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**ELECTRON TRANSFER AND K-SHELL EXCITATION IN SINGLE COLLISIONS OF  
47-365 MeV  $\text{Ca}^{17+}$  WITH Ne, Ar, AND Kr**

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**ABSTRACT**

Nous avons étudié la capture d'un électron et l'excitation de la couche K de la projectile dans des collisions uniques entre des ions de  $\text{Ca}^{17+}$  de 47 à 365 MeV dans le Ne, Ar, et Kr, par la mesure des rayons x K en coincidence avec la capture d'un électron. On trouve que ce processus à deux électrons se passe surtout par capture et excitation qui sont indépendentes; cela est le contraire de ce qu'on trouve dans une cible d'hélium, où la capture et l'excitation viennent de l'interaction entre les deux électrons.

The occurrence of electron capture and projectile K-shell excitation in single-collision events has been investigated by measuring K-x-ray emission coincident with single-electron capture for 47-365 MeV  $\text{Ca}^{17+}$  ions colliding with Ne, Ar, and Kr. The results indicate that this two-electron process takes place primarily due to independent capture and excitation events, in contrast to previous measurements for He targets which show that the capture and excitation arise from the electron-electron interaction.

Recent studies<sup>1-3</sup> have shown that electron transfer (capture) and projectile inner-shell excitation can occur together in a single encounter between an ion and an atom giving rise to the formation of a doubly-excited intermediate state. This excited state subsequently decays by either photon (x-ray) emission or electron (Auger) emission. The combined transfer and excitation can result from either electron-nucleus interactions or from electron-electron interactions. In the former case, independent particle interactions give rise to electron capture (projectile nucleus interacting with target electrons) and projectile excitation (target nucleus interacting with projectile electrons) in a single encounter. In general, this independent particle mechanism is expected to dominate the formation of the transfer-excitation process for energies where capture and excitation occur with comparable probabilities.

In addition, the electron-electron interaction can give rise to electron transfer and excitation via the inverse of an Auger transition. In this case the (weakly) bound target electrons are considered to be free relative to the fast moving ion thereby providing a "beam" of electrons in the projectile rest frame.

Hence, this latter process is resonant for relative velocities between the projectile and target which are equal to the velocities of outgoing electrons in the corresponding Auger transitions. This correlated electron mechanism can give rise to the same intermediate and final states as the independent particle interactions, so the two mechanisms, in general, compete with one another. The combined transfer and excitation mechanism due to the electron-electron interaction is called resonant transfer and excitation (RTE) while the independent particle process is called non-resonant transfer and excitation or NTE.

The existence of RTE and NTE have been clearly established in several studies,<sup>1-4</sup> showing that these processes can be distinguished and investigated separately. Furthermore, RTE and NTE are shown<sup>4</sup> to have nearly equal probabilities for some collision systems, such as  $^{16}\text{S}^{13+} + \text{He}$ . At first glance it might be expected that RTE should be a second order process, but when one considers that the Auger effect is a striking example of electron-correlation effects in isolated, excited atoms, it is, perhaps, not surprising that these same correlation effects manifest themselves in dynamic systems as well.

In addition to establishing the existence of RTE and NTE, the dependence of RTE on projectile atomic number<sup>5</sup> and charge state<sup>6</sup> have been measured. Little systematic information on these parameters is currently available for NTE, however. Furthermore, the target Z dependence of neither RTE nor NTE have been previously investigated.

In an effort to study RTE for heavy targets, as well as the relative importance of RTE and NTE in rather symmetric heavy-ion collisions and their respective contributions to K-vacancy production, we have measured K x-ray emission (following decay of the intermediate excited state) coincident with single-electron capture for 47-365 MeV  $\text{Ca}^{17+} + \text{Ne}$ ,  $\text{Ar}$ , and  $\text{Kr}$  targets. Results are compared with our previous measurements<sup>1</sup> for  $\text{Ca}^{17+} + \text{He}$  collisions.

The measurements reported here were conducted at Lawrence Berkeley Laboratory using the SuperHILAC facility. Projectiles in a given charge state pass through a differentially pumped gas cell. X rays produced in collisions with the target gas are detected with a Si(Li) detector mounted at  $90^\circ$  to the beam axis. The beam, after emerging from the gas cell, is magnetically analyzed into its charge-state components. Ions which undergo electron capture in the target gas are detected with a solid-state detector. The non-charge-changed component of the emerging beam is collected in a Faraday cup. Coincidences between K x rays and projectile ions which capture an electron are measured using a time-to-amplitude converter. The coincidence yields are measured as a function of gas pressure to obtain the desired cross sections and to ensure that single-collision conditions prevail.

The results of the coincidence measurements are shown in Fig. 1 for  $\text{Ca}^{17+} + \text{Ar}$  along with our previous results for  $\text{Ca}^{17+} + \text{He}$ . It is noted at once that the coincidence cross sections for the Ar target are found to be more than 10 times larger than those for the He target. Results obtained for the Ne and Kr targets were similar. Also shown in the figure are the calculated RTE cross sections for each of the targets. Since the RTE theory assumes the projectile velocity to be much greater than the bound target electron velocity, only those target electrons satisfying this condition were included in the calculations, namely the L- and M-shell electrons for Ar.

In the case of NTE, calculations<sup>7</sup> for  $\text{Ca}^{17+} + \text{He}$  indicate a maximum contribution to the coincidence cross section of about 5% from this process near 100 MeV with the NTE probability falling off rapidly for higher energies. No NTE calculations for targets heavier than He are currently available. Qualitatively, however, it is expected that the maximum NTE contribution for heavy targets will occur for beam energies higher than for the He target. This is because the projectile excitation generally has the same energy dependence for increasing target Z, but a larger magnitude, while the capture cross section does not decrease so steeply for targets heavier than He. Then, since the NTE cross section is roughly proportional to the product of the independent capture and excitation probabilities, the maximum NTE contribution is expected for higher beam energies for increasing target Z.

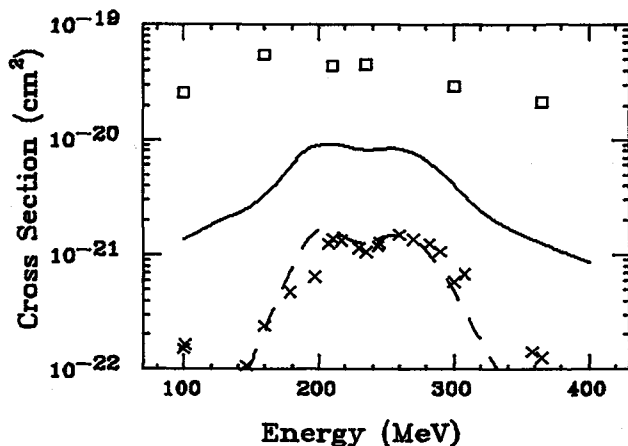


FIG. 1. Cross sections for K X-ray emission coincident with single-electron capture for  $\text{Ca}^{17+} + \text{He}$  and Ar collisions: crosses, He target; squares, Ar target. The dashed curve and the solid curve show the calculated RTE cross sections for He and Ar, respectively.

There is seen to be a large discrepancy (nearly a factor of 10) between the calculated RTE cross sections and the measured coincidence cross sections for the Ar target. (Again, the results for Ne and Kr targets are similar.) In all of the studies to date for x rays coincident with single capture involving He or  $\text{H}_2$  targets, good agreement (within  $\sim 25\%$ ) between the measured coincidence cross sections and the RTE theory is found. Based on these previous results for light targets and the large discrepancy between experiment and RTE theory observed for the heavy targets studied here, we are led to the conclusion that electron transfer and projectile excitation in single collisions is dominated by the independent particle NTE process for the heavy targets.

A qualitative physical basis for this conclusion can be argued. Since the experimental requirement that a K-excitation event occurs implicitly selects close collisions, it follows that the independent capture event also must take place primarily at small internuclear distances. In such collisions, electron capture from the inner, tightly bound target shells will be favored. (Even without the requirement of K-excitation, it is well-known that in high velocity collisions electron capture from the inner shells predominates.) Thus, it appears that the capture probability from the target inner shells is sufficiently large so that the two-step NTE process completely outweighs the one-step RTE process despite the anticipated increase in RTE due to the greater electron multiplicity in the outer shells of the heavy targets.

In summary, we have shown that combined electron transfer and projectile excitation in single collisions occurs with high probability in collisions of highly charged ions with targets heavy compared to He. Comparison with expectations based on electron-correlation effects (RTE) indicates that the transfer and excitation result primarily from independent particle interactions. This is contrary to results obtained with light targets (He and  $\text{H}_2$ ) for which the electron-electron interaction dominates the transfer-excitation process. The results point to the need for theoretical work in describing these two-electron interactions in heavy, symmetric collisions.

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1. J.A.Tanis, E.M.Bernstein, W.G.Graham, M.Clark, S.M.Shafroth, B.M.Johnson, K.W.Jones, and M.Meron, Phys. Rev. Lett. 49, 1325 (1982); J.A.Tanis, E.M.Bernstein, W.G.Graham, M.P.Stockli, M.Clark, R.H.McFarland, T.J.Morgan, K.H.Berkner, A.S.Schlachter, and J.W.Stearns, Phys. Rev. Lett. 53, 2551 (1984).
2. D.J.McLaughlin and Y.Hahn, Phys. Lett. 88A, 394 (1982).
3. D.Brandt, Phys. Rev. A27, 1314 (1983).
4. J.A.Tanis, E.M.Bernstein, M.W.Clark, W.G.Graham, R.H.McFarland, T.J.Morgan, B.M.Johnson, K.W.Jones, and M.Meron, Phys. Rev. A31, 4040 (1985).
5. J.A.Tanis, E.M.Bernstein, C.S.Oglesby, W.G.Graham, M.Clark, R.H.McFarland, T.J.Morgan, M.P.Stockli, K.H.Berkner, A.S.Schlachter, J.W.Stearns, B.M.Johnson, K.W.Jones, and M.Meron, Nucl. Instrum. Meth. Phys. Res. B10/11, 128 (1985).
6. J.A.Tanis, E.M.Bernstein, M.W.Clark, W.G.Graham, R.H.McFarland, T.J.Morgan, J.R.Mowat, D.W.Mueller, A.Muller, M.P.Stockli, K.H.Berkner, P.Gohil, R.J.McDonald, A.S.Schlachter, and J.W.Stearns, Phys. Rev. A34, 2543 (1986).
7. T.M.Reeves, J.M.Feagin, and E.Merzbacher, Proceedings of the 14th International Conference on the Physics of Electronic and Atomic Collisions, Abstracts of Contributed Papers, Palo Alto, California, 1985, eds. M.J.Coggiola, D.L.Huestis, and R.P. Saxon, p. 392.