Observation of Radiative Electron Capture into K, L, M Shells of 25-MeV/u Xe^{53+} Ions Channeled in Silicon

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We present experimental results showing that channeling measurements with fast stripped heavy ions incident on thin crystals can allow a detailed study of radiative electron capture. Charge-state measurements and photon-energy spectra have been used to deduce cross sections of radiative capture into the K, L, and M shells of 25-MeV/u Xe^{53+} ions. The orientation dependence of the positions and shapes of associated photon lines has been observed.

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We report on the new features observed in the study of the charge-exchange process of fast H-like xenon ions channeled in a thin silicon crystal. The simultaneous study of the charge state of the transmitted Xe ions and of the x rays they radiate has lead to the following results: (i) Channeled particles appear to be essentially "frozen" in their initial 53^+ charge state (a feature already observed by Datz *et al.*[1] with lighter ions), while the mean charge state for nonchanneled particles is 49.5. (ii) In the x-ray spectrum, strong, or at least well resolved, lines show up that are due to radiative electron capture (REC) into the K, L, and M shells of channeled projectiles. Both results are due to the fact that REC is the only capture process available for channeled particles, as nonradiative capture, which is by far dominant[2] for nonchanneled Xe ions of the energy used here, is excluded like any other low-impact-parameter process. This type of experiment has been undertaken by Appleton *et al.*,[3] who have obtained information on K-REC cross sections and have shown that the line shape could be explained by the velocity distribution of target electrons, as suggested by Schnopper *et al.*[4] who first observed REC. The swift heavy ions used in our experiment have great advantages; K, L and M REC can be studied precisely, and the cross sections have been measured and compared with theoretical predictions. The line shapes appear very clearly and can be analyzed in great detail. This will be done in a forthcoming paper. Moreover the joint study of charge states and REC intensity shows that electron capture by channeled particles is completely accounted for by REC.

We used 25-MeV/u Xe^{53+} ions delivered at Grand Accélérateur National d'Ions Lourds (GANIL) in the LISE beam line, which provided a beam of angular divergence lower than 0.5 mrad. Before reaching the crystal, the beam passes through a rotating chopper used for beam monitoring. The chopper blades are covered with silver and the Ag x-ray yield is measured by a Si-Li x-ray detector. The crystal, a 17-μm-thick (111) Si crystal of area about 1 cm^2, is viewed by a solid-state Ge detector positioned at 90° to the beam. The transmitted ions are charge and energy analyzed by a magnetic spectrometer associated with a wire chamber (the angular acceptance allows the detection of all the particles). The experiment has been performed around the ⟨110⟩ axial direction.

The charge-state measurements are performed as follows: The electric charges collected on each wire are integrated over an adjustable time. The multiplexer output is displayed on an oscilloscope and photographed. By stepping the intensity in the magnet we obtained the energy-loss spectrum associated to each charge state and the charge-state distribution. For a random crystal orientation all transmitted ions have lost nearly the same energy and the various charge states give regularly spaced Gaussian peaks of constant width. In axial alignment the data analysis is more difficult because channeled ions present a broad range of energy losses. The normalized charge-state distributions for random and ⟨110⟩ crystal orientations are given in Fig. 1. The first one has a regular shape that reflects charge-state equilibrium (mean charge 49.5). In the case of ⟨110⟩ alignment 80% of the incident 53^+ ions emerge in their initial charge state. The absence of 54^+ ions in the distribution

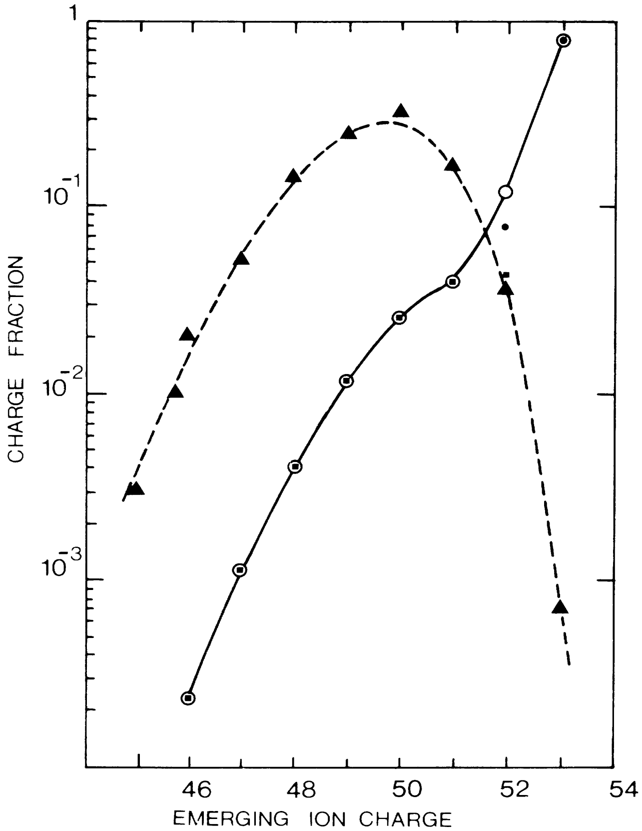

FIG. 1. Charge-state distributions measured for 25-MeV/u Xe^{53+} projectiles transmitted a path length of 21 μm through a Si crystal for random orientation (triangles) and for ⟨110⟩ alignment (open circles). In the latter case, the two separate contributions of well channeled particles (filled circles) and of the other particles (squares) are given.

shows that K-shell ionization is very unlikely. Thus the emerging 53^+ ions have certainly kept their initial charge state all along their path. These ions are all well channeled, as demonstrated by their most probable energy loss, which is 51% of the random energy loss. As the stopping cross section is proportional to the square of the ion charge, the energy loss of these ions is only 45% of the random energy loss that would be associated to ions of same charge, in very good agreement with extrapolation from lower-velocity data. The fraction of emerging 52^+ ions is 12%. Two-thirds of them have an energy spectrum similar to the 53^+ spectrum and hence are well channeled. The last third has an energy loss slightly smaller than random. These ions are channeled but with a relatively large transverse energy and will be called "poorly channeled" hereafter. The energy loss of the ions emerging with a charge state lower than 52 indicates that they are either nonchanneled or poorly channeled. The nonchanneled fraction (if one considers charge exchange) is measured to be 2% as obtained from the low-charge-state tail of the distribution which appears as a replica of the random distribution. The well channeled fraction (if one considers energy loss) is 88% (80% 53^+ and 8% 52^+). The remaining 10% fraction corresponds to the poorly channeled particles having an almost random energy loss but an electron-capture probability smaller than random particles, as demonstrated by their charge distribution.

In Fig. 2 we show the x-ray spectra obtained in the Ge detector for random and ⟨110⟩ orientations, for the same number of incident particles as measured by the chopper. We first consider the random-orientation spectrum, dominated by the Xe Lyman series. The two small peaks at 18 and 24 keV are due to an escape effect from the Ge detector in the detection of Lyman photons. Three other small and broader peaks (called K, L, and M REC, respectively) can be observed. They correspond to radiative electron capture into K, L, and M shells of the projectiles and are located at energies $E_n \simeq E_l(n) + (m/M)E_0$ where n and $E_l(n)$ are the principal quantum number and the binding energy of the shell, m is the electron mass, and M and E_0 are the projectile mass and energy. The K-REC contribution is small because the first capture that fills the single K vacancy is most often a nonradiative event, and also because, at equilibrium, the K shell is almost always filled. Lyman x-ray emission results not only from direct excitation of Xe ions but also from the electron-capture process itself. We know from measurements by Meyerhof *et al.*[2] and from predictions by Gayet and Salin[5] that nonradiative electron capture occurs almost only into excited states, and also that the K-REC contribution is small. Thus the mean number of Lyman x rays emitted by an incident 53^+ ion should be equal to one plus the corresponding number for a 52^+ ion (which results from K-shell excitation and ionization only). This has allowed us to obtain an absolute fluence measurement for the very weak incident 53^+ beam, by comparison with the case of 52^+ for which the beam intensity can be measured electrically. Following Ref. 4 we have assumed in our case a $\sin^2\theta_{lab}$ law for the Lyman emission resulting from a capture event.

The spectrum obtained for ⟨110⟩ alignment is quite different: The continuum and the Lyman lines are much lower whereas strong REC peaks appear, the most intense being the K REC one. The Lyman intensity (11% of the random value) cannot be accounted for by only the unchanneled part of the aligned beam (2%), but is also due to electron capture by poorly channeled particles and may be due to well channeled particles through L and M REC and subsequent Lyman emission if the transition is allowed.

The L- and M-REC intensities are observed to be about the same as in random conditions although they appear more clearly in the spectrum as a result of the decrease of bremsstrahlung. In contrast, the K-REC intensity is markedly larger, due to the fact that most of the incident 53^+ ions (90% when averaged over the path

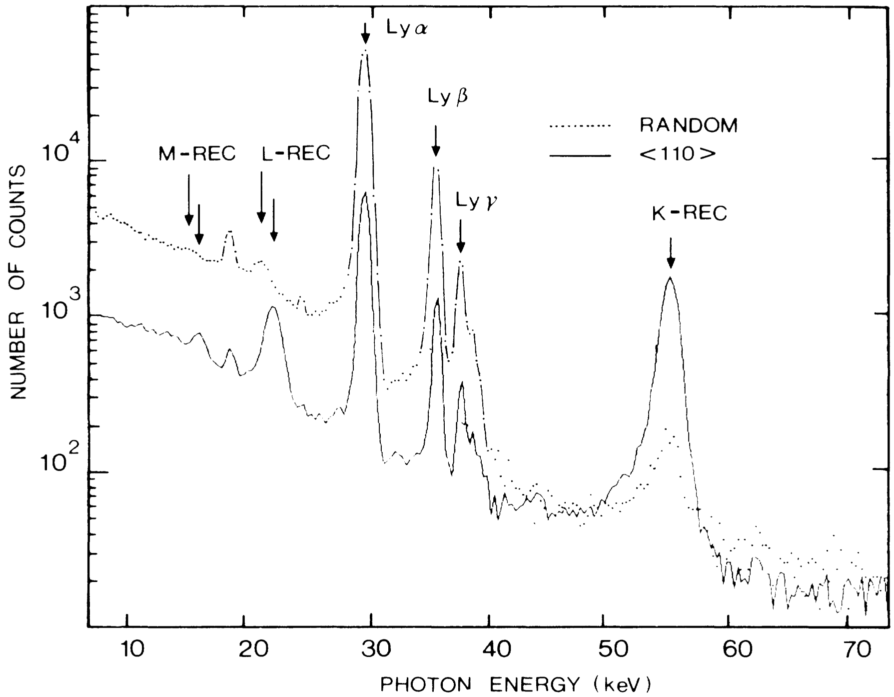

FIG. 2. X-ray spectra obtained in the Ge detector for the same amounts of Xe^{53+} ions incident on the Si crystal in random conditions and for ⟨110⟩ alignment.

length) are hydrogenlike in the crystal and then are capable of capturing a target electron into their K shell. The electron density sampled by well-channeled particles arises mainly from valence electrons. Neglecting other contributions we have deduced REC cross sections per target valence electron for well-channeled 53^+ ions and compared them with the values predicted[6] for a bare ion. Following Spindler, Betz, and Bell,[7] we have considered a $\sin^2\theta_{lab}$ angular distribution for K-REC photons. We have also assumed that L and M REC follow the same law, which is questionable[8] but seems to be confirmed by recent calculations.[9] We find 217, 106, and 17 b (estimated uncertainty 20%) for REC into the K, L, and M shells, respectively, whereas the calculated values for the bare ion are 400, 130, and 50 b. Because of the Pauli principle the K-REC cross section must be smaller by about a factor of 2 for 53^+ (our case) than for 54^+ ions (calculated values). The agreement looks satisfactory for K and L REC but is probably poorer if one considers a possible capture of L target electrons, which can be found rather far from the atomic rows.

The measured number of REC events per incident ion in alignment conditions, 0.125, is somewhat higher than the fraction of well channeled ions having captured an electron (8%). Then the REC yield can account both for all the captures by well channeled ions and, to a lower extent, for captures by poorly or nonchanneled ions.

In Fig. 3 we show the orientation dependence of some of the parameters related to the K and L REC lines, the area, the mean energy, and the width of the peaks, and also of the Ly-α yield, in order to scale our data with a low-impact-parameter process. The L-REC yield varies very little whereas the K-REC variation is large. We know that the REC yield mainly reflects the mean number of available projectile vacancies. This number, for K REC, is close to unity for alignment and, in "random" cases, depends mainly on the mean free path for a nonradiative capture.[10] K- and L-REC yields present a maximum for a tilt angle of the order of the half-width of the Lyα dip. The reason is that REC is sensitive to the mean electron density sampled by the projectile. The maximum results from the opposite variations of the sampled electron density and of the number of projectile vacancies available for REC events.

The mean energies of REC photons are also observed to be sensitive to orientation and present a maximum for exact alignment. In Fig. 3(b) we show the L-REC case for which the effect is larger than for K REC (the shifts between the peak energies of M and L REC for axial and random orientation, respectively, can be seen on Fig. 2). This can be explained as follows: The photon energy depends on the initial binding energy of the target electron to be captured and on its final binding energy in the projectile. In channeling conditions, only loosely bound electrons can be captured and the REC photon energy is maximum. Moreover, the final binding energy for a given shell depends on the projectile charge state and is then higher in channeling conditions for the L (and M)

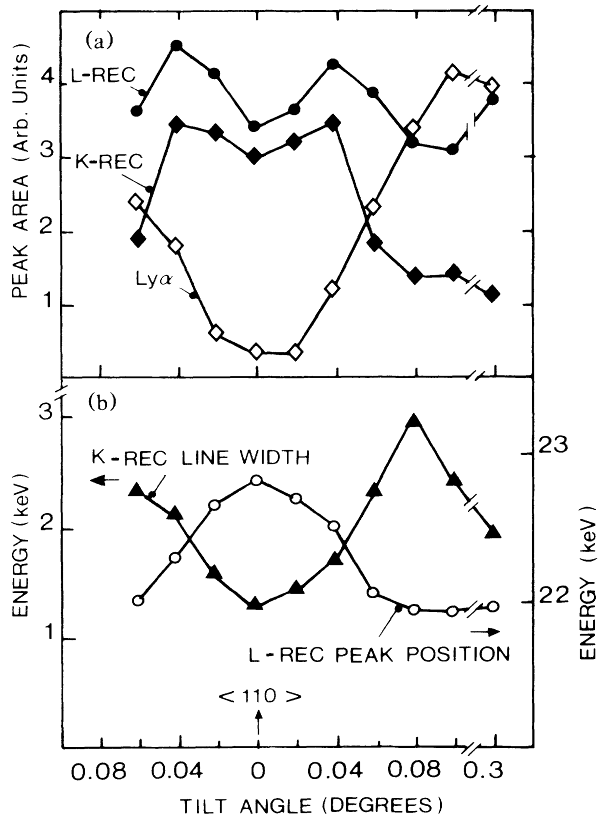

FIG. 3. Orientation dependence around the Si ⟨110⟩ direction (a) of K and L REC and Ly-α peak areas and (b) of K REC linewidth and L REC peak position.

shells, whereas the K shell is much less affected.

Finally the shape of the REC energy spectrum which strongly depends on the target-electron velocity distribution of the captured target electrons is also very sensitive to the target orientation as illustrated in Fig. 3(b) by the angular dependence of the width of the K-REC peak (in contrast the Lyman linewidths stay at a constant value of $\simeq 600$ eV, which gives the energy resolution of the detection). The effect is quite strong and the width is minimum for axial alignment and maximum for an incidence angle nearly equal to the critical channeling angle, for which the projectiles stay longer in regions of large inner-shell electron density.

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[10]As a result of channeling effects from minor planes this length may be very different for two random orientations. This explains why the aligned K-REC yield is ten times larger than the random value in the spectra of Fig. 2 and only three times larger than the random value obtained in the scan of Fig. 3 for another orientation.