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Evidence for uncorrelated electron capture and K-shell excitation in $S^{13+}+He$ collisions

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Evidence is presented for a two-step process in ion-atom collisions in which two independent interactions occur in a single encounter. Measurements for 15–200-MeV $S^{13+}+He$ collisions indicate that uncorrelated projectile K-shell excitation *and* capture of a target electron occur in a single collision with one target atom. The results are in reasonable qualitative agreement with theoretical predictions of this two-step process.

In single collisions between ions and atoms inner-shell vacancies may be created by one of three mechanisms: excitation, ionization, or charge transfer. Recent experimental studies[1,2] have provided strong evidence that two of these processes, excitation and charge transfer, can occur together as a correlated electron-electron process in a single encounter resulting in the formation of an intermediate excited state. The combined process is due to the interaction between a projectile electron and a (weakly bound) target electron in a manner analogous to the inverse of an Auger transition. Hence, resonant formation of intermediate states is expected for incident ion energies such that the target electron energy, in the rest frame of the ion, equals one of the Auger electron energies. Such resonant behavior has, in fact, been observed[1,2] by measuring x rays (resulting from the decay of the intermediate state) in coincidence with single electron capture. This process of *correlated* electron capture and projectile excitation followed by photon emission is called resonant transfer and excitation (RTE).[3] RTE is analogous to dielectronic recombination[4] (DR) except that for DR the captured electron is initially free instead of bound in a target.

A related question is whether or not electron capture by the projectile and projectile excitation can occur in an encounter with a single target atom by means of two separate *uncorrelated* interactions. The mechanisms involved in this case are electron-nucleus interactions (1) between the target nucleus and a projectile electron resulting in excitation and (2) between the projectile nucleus and a target electron resulting in electron capture. Such a combination of excitation and capture events is a two-step process which does not depend resonantly on the incident projectile velocity and hence has been given the name nonresonant transfer and excitation or NTE.[3,5] Experimentally, it is not possible to distinguish between an NTE event and an RTE event since the signature for both is a projectile x ray coincident with an ion which has captured an electron. In fact, the same intermediate states of the projectile may be formed in both processes. However, RTE can be distinguished from NTE and other competing processes since RTE has a resonant behavior. The existence of NTE is more difficult to determine since it must be distinguished from background events which, for example, can result from capture of an electron by the projectile prior to entering the target interaction region followed by excitation in the target itself. Experimentally, such background events have the same signature as RTE and NTE.

A formal theoretical treatment of simultaneous charge transfer and excitation in single collisions has recently been developed by Feagin, Briggs, and Reeves.[6] In this work separate amplitudes for the correlated and uncorrelated contributions to the capture plus excitation process are formulated. The calculations indicate that NTE and RTE can occur with comparable probabilities. Furthermore, it is predicted that the NTE probability exhibits a maximum in its energy dependence, but at a lower projectile energy than the RTE maximum. Qualitatively, this NTE maximum may be viewed as the result of the product of an increasing excitation cross section and a decreasing single electron capture cross section.

In this Rapid Communication we present evidence for the two-step process of uncorrelated projectile K-shell excitation and single electron capture in single collisions of $_{16}S^{13+}+He$. Measurements of sulfur K-shell x rays coincident with single capture events were made for energies of 15–200 MeV. The results are found to be in good qualita-

tive agreement with theoretical predictions. Experimental evidence for NTE has recently been obtained in ${}_{14}Si^{11+}+He$ collisions.[7]

This work was performed using the tandem Van de Graaff facility at Brookhaven National Laboratory. The accel-decel capability of the two coupled MP tandems was utilized in order to span the large energy range of S^{13+} ions required for the measurements. The remainder of the apparatus has been described elsewhere.[1] Briefly, the experimental technique for measuring x rays associated with electron capture is as follows. Projectiles in a given charge state pass through a differentially pumped gas cell. After emerging from the cell, the beam is electrostatically analyzed into its charge state components. Ions which undergo capture in the target gas are detected in a solid-state particle detector while the x rays are detected with a Si(Li) detector mounted at 90° to the beam. Coincidences between ions and x rays are measured with a time-to-amplitude converter (TAC). The non-charge-changed component of the emerging beam is collected in a Faraday cup. A capacitance manometer is used to measure the absolute pressure in the target gas cell. Data were obtained for 3–5 pressures in the range ~0–80 μm for each beam energy. The total x-ray yields and the coincidence yields were found to be linear with gas pressure in the range studied, indicating that single collision conditions prevailed.

Figure 1(a) shows the cross section for total projectile K x-ray emission, $\sigma_{K\alpha\beta}$, and the cross section for projectile K x rays coincident with single electron capture, $\sigma^{q-1}_{K\alpha\beta}$. Relative uncertainties in the data are generally less than ±3% for $\sigma_{K\alpha\beta}$ and less than ±5% for $\sigma^{q-1}_{K\alpha\beta}$. Systematic uncertainties due to x-ray detection efficiency, solid angle, and gas cell length lead to an overall uncertainty in the absolute cross section of about ±20%. It should be noted that $\sigma_{K\alpha\beta}$ could not be measured for energies < 25 MeV due to background x rays in the region of interest. On the other hand, measurements of $\sigma^{q-1}_{K\alpha\beta}$ could be made at lower energies since the coincidence requirement provides a selection criterion which virtually eliminates background events in the measurement of this yield.

From Fig. 1(a) it is seen that $\sigma_{K\alpha\beta}$ varies monotonically with beam energy while $\sigma^{q-1}_{K\alpha\beta}$ exhibits two widely separated maxima in its energy dependence. The maximum near 130 MeV is attributed to RTE while the low energy maximum near 30 MeV provides evidence for the two-step NTE process as discussed below. The dashed curve in Fig. 1(a) is the calculated[3] RTE cross section (multiplied by 0.85) which is seen to be in good agreement with $\sigma^{q-1}_{K\alpha\beta}$ in the RTE resonance region. This agreement between theory and experiment is consistent with other RTE results[2] for calcium and vanadium ions.

In order to determine the origin of the events giving rise to the maximum in $\sigma^{q-1}_{K\alpha\beta}$ at low energies, the contribution to $\sigma^{q-1}_{K\alpha\beta}$ due to background events must be considered. The primary source of these background events is expected to result from ions which capture an electron in the beam line prior to entering the target region followed by excitation of these ions in the target cell itself. The yield of these background events can be expressed in terms of an effective cross section $\sigma_{\rm bkg}=P^{bl}_{q-1}\sigma_{K\alpha\beta}$ where P^{bl}_{q-1} is the capture probability in the beamline and $\sigma_{K\alpha\beta}$ is the total K-shell x-ray emission cross section of the charged-changed ions in the helium target. P^{bl}_{q-1} is given by the measured fraction of ions which capture an electron with no helium present in

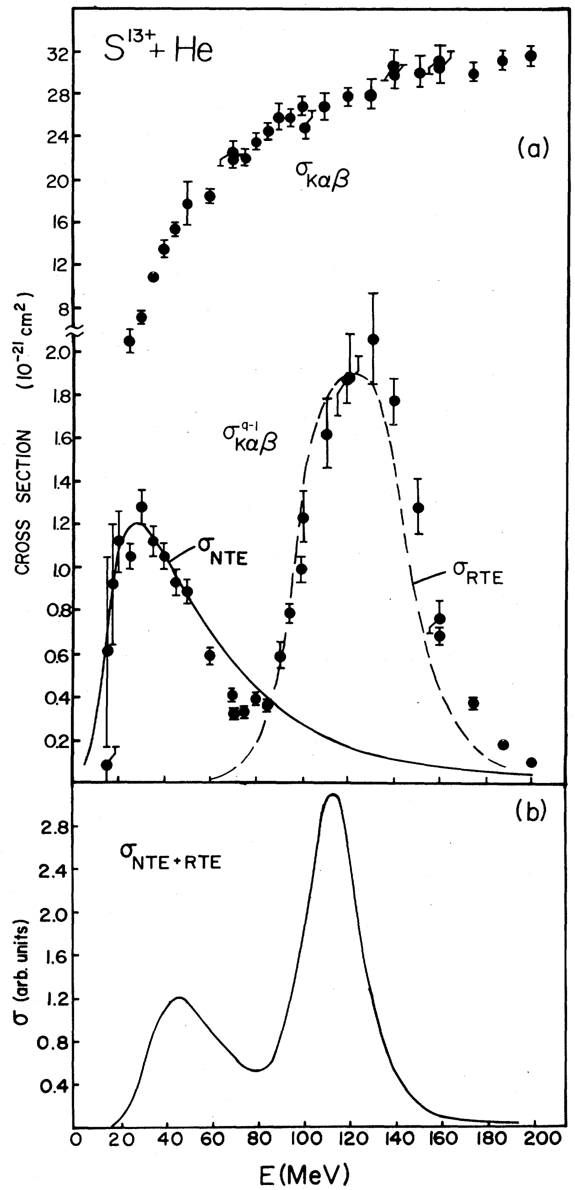

FIG. 1. (a) Projectile K x-ray cross sections for 15–200-MeV S^{13+} + He collisions. $\sigma_{K\alpha\beta}$ is the cross section for the total sulfur K x-ray production and $\sigma^{q-1}_{K\alpha\beta}$ is the cross section for sulfur K x rays coincident with single electron capture. The maximum in $\sigma^{q-1}_{K\alpha\beta}$ near 130 MeV is due to RTE and the maximum near 30 MeV is attributed to NTE. The dashed curve is the calculated (Ref. 3) RTE cross section multiplied by 0.85. The solid curve is the calculated (Refs. 8 and 9) NTE cross section normalized to the data. (b) Theoretical cross section (Ref. 10) for charge transfer accompanying K-shell excitation in single collisions of S^{13+} + He. The calculations include only the transitions $1s^22s\rightarrow 1s2s^22p$ and $1s^22s\rightarrow 1s2s2p^2$.

the target gas cell. These capture events are due to interactions with the background gas in the beam line. With helium present in the cell we observed no significant rise in the average beam line pressure for the range of target gas pressures used. P^{bl}_{q-1} varies from 1.5% at 20 MeV to 0.07% at 80 MeV. For $\sigma_{K\alpha\beta}$ we use the measured values for S^{13+} + He. Actually, values of $\sigma_{K\alpha\beta}$ for $q=12+$ ions

should be used, but these values will not be much different than those for $q=13+$ ions. Calculation of $\sigma_{\rm bkg}=P_{q-1}^{b1}\sigma_{K\alpha\beta}$ over the energy range of interest shows that $\sigma_{\rm bkg}/\sigma_{K\alpha\beta}^{q-1}$ varies from about 2% to 5%. Hence, it is concluded that at most 5% of the observed $\sigma_{K\alpha\beta}^{q-1}$ events can be accounted for from background events.

A qualitative theoretical prediction for the energy dependence of the two-step NTE process can be obtained from the product of the K-shell excitation cross section[8] and the probability for capture[9] to the L shell over impact parameters for which K-shell excitation is significant. The resulting product, labeled $\sigma_{\rm NTE}$ in Fig. 1(a), has been normalized to the data near 30 MeV. The reasonable agreement of this calculation with the energy dependence of $\sigma_{K\alpha\beta}^{q-1}$ in the range 20–70 MeV provides support for attributing the maximum near 30 MeV to NTE.

Figure 1(b) shows the calculations of Reeves and Feagin[10] based on the *ab initio* formulation of Ref. 6. These results, for the $1s^22s \rightarrow 1s2s^22p$ and $1s^22s \rightarrow 1s2s2p^2$ transitions only, include both the uncorrelated (NTE) and correlated (RTE) contributions to charge transfer and excitation in single collisions, and, hence, provide a theoretical prediction for $\sigma_{K\alpha\beta}^{q-1}$ for all energies. In the theory, the lower energy maximum arises from the uncorrelated amplitude (NTE) and the higher energy maximum arises from the correlated amplitude (RTE). There is substantial qualitative agreement between the theory and the measured $\sigma_{K\alpha\beta}^{q-1}$ for the positions of the two maxima and their relative heights. Owing to the difficulty of the theoretical calculations, reliable absolute cross section values are not yet available. Also, it is seen that the width of the RTE maximum in Fig. 1(b) is considerably narrower than the corresponding $\sigma_{K\alpha\beta}^{q-1}$ width in Fig. 1(a). This is expected since the two transitions mentioned above, involving solely the L shell, are the only ones which have been included in the calculations.[10] Inclusion of transitions to intermediate states involving the M and higher shells would broaden the theoretical peak and move it slightly higher in energy.

On the basis of the comparison of the measured $\sigma_{K\alpha\beta}^{q-1}$ with the two theoretical predictions it is concluded that the maximum near 30 MeV is due to uncorrelated electron capture and K-shell excitation in single collisions. Furthermore, the results indicate that the nonresonant contribution to $\sigma_{K\alpha\beta}^{q-1}$ is small in the resonance region near 130 MeV. This is in contrast with previous results[1] for $S^{13+}+Ar$ in which the nonresonant part of $\sigma_{K\alpha\beta}^{q-1}$ was about equal to the resonant part in the resonance region. In the work of Ref. 5 for $F^{8+}+He$, Ne, and Ar, the NTE contribution to $\sigma_{K\alpha\beta}^{q-1}$ was apparently so large that no resonant behavior due to RTE could be observed. For ${}_{20}Ca^{17+}$ and ${}_{23}V^{20+}$ ions incident on He it is predicted[10] that the NTE contribution to $\sigma_{K\alpha\beta}^{q-1}$ is small (<0.1) in the resonance region. This is consistent with the experimental results for these ions.[2]

In summary, experimental evidence for a two-step process involving electron capture and K-shell excitation (NTE) in single collisions of ions and atoms has been presented. Furthermore, the present results indicate this process can account for as much as 15% of all the K-shell excitation events at certain energies, thereby requiring that NTE be included in a complete description of K-shell excitation.

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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).

[2]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).

[3]D. Brandt, Phys. Rev. A **27**, 1314 (1983).

[4]J. B. A. Mitchell, C. T. Ng, J. L. Forand, D. P. Levac, R. E. Mitchell, A. Sen, D. B. Miko, and J. Wm. McGowan, Phys. Rev. Lett. **50**, 335 (1983); D. S. Belic, G. H. Dunn, T. J. Morgan, D. W. Mueller, and C. Timmer, *ibid.* **50**, 339 (1983); P. F. Dittner, S. Datz, P. D. Miller, C. D. Moak, P. H. Stelson, C. Bottcher, W. B. Dress, G. D. Alton, N. Neskovic, and C. M. Fou, *ibid.* **51**, 31 (1983).

[5]P. L. Pepmiller, P. Richard, J. Newcomb, R. Dillingham, J. M. Hall, T. J. Gray, and M. Stockli, IEEE Trans. Nucl. Sci. **NS-30**, 1002 (1983).

[6]J. M. Feagin, J. S. Briggs, and T. M. Reeves, J. Phys. B **17**, 1057 (1984).

[7]M. W. Clark, D. Brandt, J. K. Swenson, and S. M. Shafroth, Phys. Rev. Lett. **54**, 544 (1985).

[8]T. McAbee, Nucl. Instrum. Methods Phys. Res. Sec. A **214**, 89 (1983).

[9]D. Brandt, Nucl. Instrum. Methods Phys. Res. Sec. A **214**, 93 (1983).

[10]T. M. Reeves and J. M. Feagin (private communication).