Radiative electron capture by fully stripped channeled light ions

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The cross sections for radiative electron capture (REC) into the K shell of bare and H-like light ions of ^{12}C, ^{16}O, ^{19}F, and ^{32}S are measured at different energies, under channeling conditions using a Si single crystal as target. These cross section data using different projectiles are shown to fall on a universal curve when plotted against a scaled variable, the adiabaticity parameter η_K, of the collision systems. We have observed a definite difference in the cross section between the present solid target data and the available data for a gas target at the same η_K value. This difference, along with the observed shift in the REC photopeak energy, suggests an "ion–solid-state" effect. Further, these observations, especially their Z dependence, are consistent with the predictions of the theory.

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I. INTRODUCTION

Radiative electron capture (REC) is a recombination process in which a highly ionized ion captures a quasifree electron and emits a photon. The dominant contribution to REC comes from electron capture into the K shell of bare and H-like ions. Having a comparatively smaller cross section, the REC photopeak lies usually submerged in the background of the strongly competing x rays originating from the projectile and the target. For reliable REC cross section measurements it is desirable to suppress this background as well as preserve the charge state of the projectile. While the latter is generally easier using gas targets, the situation is much more complex in solid targets. Ion channeling provides a powerful technique to circumvent these problems as has been amply demonstrated in recent atomic-collision experiments [1–6]. When heavy ions are channeled along a crystallographic direction the yields of the low-impact-parameter processes such as inner-shell ionization and excitation, Rutherford scattering, etc. are considerably reduced. As a consequence, fully stripped and H-like channeled ions emerge essentially in their initial charge state [1,5]. This "frozen" charge state condition offers a unique advantage to investigate the REC process in detail. An additional advantage of using channeling technique is that the incident ions sample predominantly the dense quasifree electrons of the solid target.

Appleton *et al.* [6] were the first to investigate the REC phenomenon via channeling. Andriamonje *et al.* [1] have recently reported measurements of 25-MeV/amu H-like Xe ions channeled along ⟨110⟩ axis in Si single crystal, where they observed REC photons corresponding to electron capture into the K, L, and M shells of the projectile. They have deduced the K REC cross section by using the self-consistently calculated electron density along the ⟨110⟩ axis. Simultaneous observation of K, L, and M REC photons in one collision system was also reported very recently by Stoehlker *et al.* [7] in collisions of highly charged decelerated ions of Ge^{31+} with a H_2 gas target. The background under the REC photopeak was reduced by them using coincidence measurements between the x rays and the projectiles that have captured one electron.

Within the validity of the impulse approximation the cross section for REC into the K shell of a bare ion (atomic number Z and velocity v) per free electron is given by [8,9]

$$\sigma_{REC} = 9.1\left(\frac{\kappa^3}{1+\kappa^2}\right)^2 \frac{\exp(-4\kappa\cot^{-1}\kappa)}{1-\exp(-2\pi\kappa)} \times 10^{-21}\ \mathrm{cm}^2. \quad (1)$$

Here $\kappa = Z\alpha/\beta$ is the Sommerfeld parameter, α the fine structure constant, and $\beta = v/c$. It is evident from this relation that, in a generalized picture, all REC cross section data can be presented for comparison in terms of the scaled variable η_K $(= \kappa^{-2})$. For fully stripped ions this quantity is the same as the adiabaticity parameter, i.e., the ratio of the kinetic energy of the electron in the projectile frame to the binding energy of the K shell of the ion. Stoehlker *et al.* [7] have in fact shown that most of the available data on K-shell REC cross sections for a wide variety of ions at various energies when plotted against η_K lie on a smooth curve. This universality in cross section representation is shown to hold for η_K values between 0.2 and 2.0. It has been pointed out by Stoehlker *et al.* [7] that additional data on radiative capture into the K shell of heavy projectiles at higher energies would be of importance in order to test the scaling of the REC cross sections with η_K. Higher values of η_K can also be achieved with lighter ions at energies greater than a few MeV/amu. It is therefore desirable to carry out such measurements to test the theory and its universality on a wider range of η_K values.

Recent experimental data [10,11] also suggest that the REC photon energies in case of channeled ions may be less than the expected values from simple considerations of transitions from the valence band of the solid to the hydrogenic states of the moving ion. These shifts were partly explained as direct evidence for dynamical screening and depolarizing effect which lead to shifts in the energy levels of ions traveling in solid media [12,13] (referred to as the "ion-solid-state" effect). The shifts are shown, by Pitarke et al. [12], to be proportional to Z/v of the ion. It is important to check these predictions by measuring carefully the shifts for a variety of ions at different velocities. Furthermore, the enhancement of the electron density in the vicinity of the projectile ion is also predicted to be proportional to Z/v [13]. This enhancement should be reflected also in the REC photon yields as it probes predominantly the quasifree electrons of the medium. We report here a systematic study of the K REC process using a variety of fully stripped light ions, each at various energies, channeled along the ⟨100⟩ axis of a Si single crystal. The REC cross sections are measured, specifically to observe such effects of solid media on the REC cross sections.

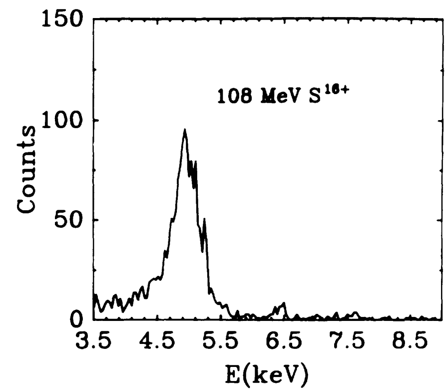

FIG. 1. A typical spectrum showing the REC photopeak for 108-MeV S^{16+} beam channeled along the ⟨100⟩ axis in a Si single crystal of thickness 0.17 μm.

II. EXPERIMENTAL DETAILS AND DATA ANALYSIS

Ion beams of ^{12}C (5–7.5 MeV/amu), ^{16}O (4.5–6.5 MeV/amu), ^{19}F (3–6 MeV/amu), and ^{32}S (3–4.5 MeV/amu) were obtained from the BARC-TIFR pelletron accelerator at Bombay. A post accelerator carbon foil stripper was used [14] to obtain fully stripped ions. The charge selected and well collimated parallel beam was directed onto a 0.17-μm-thick self-supporting Si single crystal mounted on a double-axis goniometer (the thickness of the crystal was measured from energy loss of alpha particles). The entire target chamber along with the beam dump was used as a Faraday cup. The scattered particles from a thin Au foil kept 15 cm downstream from the target provided independent normalization. A Si(Li) x-ray detector having 165-eV energy resolution at 5.9 keV was mounted outside the scattering chamber at an angle of 135° with respect to the beam direction. Suitable absorbers of accurately known thickness were kept in front of the detector to cut down the target and the projectile (for S) x rays in order to reduce the effects of pile up. Total counting rates on the x-ray detector did not exceed 25 counts/sec while collecting REC data in the aligned position of the crystal. The ⟨100⟩ axis of the crystal was aligned by monitoring the target x rays. The movement of the goniometer was controlled remotely by stepper motors with the help of a PC-based control system [15]. The yield of Si K x rays under well aligned conditions was observed to be 10% of that in the random direction. The data were collected in the same geometry for all the ion beams using the same single crystal. The beam spot on the crystal was changed from time to time to minimize the effects due to radiation damage. The alignment of the crystal was checked every time when either the beam or its energy was changed. The x-ray spectra obtained in the region of the REC peak is shown in Fig. 1. The REC photopeak is well pronounced and stands out quite well above the general background. Two procedures were tried to evaluate the REC peak area and both gave similar results. In one case, the REC peak counts were integrated under the peak after subtracting the linear background and then the area was corrected for absorption and the detector efficiency. In the second procedure, the peak spectrum near the REC peak was generated by correcting channel by channel for detector efficiency and absorption. The integrated area under the peak was then found after subtracting the background. It should be mentioned here that no contribution into the K REC peak due to L REC process is expected for bare F and S ions since for these ions the K and L REC peaks are well separated. In case of bare O ions the L REC appears as a shoulder on the low energy side of the K REC peak and the area of the K REC peak could be deduced by peak fitting procedure at all the energies.

III. RESULTS AND DISCUSSION

The total REC cross section was deduced from the measured differential cross sections assuming $\sin^2\theta_{lab}$ angular distribution for the K REC photons [16];

$$\frac{d\sigma}{d\Omega} = \frac{3}{8\pi}\, \sigma_{REC} \sin^2\theta_{lab} \quad , \tag{2}$$

where

$$\frac{d\sigma}{d\Omega} = \frac{N_x}{\epsilon \phi_p N_e N_v}. \tag{3}$$

Here θ_{lab} is the laboratory angle at which the REC photon is detected, N_x is the number of counts under the REC peak, ϕ_p is the number of incident particles, and ϵ is the total efficiency [17] of the Si(Li) x-ray detector (at a given photon energy) including the geometrical efficiency and the transmission factor for the external absorber. The quantity N_v is the number of K shell vacancies in the ion and N_e is the number of electrons sampled by the ions moving along the ⟨100⟩ axis. To derive the REC cross sections it is necessary to calculate the electron density distribution along the ⟨100⟩ axis. Andriamonje *et al.* [1,18] have used a value of 1.4×10^{23} cm^{-3} for the electron density along the ⟨110⟩ axis of a Si single crystal (which corresponds to 20% of the bulk value) in order to calculate the REC cross sections using channeled ions and Datz *et al.* [19] have used a value of 1.44×10^{23} cm^{-3} for the same system. We have calculated the electronic structure of Si via the *ab initio* self-consistent-field linear combination of atomic orbitals forming molecular orbitals (LCAO-MO) method within the local-spin-density functional formalism using the embedded molecular clusters approach to simulate the bulk [20]. The self-consistent calculations of continuum potential and electron density maps, averaged over a unit cell along ⟨100⟩ axis, were performed in order to determine the average electron density sampled by the ions. The beam divergence and hence the transverse energy of the channeled ions were taken into consideration. The details of these calculations will be published elsewhere [21]. Although the average electron density at the *center* of the channel along the ⟨100⟩ axis was obtained from these calculations to be 26.5 electrons/unit cell, the average density sampled by the ions was found to be 27.7 (±5%) electrons/unit cell (i.e., 1.73×10^{23} cm^{-3}). This was used to calculate the REC cross sections. As a check, we have been able to reproduce the continuum electron density along the ⟨110⟩ axis in Si as calculated by L'Hoir *et al.* [22].

The K REC cross sections (per electron) per K shell vacancy in the projectile were derived assuming the incident charge state to be frozen and are shown in Fig. 2. The agreement between the values obtained using bare and H-like projectiles is very good. For H-like ions η_K was calculated using screened charge for Z, i.e., $Z_{sc} = Z-0.3$. The errors in the cross section data were estimated to be about 20% (for S) to 30% (for C). The figure also shows the cross section data published by Stoehlker *et al.* (Fig. 4 in [7]) using mainly gas targets ($Ge^{31+} \rightarrow H_2$).

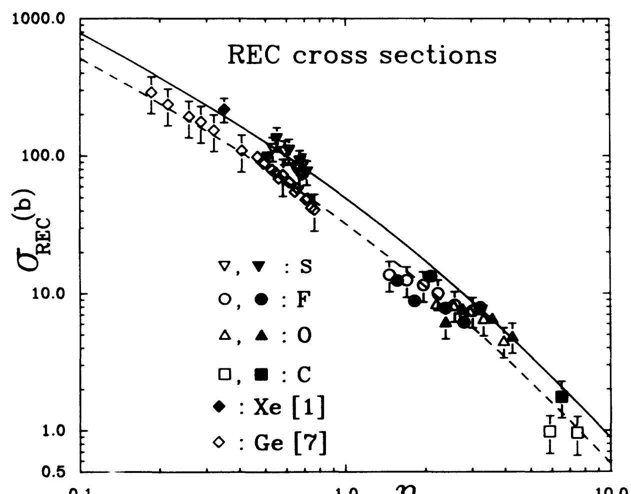

FIG. 2. The total K REC cross sections per electron per K vacancy as a function of η_K. The data for C (squares), O (triangles), F (circles), and S (inverted triangles) are from the present work. The open (filled) symbols correspond to the data for bare (H-like) ions. The data for channeled Xe^{53+} ions (filled diamond) and Ge^{31+} (open diamonds, gas target data) are from Refs. [1] and [7], respectively. The solid line represents the Bethe-Salpeter calculations and the dashed line is 35% below these calculations. For clarity we have not shown errors on all the data points. The errors vary between 20% and 30%.

The solid line in the figure represents the universal curve calculated using Eq. (1). As seen from this figure, the universality of the cross section with the adiabaticity parameter is further borne out from our experimental data up to $\eta_K = 8$. For clarity the data obtained using fully stripped ions are shown separately in Fig. 3 along with the calculations [Eq. (1)].

The universality of the cross section in this plot allows one to compare the data obtained for different projectiles having the same values of η_K (Fig. 2). Most of the data points corresponding to gas targets lie systematically below the theoretical curve, an observation also made by Stoehlker *et al.* [7]. However, the data obtained using channeled heavy ions ($Z \geq 16$) fall directly on this curve while for lighter projectiles ($Z \leq 9$) most of such data fall below this curve. In fact all the gas target data and our data for C, O, and F ions fall on the dashed line, which is drawn 35% below the theoretical curve (solid line). Although the deviations are statistically not very significant, the systematic difference, which is large for $Z \geq 16$ and negligible for $Z \leq 9$ (if one extrapolates the gas target data to high η_K values; dashed line in Fig. 2), however, is suggestive of a weak Z-dependent solid state effect with respect to the gas target data, i.e., the measured yield of REC at a given η_K is dependent on whether the target is solid or a gas.

In this respect it is interesting to compare the gas target data of Stoehlker *et al.* [7] with our S data, which have a full overlap in η_K values (Fig. 4) and the Xe data, also from a solid target, from Ref. [1]. The difference in the derived cross section values using a gas or a solid target is very obvious. The gas target yield for REC photons is about 50% lower than that from solid targets. No such comparison is possible for lighter ions in the absence of gas data of corresponding η_K values. One would, however, expect this difference to be small for lighter ions. It should be mentioned here that the REC cross sections have been obtained assuming complete freezing of the charge state. Any small deviation from this, which we

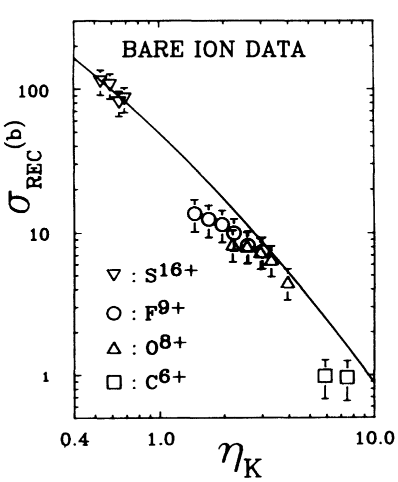

FIG. 3. The K REC cross sections as obtained using fully stripped ions in the present work. The line and the symbols have the same meanings as in Fig. 2.

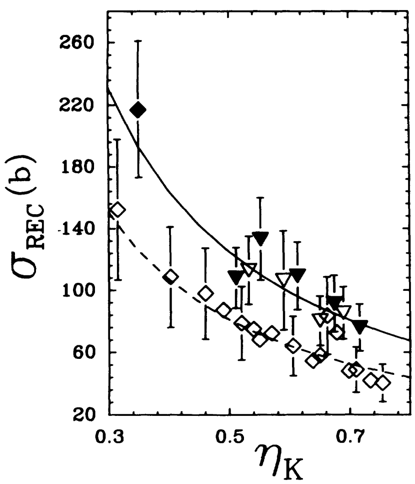

FIG. 4. Comparison between the solid (present work and Ref. [1]) and gas (Ref. [7]) target data at same η_K values. The lines and the symbols have the same meanings as in Fig. 2.

do not expect to be more than ~ 10% [1,19], would increase the measured cross section values thereby further increasing the difference between the gas and solid target data.

As mentioned earlier the solid-state effect leading to small energy shifts in the REC photopeak, for channeled ions, has recently been identified [10] and qualitatively explained [12] in terms of the dynamical screening and depolarizing effects which lead to shifts in the energy levels of ions traveling in the solid medium. We have also observed similar shifts for S ions. Figure 5 shows the peak energy (corrected for the Doppler shifts) of the REC photopeak as a function of the projectile energies for F^{9+} and S^{16+} ions. Typical values of Doppler shifts

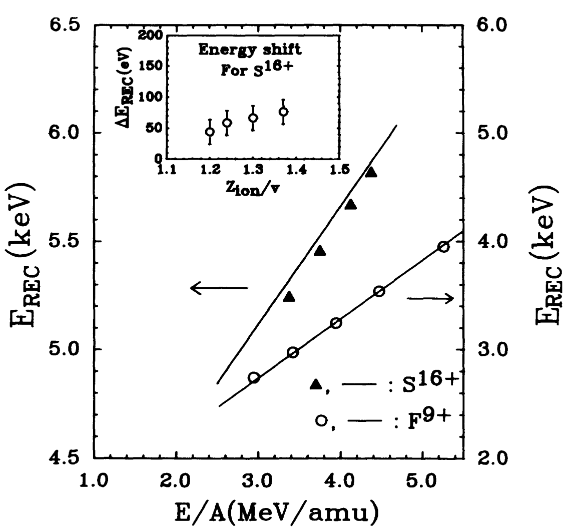

FIG. 5. The REC peak energies for fully stripped S and F ions as a function of beam energy. The lines correspond to the values predicted by Eq. (4). The inset shows the shift in the measured data from the expected values for bare S ions as a function of Z/v where v is in units of v_0, the Bohr velocity.

of REC photons in case of S ions (100–140 MeV) are about ~ 330 eV and the uncertainty in this quantity was less than ~ 10 eV. The lines correspond to the REC peak energy calculated in the projectile frame using the following relation:

$$E_{REC} = \frac{m}{M_p} E_p + E_B, \quad (4)$$

where m and M_p are the electron and the projectile mass, E_p is the projectile kinetic energy, and E_B is the K-shell binding energy of the fully stripped ions. It is evident from Fig. 5 that no measurable deviations (within our measuring accuracy of ~ 20 eV) are seen in the peak energy for F ions. Similar results hold also for other lighter ions such as C and O. Small deviations are, however, seen in the case of S projectiles. All the data points (filled triangles) fall systematically below the values calculated from Eq. (4) (solid line) for bare S ions. The shifts are found to be between 44 and 76 eV at various energies as shown in the inset. A similar shift in REC peak energy for S ions (having similar velocities) channeled along the ⟨110⟩ direction in a Si single crystal was also observed by Vane et al. [11]. Pitarke *et al.* [see Fig. (5b) in Ref. [12]] have shown that a shift of ~ 50 eV in REC peak energy for S ions channeled along the ⟨110⟩ direction in a Si crystal could be explained by invoking the ion-solid-state effect, i.e., the dynamic screening due to the wake of electron density at the position of the ions moving through the sea of conduction electrons.

This dynamical screening is a consequence of electron density fluctuations in the medium caused by the moving charged particle. The slight increase in the derived value of the cross section observed for certain heavy projectiles in solid targets (see Fig. 4) can be qualitatively understood as due to the enhancement of the electron density in the vicinity of the projectile. Such an enhancement in the REC photon yield has not been observed before.

The enhancement of the electron density as well as the shift in the K shell binding energy of the ions are shown [12,13] to be proportional to Z/v where v is in atomic unit. It is seen from this relation that such effects will be less pronounced for C, O, and F ions as compared to S ions in the similar velocity range. Indeed this is borne out from the present data for both the energy shift and the derived cross section. The average enhancement in the REC yield is about 55% in case of S ions (at average Z/v ~ 1.3). Using this value for S and assuming that enhancement varies linearly with Z/v, the expected increase in the REC yield for Xe ions (Z/v ~ 1.7) is 77% and that for O ions (Z/v ~ 0.55) is 23%. These values are in reasonable agreement with the experimental data within the measurement errors. However, the observed enhancements in the REC yield for both the S and Xe ions are lower compared to the theoretical prediction for the electron density enhancement [Eq. (29) in Ref. [13]].

It may be mentioned here that a similar process was indeed considered by Lindhard and Winther [23] to explain the transient magnetic fields (TMF) which act on excited nuclei moving in polarized ferromagnetic media. Such an enhancement in the electron density could not be identified separately in TMF measurements due to the large contribution to it from the bound polarized K-shell electrons in case of light ions [24]. The present REC measurements provide a direct evidence for such an enhancement. The observed enhancement is, however, considerably lower than that predicted by Lindhard and Winther [23].

IV. CONCLUSIONS

We have measured the cross sections for radiative electron capture into the K shell of several bare and H-like projectiles at different energies using crystal channeling technique. All the REC cross sections can be presented for comparison as a universal function of a scaled variable, viz. η_K. The cross section data of Stoehlker *et al.* [7] and the present data for channeled lighter ions ($Z \leq 9$) suggest a small deviation from the theory. The small enhancement in the REC cross sections with respect to the gas data of Stoehlker *et al.* [7] at the corresponding η_K value as well as the shift in the REC photopeak energies for S ions suggest an ion-solid-state effect.

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