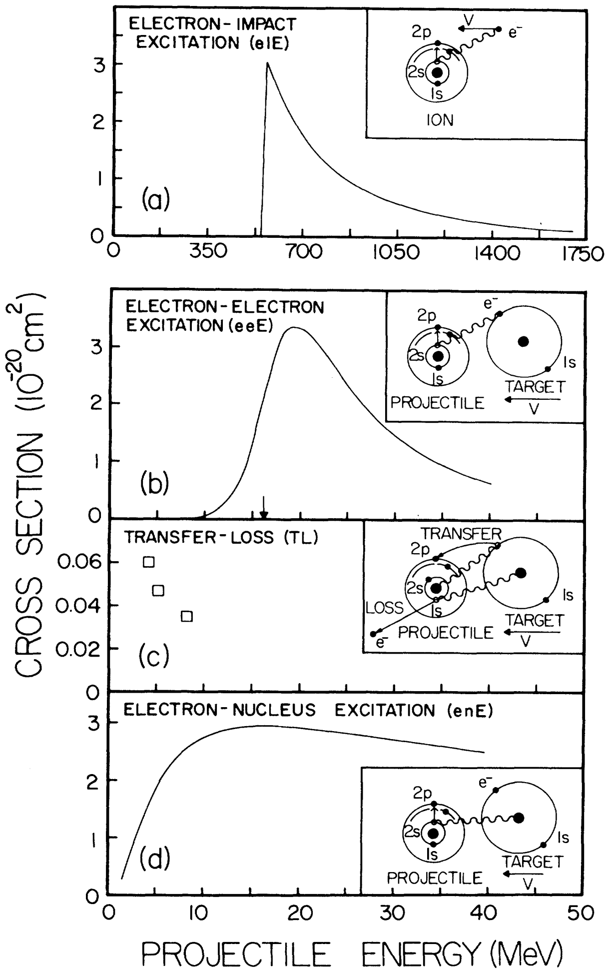

FIG. 1. Various O^{5+} $1s \rightarrow 2p$ electron excitation mechanisms as seen from the projectile frame, and their energy dependence. The wiggly line represents the Coulomb interaction. (a) $1s2s2p\,^4P$ state production by electron-impact excitation (Ref. 27). (b) $1s2s2p\,^4P$ state production due to interaction with a target electron. Equation (1) for a H_2 target was used in the cross-section calculation. Both eIE and eeE require electron exchange to give rise to ^4P states. (c) $1s2s2p\,^4P$ state production by transfer loss. The squares are the result of a coupled-change calculation (Ref. 23) for O^{5+}+H. An electron with the necessary spin must be captured to give rise to ^4P states. (d) $1s \rightarrow 2p$ excitation due to interaction with the target nucleus. Semiclassical calculation for H target. The production of ^4P states by this process is forbidden due to spin flip.

The most likely $1s \rightarrow 2p$ excitation mechanisms resulting in the production of a $1s2s2p$ configuration are shown schematically in Fig. 1, together with their expected energy dependence. In the production of the $1s2s2p\,^4P$ state, of interest here, enE [Fig. 1(d)] cannot contribute, since it is forbidden by spin-flip considerations.[7] In the case of eeE [Fig. 1(b)], the ^4P state can be formed if electron exchange[5] is included. Finally, in the case of transfer loss (TL) [Fig. 1(c)], the production of the ^4P state requires[7] the transfer of a target electron to the $2p$ projectile orbital with the simultaneous loss of a projectile $1s$ electron, resulting in a net $1s \rightarrow 2p$ excitation of the projectile. TL is expected to be less important at high velocities due to the rapid falloff of the capture cross section with increasing projectile energy. Preliminary calculations[23] [squares in Fig. 1(c)] have shown TL cross sections to be about 2 orders of magnitude smaller than the measured $1s2s2p\,^4P$ cross sections. Thus, only eeE remains a likely contributor at energies near and above the threshold projectile energy. Included for comparison [Fig. 1(a)] is the electron-impact excitation process and its dependence on the energy of the impinging free electron.

The production cross sections are displayed as a function of projectile energy in Fig. 2. The normalized electron yields were converted to production cross sections assuming the unresolved J sublevels of the ^4P state to be statistically populated and using calculated[24] Auger yields. In addition, the ^4P_J states are metastable and therefore the measured yield depends on their lifetimes.[25] Corrections for this effect resulted in an overall change of the measured yields by a factor of $\sim$0.9–1.2 depending on projectile velocity.

Electron-electron excitation should become important at projectile energies close to the threshold energy for eIE. The average $1s \rightarrow 2p$ excitation energy[24] $\Delta E_{1s\text{-}2p}$ is $\sim$560 and $\sim$721 eV for O^{5+} and F^{6+}, respectively, corresponding to a threshold projectile energy K_0^{eeE} equal to 16.3 and 25.0 MeV for O^{5+} and F^{6+}, respectively. We note in Fig. 2, that the cross sections for He and H_2 are approximately equal above these thresholds (marked with arrows in Fig. 2), as one would expect for eeE from targets with an equal number of electrons. In eIE, elec-

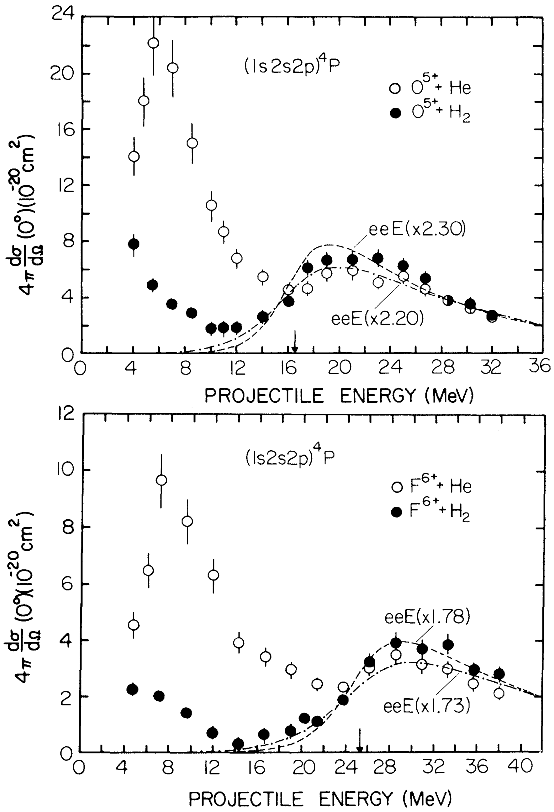

FIG. 2. Data: Cross sections for the production of $1s2s2p\,^4P$ states by $1s \rightarrow 2p$ projectile excitation in collisions of F^{6+} $(1s^2 2s)$ projectiles with He and H_2 targets vs projectile energy. Only statistical errors are shown. Total absolute error is $\sim$30%. Calculation: electron-electron excitation cross sections using $1s2s2p\,^4P$ theoretical electron-impact excitation cross sections (Ref. 27) folded by the Compton profile of the target [see Eq. (1) in text]. Dashed lines, calculated eeE for H_2 targets; dash-dotted lines, calculated eeE for He targets. Arrows (at 16.3 and 25.0 MeV), the projectile energy corresponding to the threshold for $1s \rightarrow 2p$ electron-impact excitation.

tron excitation is produced by *free*-electron-ion collisions. In the fast ion-atom collisions of interest here, eeE is produced by impact with *bound* target electrons. The He and H_2 electrons can be considered to be practically free, since their binding energies E_t (15.5 and 24.6 eV for H_2 and He, respectively) are much smaller than their average kinematic energies ϵ in the projectile frame. Thus the analogy to eIE is expected to hold and we can apply an impulse-approximation treatment[15] to eeE relating the cross section, σ_{eeE}, for excitation of ions in collisions with weakly bound target electrons to the eIE cross sections, σ_{eIE}, by

$$\sigma_{\text{eeE}}(K) = \int \sigma_{\text{eIE}}(\epsilon(p_z))J(p_z)dp_z\,, \tag{1}$$

where K, ϵ, and p_z, the electron momentum component due to its orbital motion around the target along the beam direction (z axis), are kinematically related by[15]

$$\epsilon(p_z) = \frac{m}{M}K - E_t + \left(\frac{2K}{M}\right)^{1/2} p_z\,. \tag{2}$$

Experimentally determined Compton profiles[26] for He and H_2 targets were used for $J(p_z)$. The eIE cross sections were taken from the Coulomb-Born-exchange calculations of Goett and Sampson[27] for O^{5+} and F^{6+} ions. Calculations of σ_{eeE} by Eq. (1) are also included in Fig. 2 for comparison. Good agreement is observed in the energy dependence over the entire high-energy region near and above threshold. The measured H_2 cross sections are slightly larger than the He cross sections due to the narrower Compton profile of the H_2 target. In absolute magnitude, the data are found to be larger than the calculation by a factor of $\sim$1.73–2.30. Integration over $J(p_z)$ spreads out the underlying sharp threshold of eIE [Fig. 1(a)].

We finally note that a more complicated two-step three-body interaction, in which the projectile is excited by enE followed by the exchange of the excited $2p$ projectile electron with a target electron, could also give rise to the ^4P state. We would expect such a two-step enE process to be much less probable than eeE, particularly at high velocities where the overall interaction time is limited. The eeE process (in the production of the ^4P state) involves only two electrons in a one-step mechanism, since the electron exchange is included directly in the antisymmetrization of the wave functions involved in calculating[27] σ_{eIE}. This is borne out by our data where at the higher projectile energies our calculations [Eq. (1)] for eeE seem to be in fair agreement with the data. On the other hand, this two-step enE process could be the main contributor at the lower collision energies, where the calculated TL cross sections[23] [Fig. 1(c)] were found to be much smaller than experiment. A fully correlated calculation of enE with exchange is difficult and has not been reported to date. More theoretical work is needed before the low-energy peak in the cross sections can be fully understood.

In conclusion, we have determined excitation cross sections for producing the $1s2s2p\,^4P$ state in 0.25–2-MeV/u collisions of O^{5+} $(1s^2 2s)$ and F^{6+} $(1s^2 2s)$ projectiles with He and H_2 targets. At high collision energies above $\sim$0.75 MeV/u, the excitation can be attributed to an interaction between the $1s$ projectile electron and a target electron. This process can be related to impact excitation of ions by free electrons on applying an impulse-approximation treatment to projectile excitation by weakly bound target electrons. Strong excitation threshold effects were observed, particularly in the case of H_2 targets. The energy dependence was well described by this model. The absolute magnitude of the measured cross sections was larger than theory by a factor of $\sim$1.73–2.30 depending on the collision system. By relating ion-atom excitation to electron-impact excitation, ion-atom measurements could possibly provide cross sections for inner-shell electron-impact excitation of ions for which there are presently no measurements.

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[25]The lifetimes τ_J used in correcting the measured yields were $\tau_{1/2}=9.2$ and 8.3 ns, $\tau_{3/2}=2.2$ and 0.95 ns [C. P. Bhalla and T. W. Tunnell, in *Inner-Shell and X-ray Physics of Atoms and Solids*, edited by D. J. Fabian, H. Kleinpoppen, and L. M. Watson (Plenum, New York, 1981), p. 285], $\tau_{5/2}=28.3$ and 16.2 ns (Bhalla and Tunnel, Ref. 24) for O^{5+} and F^{6+}, respectively.

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