Separated Resonances in Simultaneous Capture and Excitation of S^{15+} in H_2 Observed by *K*-X-Ray–*K*-X-Ray Coincidences

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We have measured cross sections for the correlated emission of two *K* x rays following the collision of hydrogenlike sulfur ions with H_2 in the energy range between 70 and 160 MeV. The observation of the two correlated x rays is interpreted as a resonant capture of a target electron accompanied by simultaneous excitation of the projectile in the collision (RTE). By our distinguishing between $K\alpha$ and $K\beta$ lines, contributions from *KLL* and *KLn* ($n \geq M$) resonances could be determined independently.

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In recent years much effort has been invested in studies of dielectronic recombination (DR)[1-4] in electron-ion collisions. This process can be pictured as the time reversal of an Auger transition whereby a continuum electron excites a bound electron of an ion charge state $q+$ and is simultaneously captured into a doubly excited state of the resulting ion in charge state $(q-1)+$. The decay of the so-formed doubly excited state through the emission of a stabilizing photon accomplishes the recombination. Both theory and experiment agree that DR leads to very sharp resonances in the simultaneous capture and excitation cross section as functions of the electron kinetic energy. In ion-atom collisions a related process, resonant transfer and excitation (RTE), has been shown to occur by Tanis and collaborators.[5] In the impulse approximation for the RTE process[6] the target atom is regarded as a source of quasi free electrons with kinetic energy $(m_e/m_p)E_p$ in the projectile rest frame (where m_e is the electron mass, m_p is the projectile mass, and E_p is the projectile kinetic energy in the laboratory frame). The momentum distribution of the bound target electrons leads to a broadening of the DR resonances governed by the Compton profiles of these electrons. Interest in these phenomena arises from various sources, such as, for example, the understanding of the role played by electron correlations in atomic collisions, the study of astrophysical plasmas,[7] fusion research,[8] and lately, with the design and construction of heavy-ion storage rings, also accelerator physics. For the latter, DR is expected to play an important role in the planned electron cooling regions.[9]

RTE experiments done to date have dealt mostly with many-electron projectiles (Li-like or higher).[5] On the other hand, H-like projectiles are of large interest in that they offer maybe the best case for RTE studies. For this type of projectile one has the smallest multiplicity of the doubly excited states that can be populated through RTE. The energetic separation between these states is at its largest and therefore one expects to see, to a given extent, contributions from isolated resonances even in spite of the wide Compton profiles that one is confronted with. Experiments to study x-ray emission following RTE with H-like projectiles have up to now explored two different methods. High-resolution spectroscopy was performed for *F* projectiles and did not lead to positive results.[10] *K*-x-ray–charge-changed-projectile coincidences[5] have recently been extended to H-like Ca ions[11] and RTE was observed. Those resonances were, however, superimposed on a large background from pure electron capture to excited states that decreases with increasing projectile energy. The method presented here extends and complements that of Ref. 11, allowing RTE for H-like ions to be investigated in greater detail.

In this work we investigate the correlated emission of two *K* x rays following collisions of H-like sulfur ions with H_2. Here we use the fact that the radiative stabilization (required by DR) of the doubly excited two-electron ion produced by RTE decays necessarily into the *K* shell. In other words, the signature of RTE for collisions of H-like projectiles and atoms is the emission of two correlated *K* x rays. Events characterized by the same signature could arise from the competing process known as nonresonant transfer and excitation (NTE)[5]; however, this process is of importance only at projectile energies that are much lower (≈ 30 MeV) than the ones employed here, and we will neglect it in what follows. The choice of the H_2 target gas is dictated by the constraints of having the narrowest possible Compton profile, and of avoiding uncorrelated capture and excitation through multiple collisions.

In the present experiment beams of S ions with energies between 70 and 156 MeV from the MP tandem accelerator of the Max-Planck-Institut für Kernphysik in Heidelberg were post stripped to charge state 15+ (H-like) and made incident upon a gaseous H_2 target. Before entering the target region the beam was magnetically steered by approximately 10° in order to reduce contamination by projectiles that have captured electrons from the background gas in the beam line. After being collimated down to 2 mm×2 mm the beam entered a triply differentially pumped gas cell filled with H_2. The target-gas pressure was measured with a capacitance manometer. The gas cell was so constructed that even at the highest employed pressure of 40 mTorr only a negligible increase of the background pressure in the beam line was observed. Sulfur K x rays emitted from the 5-mm-long collision region were detected by two Si(Li) detectors mounted at right angles to the incident beam. A time-to-pulse-height converter (TAC), started by counts in one of the x-ray detectors and stopped by counts in the other, determined the time correlation between the two K x rays. The beam was stopped in a Faraday cup where the deposited charge was measured for normalization.

We show in Fig. 1 a two-dimensional spectrum taken at 140 MeV collision energy where each event is represented by the energies of the two detected x rays. This spectrum was obtained under the requirement that the two x rays are time correlated, i.e., for events in the time peak of the TAC spectrum. The arrows in Fig. 1 indicate the positions of the hypersatellite, $K\alpha^h$ and $K\beta^h$, and satellite, $K\alpha^s$ and $K\beta^s$, transitions for each detector calculated with a Hartree-Fock program.[12] In this figure one can clearly identify three "islands," one corresponding to two $K\alpha$ transitions, and two for detection of a $K\alpha$ and a $K\beta$ (or higher, e.g., $K\gamma$) x ray. One may also notice that practically no events can be observed in this figure for two $K\beta$ x rays.

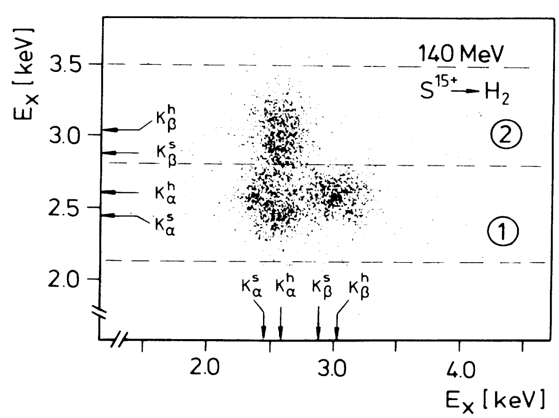

FIG. 1. Two-dimensional x-ray–x-ray spectrum for time correlated events. The arrows indicate the energies for hypersatellite and satellite $K\alpha$ and $K\beta$ transitions. Regions marked 1 and 2 were projected onto the x axis to give the one-dimensional spectra of Fig. 3.

In order to ensure single-collision conditions we performed measurements at different target-gas pressures and found that the integrated intensity of these event areas shows a clear linear dependence with pressure. Therefore the two time-correlated x rays observed are emitted after single collisions in the gas target. This leads to the conclusion that the physical process responsible for this x-ray emission is one where capture of one target electron into a projectile excited state takes place simultaneously with the excitation of the single projectile K electron in S^{15+}. After the collision the first radiative decay takes place always in the presence of an empty K shell, leading therefore to a hypersatellite x ray, while the second decay must lead to a satellite x ray. In our data some indication for such a behavior can be seen. We present in Fig. 2 a similar two-dimensional spectrum as that of Fig. 1 but obtained by selection of (uncorrelated) events that fall outside the TAC time peak. One notices that the islands in this figure are more evenly distributed relative to their counterparts in Fig. 1. This is because the uncorrelated events come mainly from detection of two satellite or hypersatellite K x rays following single capture or excitation, respectively, of two independent projectiles. Closer inspection of Fig. 1 shows, to the extent allowed by the energy resolution of the x-ray detectors, that the time-correlated events seem to concentrate around the loci predicted for events of the type, e.g., $K\alpha^h$-$K\alpha^s$ in the $K\alpha$-$K\alpha$ island whereas those of Fig. 2 do not show this feature. It is also important to note that $K\beta$-$K\beta$ events can be clearly identified in Fig. 2, whereas they are obviously strongly suppressed in the case of correlated events (Fig. 1).

The data analysis proceeded first of all by projection of the two-dimensional regions indicated in Fig. 1 onto the x axis. This was done not only for the case of time-correlated events but also for uncorrelated events. The latter were used for subtraction of accidental coincidences from the data. The ratio of correlated to uncorrelated events varied between 2:1 and 30:1 depending on the beam energy. The true coincident K-x-ray spec-

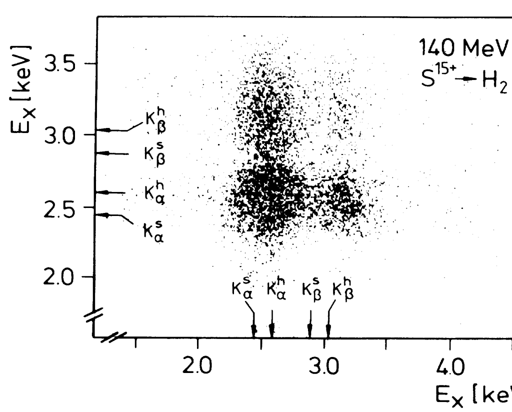

FIG. 2. Same as Fig. 1 for uncorrelated events.

tra so obtained (from region 1 of the respective two-dimensional spectra) are shown in Fig. 3 for 110- and 140-MeV collisions. Also presented in Fig. 3 are the corresponding singles spectra. The singles spectra show virtually no change of spectral shape with collision energy, whereas the true coincident spectra show dramatic differences. Here one observes that at 110 MeV only an almost negligible amount of $K\beta$ x rays are emitted while, at 140 MeV, the $K\beta$ intensity almost equals that of the $K\alpha$ line. In fact, since half of the $K\alpha$-$K\beta$ intensity is not shown in this spectrum (since it comes from region 2 in Fig. 1), the true coincident $K\beta/K\alpha$ intensity ratio is actually greater than 1 for 140-MeV collisions. This indicates already that the process leading to the doubly excited states in these collisions is not only very sensitive to the collision energy but also selective in the intermediate states populated.

The true coincident K-x-ray spectra were fitted by Gaussian functions (full and dashed lines in Fig. 3) for obtaining integrated $K\alpha$ and $K\beta$ intensities. These were normalized by the charge deposited in the Faraday cup and corrected for solid angles and detector efficiencies. The so-obtained normalized K-x-ray yields were finally scaled for the target thickness at the different target-gas pressures employed to give the correlated K-x-ray emission cross sections, σ_{xx}.

Figure 4 shows a plot of σ_{xx} as function of the collision energy E for the three types of x-ray transitions investigated here. In Fig. 4 the solid points are the cross sections for the correlated emission of $K\alpha^h$-$K\alpha^s$ x rays ($\sigma_{\alpha\alpha}$); the crosses, $K\alpha^h$-$K\beta^s$ and $K\beta^h$-$K\alpha^s$ ($\sigma_{\alpha\beta}$); and the open points, $K\beta^h$-$K\beta^s$ ($\sigma_{\beta\beta}$). The error bars shown in this figure represent statistical errors only. The absolute scale is estimated to be accurate to within 50%. The lines drawn through the points are guides for the eye only. The different behavior shown by these cross sections as a function of the projectile energy is evident. The $\sigma_{\alpha\alpha}$ cross section shows a maximum around 107 MeV (≈ 24 MeV FWHM) that rises by about two orders of magnitude over the value measured at 70 MeV. After passing through a minimum near 125 MeV a second, less intense maximum (≈ 33 MeV FWHM) is observed around 140 MeV. In the energy range of the present experiment $\sigma_{\alpha\beta}$ shows a single maximum (≈ 27 MeV FWHM) around 140 MeV. This maximum is higher than those in $\sigma_{\alpha\alpha}$ and also orders of magnitude larger than $\sigma_{\alpha\beta}$ at lower energies. Finally, one finds that $\sigma_{\beta\beta}$ remains small over the whole energy range measured, showing only a small increase starting at approximately 130 MeV.

The strong projectile-energy dependence of these cross sections suggests that the correlated emission of two x rays in these collisions can be attributed to RTE. The various event types can be identified as follows (in what follows we use Auger notation): (i) $K\alpha^h$-$K\alpha^s$ events are produced when the projectile electron is excited to the L shell while simultaneously capture takes place also into this shell, i.e., a KLL state. A second possibility is that KLn ($n > 2$) state is populated and the higher-shell electron cascades down into the L shell; (ii) $K\alpha^h$-$K\beta^s$ and $K\beta^h$-$K\alpha^s$ events correspond to KLn ($n > 2$) states; (iii) $K\beta^h$-$K\beta^s$ events correspond to Knm ($n,m > 2$) states.

The arrows in Fig. 4 indicate the energies where one expects resonances in the RTE cross section for population of different intermediate states. The arrows between 105 and 108 MeV show the resonance energies for KLL states, the ones around 132 MeV those for KLM states, and the arrows above 140 MeV, KLn ($n > M$) states. The positions of the expected resonances for population of KLL states agree perfectly with the maximum in the data of $\sigma_{\alpha\alpha}$ at around 107 MeV. Comparing the second maximum in $\sigma_{\alpha\alpha}$ and the maximum in $\sigma_{\alpha\beta}$ with the reso-

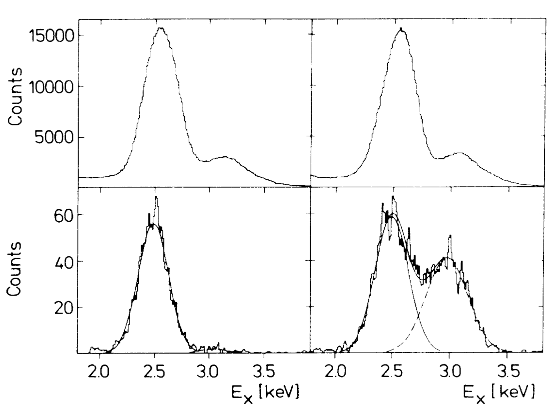

FIG. 3. X-ray spectra for 110-MeV (left) and 140-MeV (right) collisions. The time-correlated spectra (region 1 of Fig. 1) are shown on the bottom. Corresponding singles spectra are shown above. The lines are fits with Gaussian functions.

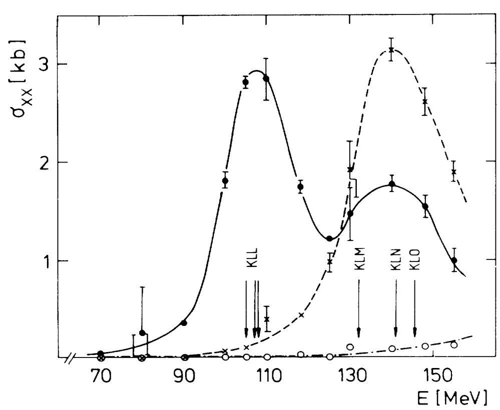

FIG. 4. Cross sections for the correlated emission of two K x rays as function of the collision energy: $K\alpha$-$K\alpha$, solid dots; $K\alpha$-$K\beta$, crosses; and $K\beta$-$K\beta$, open dots. The arrows indicate the predicted positions of various resonances. The lines are guides for the eye only.

nance energies for population of KLn ($n \geq M$) states we see that most of this cross section comes from population of intermediate states with n higher than M. This indicates that the cascading mentioned above may contribute strongly. The drift length seen by the Si(Li) detectors allowed for cascading times between 170 and 250 psec depending on the beam energy. We estimate on the basis of Ref. 1 that this time is long enough for observation of cascades from states as high as $n \approx 20$. High Rydberg states are known to play an important role in DR for weakly charged ions.[13] The present results may be an indication that RTE for highly charged ions is also influenced by intermediate highly excited states. In this context we should also point out one further advantage of the present method. Since the final projectile charge state is not analyzed (and therefore field ionization of the projectile is of no concern) we are not limited, in principle at least, to detection of RTE into low-lying states as in the case of photon-particle coincidences. Finally, the population of states Kmn with $m,n \geq M$ at the beam energies employed here is suppressed, as seen from $\sigma_{\beta\beta}$. Indeed for these states resonances are only expected at energies larger than 160 MeV.

A comparison of these results with predictions of the model of Brandt[6] by use of the DR cross sections of McLaughlin and Hahn[14] and Compton profiles from Eisenberger[15] shows agreement in the order of magnitude of the cross sections. Since the DR cross sections of Ref. 14 are calculated for Li-like S, a more detailed comparison is of dubious value. This is because of the large difference in multiplicities between four-electron and two-electron intermediate configurations. A detailed comparison of the present results with theoretical predictions using correct configurations deserves further investigation.,

In conclusion, we have seen strongly correlated double K-x-ray emission from H-like S ions after single collisions with H_2. These are interpreted as due to RTE, i.e., the resonant transfer of a target electron with simultaneous excitation of the electron bound in S^{15+}. Two separate resonance groups were excited in the beam energy range investigated, KLL and KLn ($n \geq M$). The observed inversion of the $K\alpha$ and $K\beta$ line intensities shows the selectivity of this process. It is also demonstrated in this work that x-ray–x-ray coincidences provide a new powerful tool for the investigation of RTE and therefore also of dielectronic recombinations in the cleanest system of one-electron ions.

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