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Trajectory and charge state dependence of energy loss of relativistic heavy ions channeled in a silicon surface barrier detector

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Abstract

We measured the emerging charge-state distribution of hydrogen-like 390 MeV/u Ar^{17+} ions planar channeled in a silicon surface barrier detector for the ΔE measurement, and observed their energy deposition in the detector simultaneously. We simulated the energy loss spectrum of specific emerging charge state, and succeeded in reproducing it with an adjusting parameter for the cut-off momentum transfer between close and distant collisions. © 2002 Elsevier Science B.V. All rights reserved.

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1. Introduction

Charge exchange and energy loss of energetic heavy ions channeled in a crystal have been widely studied for years [1]. The charge state and energy loss measurements of axially channeled 27 MeV/u Xe^{35+} ions at GANIL [2] were recently extended to those of 300 MeV/u U^{73+} at GSI [3]. Dielectronic recombination (DR) was studied through measurements of a combination with charge exchange, X-ray emission, or energy loss in the channeling condition where travelling ions mainly sample the target electrons in the central region of the axial channel [4].

Recently we have investigated resonant coherent excitation (RCE) of relativistic heavy ions in the $(2\bar{2}0)$ planar channeling condition [5–8]. For this observation we have measured the emerging charge-state distribution of hydrogen-like 390 MeV/u Ar^{17+} ions planar channeled in a Si crystal. In such an energetic region, we take only electron loss into account, because electron capture is negligible. Moreover, the electron-loss probability is also reduced, and we can observe emerging ions keeping their initial charge state (i.e. the frozen charge

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state) even after passing through a thick crystal. One of the advantages to use a thick crystal in the transmission type experiment is that we can adopt a silicon surface barrier detector (SSD) for the ΔE measurement as a target crystal which requires substantial thickness in the manufacturing process. This SSD directly gives information of energy deposition. In the planar channeling condition, energy loss is uniquely related with the ion trajectory, which leads to straightforward analysis to extract trajectory information from energy loss. For instance, the small energy loss corresponds to ions travelling in the region of the channel center with a small oscillation amplitude, since the target electron density there is small. Therefore we can observe the emerging charge state of the channeled ion with the specific ion trajectory by the use of the SSD. It is in contrast with the axial channeling where we have to treat the trajectory in statistical equilibrium assumption. The ionization probability of ions is also suppressed in the region of the channel center.

When we change a viewpoint from the laboratory frame into the projectile frame, we can discuss K-shell ionization probability of Ar^{17+} ions by electron impact and nucleus impact with the same velocity as that of the projectile (i.e. 210 keV electron and 390 MeV/u Si). With help of a simulation, we deduce their dependence on the impact parameter, i.e. the distance between the projectile and spatially distributed electrons or nuclei.

2. Experimental

The experimental setup had already been described in previous papers [5–8]. A heavy ion synchrotron, Heavy Ion Medical Accelerator at Chiba (HIMAC) supplies hydrogen-like Ar^{17+} ions of 390 MeV/u ($\beta = v/c = 0.7$ and $\gamma = 1.4$). Relativistic channeling experiments require a beam with a very small divergence because of its small critical angle. The beam divergence of 0.15 mrad and the beam spot size of a few mm were attained. The Ar^{17+} ions passed through an SSD. We employed an SSD with thickness of 94.7 μm, whose surface was specially cut so that the normal direction to the surface is along $\langle 1\,1\,0 \rangle$ axis in the manufacturing process. The entrance and exit surfaces of the SSD were covered by the Au and Al electrodes of the thickness of 40 $\mu g/cm^2$. We neglected the energy loss and the charge exchange of the ions in the electrodes. The SSD target was mounted on a high-precision goniometer. The charge states of the emerging ions were measured by a combination of a charge separation magnet of 0.5 T and a two dimensional (2D)-position-sensitive Si detector placed 560 mm downstream of the target crystal. The crystal orientation was adjusted so that the Ar^{17+} ions passed thorough the SSD parallel to the $(2\,\bar{2}\,0)$ plane.

The data of the 2D-position-sensitive detector and the energy deposition in the SSD were simultaneously collected in a list mode. For this purpose, we restricted the beam intensity to keep the counting rate less than a few thousand cps during measurements.

3. Experimental results

In random incidence we observed merely fully-stripped Ar^{18+} ions in the emerging charge-state distribution, as is expected from our previous measurement with 390 MeV/u Ar^{17+} ions passing through amorphous carbon foils [9] and the charge-state calculation code, ETACHA [10]. Fig. 1(a) shows the corresponding energy deposition spectrum of the ions. A Gaussian-shaped single peak at 16.4 MeV with the FWHM of 1.0 MeV was obtained. The origin of this width is mainly attributed to the energy straggling of the ions.

In the $(2\,\bar{2}\,0)$ channeling condition, however, $\sim$20% of incident Ar^{17+} ions maintained the initial charge state throughout the passage of the 94.7 μm thick SSD. The energy deposition spectra of the emerging charge states, q_{out}, of 18+ and 17+ are shown in Fig. 1(b) and (c), respectively. The spectrum for $q_{\text{out}} = 18$ consists of two components. It is remarkable that the peak position of the non-channeled component in the channeling condition (Fig. 1(b)) is somewhat higher than that for random incidence (Fig. 1(a)). This is attributed to "quasi-channeled ions" which spend long time in the neighborhood of the channel wall, where the electron density is larger than the mean target

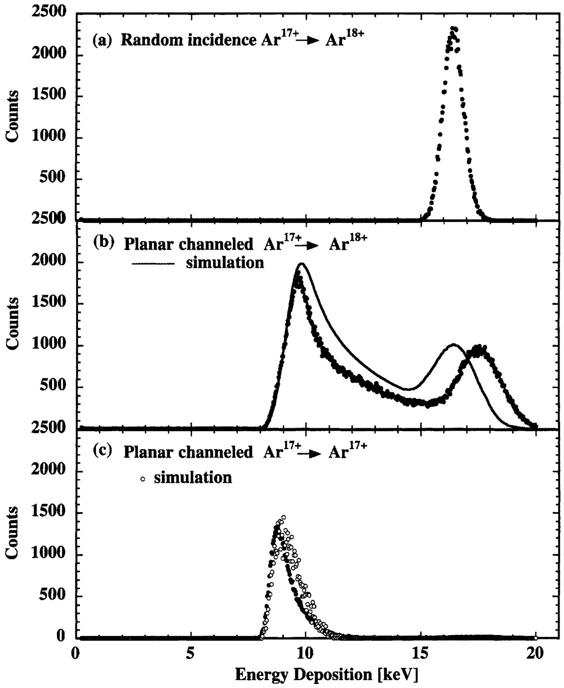

Fig. 1. (a) Energy deposition spectrum of emerging Ar^{18+} ions for the random incidence of 390 MeV/u Ar^{17+} ions to 94.7 μm Si crystal. (b) Energy deposition spectrum of emerging Ar^{18+} ions for the $(2\bar{2}0)$ planar channeling incidence of 390 MeV/u Ar^{17+} ions to 94.7 μm Si crystal. The solid line shows the simulation. (c) Energy deposition spectrum of emerging Ar^{17+} ions for the $(2\bar{2}0)$ planar channeling incidence of 390 MeV/u Ar^{17+} ions to 94.7 μm Si crystal. The open circles show the simulation.

electron density. On the other hand, the energy deposition spectrum for $q_{\mathrm{out}} = 17$ ions has only the channeled component (Fig. 1(c)), which means that only the ions passing through the neighbourhood of the channel center keep their initial charge state. The minimum edge energies of the channeled components are identical regardless of the emerging charge state, which is natural since the ions with $q_{\mathrm{out}} = 18$ and with the lowest energy loss travel just along the channel center, and are ionized in a region close to the exit.

4. Simulation and discussion

The Bohr parameter, $\kappa = (2Z_1 v_0)/v$ (Z_1: projectile charge, v_0: the Bohr velocity, v: projectile velocity) for the present condition is 0.37, which implies that we need quantal treatment of stopping power described by the Bethe formula. We tried to calculate the energy deposition of channeled ions in order to obtain a relation between the energy deposition and the ion trajectory. Generally the stopping power can be divided into two parts, i.e. contributions from distant and close collisions by an appropriate cut-off momentum transfer, $\hbar K_0$. We assumed the energy deposition due to close collisions is proportional to the local electron density along the ion trajectory. Moreover we regarded the cut-off momentum transfer as $\hbar K_0 = f\hbar/a_{\mathrm{TF}}$, where a_{TF} is a Thomas–Fermi radius, and f is a free parameter to be fixed. The value of $f = 1$ roughly corresponds to the condition where the contribution from the distant collision is a half of the total stopping power which is known as "equi-partition rule". The local stopping power for planar channeled ions at a position of x is then expressed as

$$S(x) = \frac{4\pi e^4}{mv^2}\left[q_1^2 Z_2 N\left(\ln\frac{\hbar K_0 v\gamma}{I} - \frac{\beta^2}{2}\right) + Z_1^2 n_e(x)\left(\ln\frac{2mv\gamma}{\hbar K_0} - \frac{\beta^2}{2} + \frac{\pi Z_1 \alpha\beta}{2}\right)\right], \tag{1}$$

where m is mass of electron, v is ion velocity, q_1 is charge of the incident ion, Z_1: atomic number of the projectile, Z_2: atomic number of the target atom, N is atomic density of the target, I is mean excitation energy of the target atom, and $n_e(x)$ is the local electron density. The first term describes the contribution from the distant collision, and the second term from the close collision. We adopted q_1 instead of Z_1 for the distant collision because of screening by a bound electron, and retained Z_1 for the close collision. The local density of the target electrons was simply derived from the planar potential employing the Molière potential with the thermal vibration of atoms taken into account.

Then, the averaged stopping power along the ion trajectory with oscillation amplitude x_0 is obtained by

$$\overline{S}(x_0) = \frac{4}{T_{\mathrm{osc}}(x_0)}\int_0^{x_0} \frac{S(x)}{v_\perp(x)}\,\mathrm{d}x, \tag{2}$$

where $T_{osc}(x_0)$ is a period of the oscillation, and $v_\perp(x)$ is the ion velocity perpendicular to the channel plane. Since the present target thickness is more than several times larger than the ion path length per oscillation, the total energy loss throughout the path is evaluated by $\Delta E_L(x_0) = \overline{S}(x_0)z_0$, where z_0 is the target thickness.

The energy deposition of the relativistic ions in the detector deviates from the energy loss, because a non-negligible fraction of energetic secondary electrons produced in binary collision escape from the detector [12]. We subtracted this component from the simulated energy loss to compare with the measured energy deposition. Then, the energy deposition per path is expressed as $\Delta E_D(x_0) = \Delta E_L(x_0) - [\bar{n}_e(x_0)/NZ_2]E_{es}$, where $\bar{n}_e(x_0)$ is the averaged local electron density along the ion trajectory. The total energy, E_{es}, of the energetic secondary electrons escaping the SSD in random incidence was evaluated via a Monte Carlo simulation, and modified for the case of the planar channeling by considering the difference of target electron densities. This correction amounts to a few percent of the total energy loss of the ions.

We simulated the experimental data of the energy deposition spectrum of $q_{out} = 18$ in the channeling condition so that the channeled component was well reproduced by Eq. (1), assuming that the ions keep the charge state of 18+ throughout the passage. The incident beam divergence was taken into consideration assuming the Gaussian distribution. When the ions approached the channel wall within the distance of the one-dimensional amplitude of the thermal lattice vibration, 0.075 Å for Si, they were treated as random incident ions, i.e., the energy loss was simply calculated by Bethe's formula with the linear Mott correction. The dechanneling effect was neglected in the present simulation.

We, then, obtained 0.45 for the best fitted parameter of f, and simulated spectrum was shown in Fig. 1(b) by a solid line. This value means the cut-off momentum transfer is $0.45\hbar/a_{TF}$, and the largest impact parameter for the close collision is considered to be effectively twice of the case for the equipartition rule, since it is given by $\sim 1/K_0$. This result is consistent with the previously reported analysis for 290 MeV/u C^{6+} ions planar channeled in a Si crystal [11].

Here we discuss the energy broadening due to the straggling. When the ions pass through the channel center, the non-symmetrical Landau distribution with a tail to the higher energy side is appropriate rather than the Gaussian distribution because of small number of collisions with the target electrons there ($n_e(0) = 1.8 \times 10^{23}$ cm^{-3} and $z_0 = 94.7$ μm). It is indeed observed for the case of $q_{out} = 17$ (Fig. 1(c)), which is in good contrast to the case of $q_{out} = 18$ (Fig. 1(b)), where the spectrum results from various trajectories. As a trial, we traced the every close collisions with the target electrons in a Monte Carlo simulation to deduce the corresponding energy of Ar^{17+} ions in the condition where $x_0 < d_p/4$ ($d_p = 1.92$ Å: the $(2\bar{2}0)$ inter-planar distance). This condition was roughly selected just as the channeled ions keep the initial charge state throughout the passage. As seen in Fig. 1(c), such a simulation shows a good agreement with the experimental data.

We simulated the energy deposition spectrum and succeeded in reproducing it by the stopping power with adjusting parameter of the cut-off momentum transfer between close and distant collisions. Further we well reproduced the energy deposition spectrum for the case of the ions keeping the initial charge state of 17+ also by tracing every close collisions via a Monte Carlo simulation. Detailed analysis of trajectory-dependent ionization probability is in progress now.

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References

[1] A general review on this subject is H.F. Krause, S. Datz, Channeling heavy ions through crystalline lattices, Adv. At. Mol. Opt. Phys. 37 (1996) 139.

[2] A. L'Hoir, S. Andriamonje, R. Anne, N.V. De Castro Faria, M. Chevallier, C. Cohen, J. Dural, M.J. Gaillard, R. Genre, M. Hage-Ali, R. Kirsch, B. Farizon-Mazuy, J. Mory, J. Moulin, J.C. Poizat, Y. Quéré, J. Remillieux, D. Schmaus, M. Toulemonde, Nucl. Instr. and Meth. B 48 (1990) 145.

[3] D. Dauvergne, C. Scheidenberger, A. L'Hoir, J.U. Andersen, S. Andriamonje, C. Böckstiegel, M. Chevallier, C. Cohen, N. Cue, S. Czajkowski, J.S. Forster, H. Geissel, H. Irnich, T. Kandler, R. Kirsch, A. Magel, P.H. Mokler, G. Münzenberg, F. Nickel, Yu.L. Pivovarov, J.-C. Poizat, M.F. Politis, J. Remillieux, D. Schmaus, Th. Stöhlker, T. Suzuki, M. Toulemonde, Phys. Rev. A 59 (1999) 2813.

[4] J.U. Andersen, J. Chevallier, G.C. Ball, W.G. Davis, J.S. Forster, J.S. Geiger, J.A. Davies, H. Geissel, E.P. Kanter, Phys. Rev. A 54 (1996) 624.

[5] T. Azuma, T. Ito, K. Komaki, Y. Yamazaki, M. Sano, M. Torikoshi, A. Kitagawa, E. Takada, T. Murakami, Phys. Rev. Lett. 83 (1999) 528.

[6] T. Azuma, Phys. Scr. T 80 (1999) 79.

[7] T. Azuma, T. Ito, Y. Yamazaki, K. Komaki, M. Sano, M. Torikoshi, A. Kitagawa, E. Takada, T. Murakami, Nucl. Instr. and Meth. B 135 (1998) 61.

[8] K. Komaki, T. Azuma, T. Ito, Y. Takabayashi, Y. Yamazaki, M. Sano, M. Torikoshi, A. Kitagawa, E. Takada, T. Murakami, Nucl. Instr. and Meth. B 146 (1998) 19.

[9] Y. Takabayashi, T. Ito, T. Azuma, K. Komaki, Y. Yamazaki, H. Twara, M. Torikoshi, A. Kitagawa, M. Sano, E. Takada, T. Murakami, Phys. Scr. T 80 (1999) 249.

[10] J.P. Rozet, C. Stéphan, D. Vernhet, Nucl. Instr. and Meth. B 107 (1996) 67.

[11] T. Ito, T. Azuma, K. Komaki, Y. Yamazaki, T. Murakami, E. Takada, M. Torikoshi, M. Sano, Phys. Scr. T 73 (1997) 345.

[12] T. Ito, T. Azuma, K. Komaki, Y. Yamazaki, M. Torikoshi, A. Kitagawa, T. Murakami, Phys. Scr. T 80 (1999) 256.