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Nuclear Instruments and Methods in Physics Research B 230 (2005) 85–89

NIM B
Beam Interactions with Materials & Atoms

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X-ray yields from high-energy heavy ions channeled through a crystal: their crystal thickness and projectile dependences

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Abstract

X-rays emitted from Ar^{17+}, Fe^{24+} and Kr^{35+} ions of about 400 MeV/u transmitting through a thin Si crystal of about 20 μm thickness have been measured in a planar channeling condition and compared with those in a random incident condition. We have found that the X-ray yield from Ar^{17+} ions is larger for the channeling condition than for the random incidence, while those from Fe^{24+} and Kr^{35+} ions are rather smaller. Such tendencies are explained by considering the projectile dependences of excitation and ionization probabilities together with X-ray emission rates. A crude simulation has qualitatively reproduced these experimental results. When the crystal thickness is small, the X-ray yield is smaller in the channeling condition than in the random incident condition, because excitation is depressed. However, for thicker crystals, the X-ray yield is larger, since the survived population of projectile-bound electrons is larger due to small ionization probabilities under the channeling condition. This inversion occurs at a specific crystal thickness depending on projectile species. Whether the thickness of the used crystal is smaller or larger than the inversion thickness determines enhancement or depression of the X-ray yield in the channeling condition.

PACS: 61.85.+p; 25.75.−q
Keywords: Channeling; X-ray emission; Heavy ions

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1. Introduction

A heavy ion passing through a solid experiences a variety of atomic processes, such as excitation, ionization, and electron capture, as well as X-ray emission. Concerning the target atoms, all of these

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doi:10.1016/j.nimb.2004.12.022

processes are, in general, reduced under channeling conditions. For projectile ions, excitation, ionization and electron capture are depressed as well. However, yield of the projectile X-rays from heavy ions is not so straightforward. Due to competition between electron loss (ionization) and capture processes and competition between X-ray emission and ionization of excited states, the projectile X-ray yields in channeling and random incidence conditions depend on the crystal thickness and the atomic number of the ions in a complicated manner. The evolution of the electronically excited states of heavy ions plays a crucial role. Such evolutions have been extensively studied in the case of amorphous targets in projectile X-ray measurements and theories [1,2]. The secondary electron emission reflecting the evolution had been reported [3]. However, the X-rays from projectile heavy ions channeling through crystals have been mainly studied from a viewpoint of radiative electron capture (REC), and measurements of projectile X-ray in channeling conditions are limited [4,5]. In this paper, we report on incident direction dependence of X-ray yields from H-like or He-like Ar, Fe and Kr ions of about 400 MeV/u channeled through a thin Si crystal, where the electron capture process is negligibly small. We demonstrate that the projectile X-ray yields in the planar channeling are not always depressed but sometimes enhanced depending on the conditions.

2. Experiment

The experiments were performed at Heavy Ion Medical Accelerator in Chiba, HIMAC using 390 MeV/u H-like Ar^{17+}, 423 MeV/u H-like Fe^{24+} and 430 MeV/u H-like Kr^{35+} ions. The beam divergences were less than 0.15 mrad in the two transverse directions. Fig. 1 shows schematic layout of the experiments [6]. The beams were collimated by a 5-cm thick Fe collimator with an inner diameter of 1 mm located at 6.5 m upstream from a target. Then the beams were injected to a Si crystal target of 21 μm or 28 μm in thickness mounted on a 3-axis goniometer. We scanned the crystal orientation across a (220) planar channeling condition. The beam intensities for X-ray and charge state measurements were about 10^4 to 10^5 s^{-1} and about 10^3 s^{-1}, respectively.

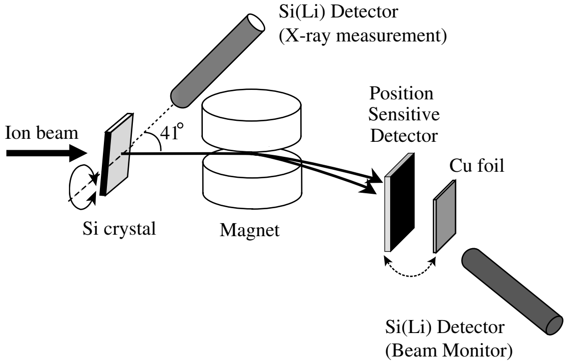

Fig. 1. Schematic layout of the experimental setup.

A Si(Li) detector for measuring de-excitation X-rays was located at an angle of 41° with respect to the beam direction. The resolution for 5.9 keV X-ray of ^{55}Fe was about 170 eV. The primary beam intensity was monitored by measuring Kα X-rays from a Cu foil placed at the end of the beam line with another Si(Li) detector. We also measured the charge state distribution of the ions after they passed through the target. The transmitted ions were charge-separated by a magnet at 1.3 m downstream of the target, and detected by a two-dimensional position-sensitive detector located at 5.6 m downstream from the target.

We observed SiK X-rays at 1.7 keV and K X-rays from projectile Ar^{17+}, Fe^{24+} and Kr^{35+} ions at around 5, 10 and 21 keV, respectively, in the X-ray spectra. The X-ray energies from the projectile ions were shifted higher from their intrinsic energies by about 50% due to the Doppler effect. When He-like Fe^{24+} ions were injected, we recognized K X-rays both from the He-like and H-like Fe ions, the latter charge state being produced inside the target. Due to the limited resolution we defined the intensity of the projectile X-rays as a summation of the two X-ray intensities.

3. Result and discussion

In Fig. 2, we present the charge state fraction (a), the target X-ray yield (b) and the projectile

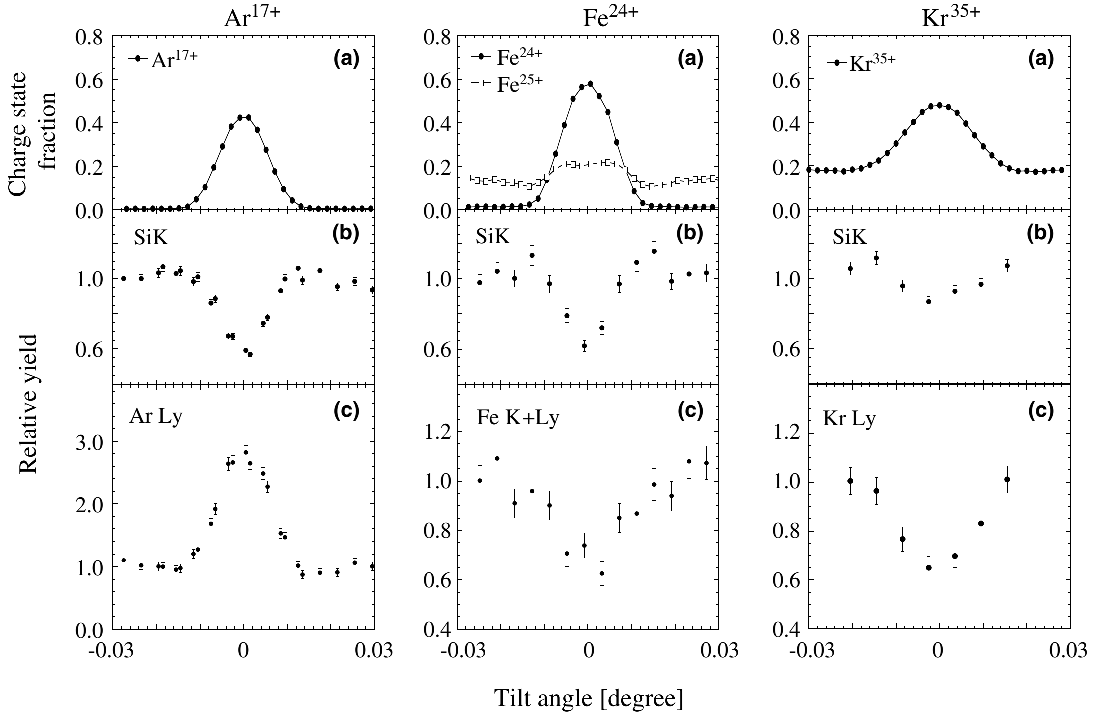

Fig. 2. Channeling profiles of (a) charge state fraction, (b) yield of target X-rays, (c) yield of projectile X-rays as a function of the incident angle with respect to the (2 2 0) channel plane for 390 MeV/u Ar^{17+} (left), 423 MeV/u Fe^{24+} (center) and 430 MeV/u Kr^{35+} ions (right). X-ray yields are normalized to unity for random incidence.

X-ray yield (c) as a function of incident angle with respect to the (2 2 0) plane for H-like Ar^{17+} (left) and He-like Fe^{24+} ions (center) injected to a 21-μm thick Si crystal, and H-like Kr^{35+} ions (right) injected to a 28-μm thick crystal. For all the ions injected under the channeling condition, the survived fractions increase and the target X-ray yields decrease. On the other hand, the projectile X-ray yields under the channeling condition are enhanced for Ar^{17+} ions, and depressed for Fe^{24+} and Kr^{35+} ions.

This peculiar behavior of the projectile X-ray yields comes from the fact that projectile X-ray emission is a two step process, i.e. collisional excitation of an electron and its radiative decay, and the latter process is in competition with collisional ionization. The observed behavior of X-ray yields from the projectile ions is explained by comparing the rates of these processes as follows. Since channeled ions undergo less collisional excitation than random-incident ions, they emit less de-excitation X-rays for a thin crystal. When a crystal is thick enough, on the other hand, the X-ray yield is rather larger for channeled ions, since smaller ionization probabilities lead to more emission of de-excitation X-rays. Therefore the X-ray yields in channeling and random conditions are inverted at a certain thickness, which depends on projectile species. For heavy ions, the inversion thickness is larger due to smaller ionization probabilities than light ions. In our experiments, the crystal is thick enough for the light Ar^{17+} ions to allow larger X-ray yields under the channeling condition, not being thick enough for the heavy Fe^{24+} and Kr^{35+} ions. Although one must also take account of X-ray attenuation in the crystal, the experimental results are basically understood from this discussion.

In order to estimate projectile X-ray intensities, we traced the electronic state evolution of the projectile ions by a Monte-Carlo method. Experimental angular spreads of the incident beams were taken into account. The planar continuum potential was calculated from the Moliére potential with thermal vibration folded (amplitude of the vibration is 0.075 Å at room temperature). Ignoring the dechanneling effect, we simply followed the ion trajectories of channeled and unchanneled ions. Electronic states considered were $1s^2$, 1s2s and 1s2p for the He-like ions, and 1s, 2s and 2p for the H-like ions.

Electronic transitions taken into account were excitation, ionization, intrashell-mixing and X-ray emission. Electron capture process was neglected in the present energy region. We assumed the transition rates of ionization, excitation and intrashell-mixing are given by $(n_e\sigma_e + Z_t^2 n_n \sigma_p)v$, where Z_t is the atomic number of the target, and v is the velocity of the incident ion. The local electron and nuclear densities of the target at the ion position, n_e and n_n, were derived from the Moliére potential and a Gaussian distribution of thermally vibrating atoms. σ_e and σ_p are the cross-sections of each process for electron and proton impacts, respectively. Since highly excited states are easily ionized, the ionization cross sections were defined as summation of cross sections of ionization and those of excitation to states of $n \geqslant 3$ (n is a principal quantum number). In the present high velocity region, the proton impact cross sections are considered to be equal to the electron impact ones [7]. For the He-like ion, we adopted an independent electron model where correlation between electrons is ignored. Table 1 summarizes the values of the cross-sections $\sigma_e(\sim \sigma_p)$ for various processes which are commonly adopted for the electron and proton impacts in the simulation. These values were evaluated using a relation, $\sigma_{\text{random}} = Z_t\sigma_e + Z_t^2\sigma_p \sim (Z_t + Z_t^2)\sigma_e$, from electronic transition cross-sections

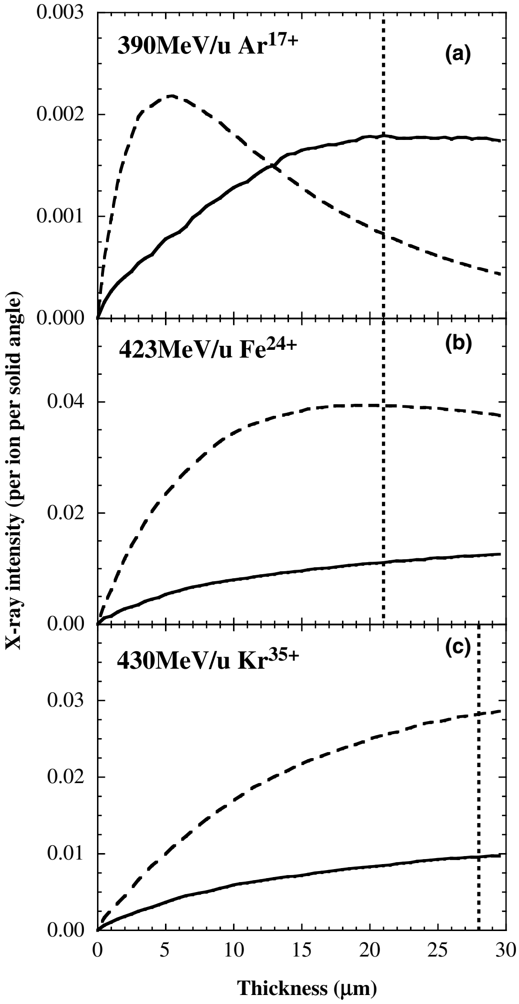

Fig. 3. Simulated X-ray intensities from projectiles as a function of the target thickness: (a) for 390 MeV/u Ar^{17+}, (b) for 423 MeV/u Fe^{24+} and (c) for 430 MeV/u Kr^{35+} ions. The solid lines show the X-ray intensities in the channeling condition, and the dashed lines in the random condition. Thicknesses of the target used in the experiment are indicated by the vertical dotted lines.

Table 1
Adopted cross-sections of ionization, excitation, and intrashell mixing for electron or proton impacts (in barns) evaluated by the computer code ETACHA [8]

Projectile ion	$\sigma_{\text{1s-ion}}$	$\sigma_{\text{1s-2s}}$	$\sigma_{\text{1s-2p}}$	$\sigma_{\text{2s-ion}}$	$\sigma_{\text{2p-ion}}$	$\sigma_{\text{2s-2p}}$
390 MeV/u Ar^{17+}	10.0	107.6	245.5	1240.0	1384.6	857.1
423 MeV/u Fe^{24+}	5.0	61.4	118.9	856.3	965.7	604.7
430 MeV/u Kr^{35+}	2.7	32.4	58.1	458.7	542.7	430.0

for unchanneled ions calculated by the computer code of ETACHA [8] in a Si crystal. The attenuation of X-ray by the target was included (attenuation lengths in Si crystal are 17, 130 and 1000 μm for 5, 10 and 21 keV, respectively [9]).

Fig. 3 shows the simulated projectile X-ray intensities (the number of photons per ion emitted out of the crystal into the unit solid angle in the direction of the detector) under the random (dashed line) and channeling (solid line) conditions for Ar^{17+}, Fe^{24+} and Kr^{35+} ions as a function of thickness. We defined the random condition as the mean incident angle of 0.03°. The crystal thicknesses used in the experiments are indicated by the vertical dashed lines. In the case of Ar^{17+} ions, the X-ray intensities in the channeling condition and in the random condition are inverted at 12-μm thickness. The inversion thicknesses for Fe^{24+} and Kr^{35+} ions are about 120 and 600 μm, respectively. Thus the simulation qualitatively reproduced the experiments.

In summary, we have demonstrated that the projectile X-ray yields under channeling condition show peculiar behavior, i.e. the X-ray yield from Ar^{17+} ions is larger for the channeling condition than for the random incidence, while those from Fe^{24+} and Kr^{35+} ions are rather smaller. We have also succeeded in reproducing the tendency by a crude Monte-Carlo simulation. Quantitative agreement may require more elaborate treatments such as one taking account of the dechanneling effects.

Acknowledgements

This work was supported by Grants-in-Aid for Scientific Research (No. 13440126 and 162040302) from Japan Society for the Promotion of Science. This experiment is one of research projects with heavy ions at NIRS-HIMAC.

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