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Resonant coherent excitation of relativistic Ar^{17+} ions channeled in a Si crystal

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Abstract

We observed resonant coherent excitation (RCE) of 1s electron to $n = 2$ states in Ar^{17+} through measurements of the survived fraction of 390 MeV/u hydrogen-like Ar^{17+} channeled in a Si crystal. We adopted a totally depleted Si surface barrier detector as a target crystal as well as a probe of the energy deposition. The charge state of emerged ions was measured by a combination of a charge separation magnet and a 2D-position sensitive detector. We observed the RCE for planar channeled ions by tilting the target Si crystal from the direction of [1 1 0] axis in the $(2\,\bar{2}\,0)$, (0 0 4), and $(1\,\bar{1}\,1)$ planes. Prominent resonances at tilt angles under the resonance condition were observed. Moreover, each resonance profile is split into several lines due to the $l \cdot s$ interaction and the Stark effect originating in the static crystal field. The energy deposition in the crystal gives the information of the amplitude of the ion trajectory. The resonance peak position, intensity and width in the survived fraction of Ar^{17+} reflect the position dependent strength of the crystal field, the RCE and the electron loss probabilities. They are in good accord with our calculation of the transition energy and probability. © 1998 Elsevier Science B.V.

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1. Introduction

An ion passing through a crystal channel feels a perturbative potential of frequency, $\nu = \gamma\beta c/d$, where $\beta = v/c$, v is the ion velocity, c the light velocity, $\gamma = 1/\sqrt{1-\beta^2}$, and d the lattice spacing along the axis. When the energy of this perturbation, $h\nu$, corresponds to the difference of internal energy levels of the ion, E, then resonant coherent excitation (RCE) occurs. Since the electric field in the crystal is not a pure sinusoid, the ion is also perturbed at the integral multiples of the fundamental frequency. The resonance condition is described as

$$k = Ed/\gamma\beta hc, \tag{1}$$

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where k is an integer.

The RCE process and the possibility of radiative de-excitation was first predicted by Okorokov [1]. If an orbital radius of the excited electron is smaller than the channel size, the radiative decay is expected, otherwise the ionization of the excited ion is rather preferred. The first observation of RCE through the charge state distribution of emerging low-Z heavy ions was reported by Datz et al. in 1978 [2]. Since then, much progress in the understanding of RCE has been made in the last two decades [3]. The removal of the degeneracy of 2s and 2p states induced by the crystal and wake fields were investigated in detail experimentally and theoretically [2,4,5]. Measurements of the charge fraction of emerged ions and X-ray have been recently reported [6,7].

So far observations of RCE have been limited in the ion energy region upto several tens MeV/u. Here we report the first observation of RCE of 1s electron to $n=2$ states in Ar^{17+} through measurements of a survived fraction of Ar^{17+} channeled in the Si crystal in the relativistic ion energy region. Argon is the heaviest ion with the largest transition energy to be observed among ever reported experiments on RCE. The electrons excited to $n=2$ states through RCE are easier to be stripped off by the target atom than those at the ground state, which results in a decrease of the surviving probability of Ar^{17+} ions.

The higher ion energy has various advantages. First, the lower order Fourier components of the crystal potential are available, which leads to the larger resonance amplitude. Second, the charge exchange probability of ions is much reduced in comparison with the lower energy case, so that we can extract the resonance phenomena without being obscured by the charge exchange.

2. Experiments

A beam of hydrogen-like Ar^{17+} ions of 390 MeV/u, the angular divergence of which was less than 0.15 mrad, was supplied at Heavy Ion Medical Accelerator at Chiba (HIMAC), and passed through the target Si crystal mounted on a high precision goniometer. Channeling in the present high energy region requires a small critical angle of the order of submilliradian. We have developed a parallel beam by a combination of a doublet and a triplet quadruple-magnetic lenses, and collimated it by an Fe-made collimator of 50 mm thickness and 1 mm inner diameter located downstream of the magnets [8]. The synchrotron was operated in a pulse mode with a repetition period of 3.3 s and a width of 1.5 s. The beam intensity was reduced to a few thousand pps (particles per second) to avoid pileup.

A very thin crystal of several thousand angstroms had often been employed in order to avoid the effect of the charge exchange on RCE. In the present condition, however, we do not necessarily need such thin crystals. We adopted totally depleted Si surface barrier detectors of 78.5 and 94.7 μm in thickness as target crystals for probing the energy deposition simultaneously, which is a technique well developed by our group [9]. The crystal orientation was searched out by X-ray diffraction in advance.

A vertical slit of 1 mm in width was placed at 615 mm downstream of the Si crystal target. The charge state of emerging ions was measured by a combination of a charge separation magnet of 0.5 T located at 660 mm further downstream of the vertical slit and a 2D-position sensitive Si detector.

The data of the charge fraction, the energy deposition in the Si target crystal, and the vertical scattering angle were collected in a "list mode" as a function of the crystal orientation. Accordingly, the charge fraction distribution could be re-histogrammed later by gating on the measured energy deposition or scattering angle.

3. Results and discussion

Instead of changing the ion energy for realizing RCE under the axial channeling, we observed RCE under the planar channeling by tilting the angle from the direction of the $[1\,1\,0]$ axis in the $(2\,\bar{2}\,0)$, $(0\,0\,4)$, or $(1\,\bar{1}\,1)$ plane. The resonance condition in this case is described as

$$\frac{k\cos\theta}{A}+\frac{l\sin\theta}{B}=\frac{E}{\gamma\beta hc}, \qquad (2)$$

where k and l are integers, and θ is a tilt angle from the $\langle 1\,1\,0\rangle$ axis in the plane. (A,B) is $(a/\sqrt{2},a)$, $(a/\sqrt{2},a/\sqrt{2})$, and $(a/\sqrt{2},\sqrt{3}a/\sqrt{2})$ for the $(2\,\bar{2}\,0)$, $(0\,0\,4)$, and $(1\,\bar{1}\,1)$ planes, respectively, and a is a lattice constant.

The survived fraction of Ar^{17+} ions passing through the present Si crystal of ca. 100 μm thickness in the random direction was less than 1×10^{-3}. Under the channeling condition, however, we observed several tens percent of emerged Ar^{17+} ions. Varying the angle from the [1 1 0] axis in the $(2\,\bar{2}\,0)$ plane, resonances of the electron transition from 1s to $n=2$ states in Ar ions corresponding to $(k,l)=(1{,}1)$, (1,2), and (1,3), were very clearly observed as a decrease of the survived Ar^{17+} fraction. The case for $(k,l)=(1,1)$ is shown in Fig. 1. A resonance at a given tilt angle can be associated with a corresponding transition energy with the relation of Eq. (2), which is also shown in the upper scale in Fig. 1. The two arrows in Fig. 1 represent the resonance positions calculated from Eq. (2) substituting 1s–2p transition energies in vacuum, 3.318 and 3.323 keV, which are the values of $j=1/2$ and 3/2. We changed the tilt angle, θ, also in the $(0\,0\,4)$ and $(1\,\bar{1}\,1)$ planes. Resonances corresponding to $(k,l)=(1{,}1)$, (1,2), (1,3), (1,4) for the $(0\,0\,4)$ plane, and to $(k,l)=(1,1)$, (1,3) for the $(1\,\bar{1}\,1)$ plane were observed.

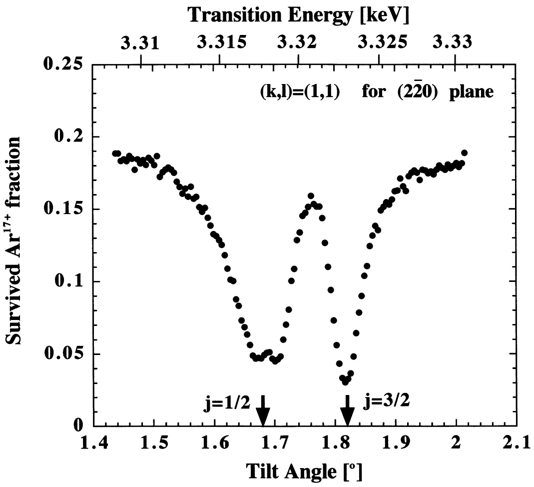

Fig. 1. Resonance peaks of $(k,l)=(1,1)$ in the $(2\,\bar{2}\,0)$ plane. The survived Ar^{17+} fraction passing through 94.7 μm Si crystal as a function of the tilt angle from the [1 1 0] axis, θ, in the $(2\,\bar{2}\,0)$ plane is shown. The corresponding transition energy is shown in the upper scale. The two arrows represent the resonance positions for 1s–2p energy levels ($j=1/2$ and 3/2) of Ar in vacuum.

It is noticed that the selection rule, destructive or constructive interferences of potentials in a diamond-like lattice of a Si crystal [10], limits the combination of (k,l); we have no resonance of $(k,l)=(1{,}4)$ for the $(2\,\bar{2}\,0)$ plane, all resonances are allowed for the $(0\,0\,4)$ plane, and resonances of even number of $k+l$ are allowed for the $(1\,\bar{1}\,1)$ plane.

Each resonance peak is split into several lines. It implies that the degeneracy of $n=2$ states is removed due to the $l\cdot s$ interaction and the Stark effect originating mainly in the static crystal field. Note that an induced wake field, which plays an important role in the lower ion energy region, contributes very little in the present high ion energy case. We observed three split lines for all resonances of (k,l) for the $(2\,\bar{2}\,0)$ plane; a single peak at the higher energy side, and on the other hand, a doublet line at the lower energy side. The skewed single peak has a tail to the higher energy side, and the doublet also has a tail in the lower energy side. These features are commonly observed for other planes.

We also measured the energy deposition, i.e., energy loss in the crystal simultaneously. A given energy loss has close correlation with a specific ion trajectory. An ion passing through the center of the channel has a small possibility of colliding with the target electron, which leads to lower energy loss and vice versa. Energy loss and amplitude of the ion trajectory are related uniquely, when the crystal is thick enough for channeled ions to oscillate many times.

We observed that the energy loss of survived Ar^{17+} ions under the planar channeling is reduced to 8.8 MeV at the peak, compared to that of the emerged ions in the random condition of 17.6 MeV.

The difference of energy loss between Ar^{17+} and Ar^{18+} is considered to be at most 10%, i.e., $[(18^2-17^2)/18^2]$, even in the case of the perfect screening. Therefore, we neglect the ion charge dependence of energy loss as a crude approximation.

The resonance peak intensity, position and width of the survived Ar^{17+} fractions reflect the

Stark splitting due to position (i.e., trajectory) dependent crystal field strength as well as position dependent RCE and electron loss probabilities.

We evaluated the survived Ar^{17+} fraction, $F(\theta, \Delta E)$, as functions of the incident angle, θ, (i.e., the transition energy, which relates to the position dependent crystal field) and the energy deposition, ΔE (i.e., energy loss) by analyzing the list mode data for the RCE peak of $(k, l) = (1, 1)$ in the $(2\,\bar{2}\,0)$ planar channeling. The resonance was observed as a decreased Ar^{17+} fraction. The result is shown in Fig. 2. The survived Ar^{17+} fraction from only 1s electron ionization is observed at the region of off-resonance condition. We noticed that at the region of the minimum ΔE under the resonance condition, sharp peaks of the transition energy exist. As ΔE increases, they shift and broaden simultaneously. The oscillatory ion trajectory with a finite amplitude results in various transition energies, which induces the broadening. However, the channeled ions spend longer time at the position of larger amplitude than at the center of the channel, thereby, the edge energy of the broadened peak of the transition energy gives the transition energy at the position of the largest amplitude of the trajectory.

We calculated transition energies from 1s to $n = 2$ states under the present condition as a function of the distance from the center of the channel, to compare with the observed feature. The result is shown in Fig. 3. Regarding the distance as the trajectory amplitude, we showed the corresponding ΔE also for the amplitude calculated by our simulation [11] in Fig. 3. We obtained energies of eigenvalues of $n = 2$ states of Ar^{17+} in vacuum by the Dirac equation. The perturbation of the Stark field was calculated using the basis set of a combination of nonrelativistic wave functions of 2s, $2p_x$, $2p_y$ and $2p_z$ with spin states, which results in eight sublevels. We take the z-axis parallel to the plane, and x-axis perpendicular to the plane. Each of the calculated four levels is almost degenerated with respect to spin states. We adopted the Hartree–Fock type (Doyle–Turner) potential for the crystal static field. It is noted that the $l \cdot s$ interaction determines the main energy splitting at the channel center, where the native character of a heavy ion like Ar appears because of the small perturbation of the crystal field. This feature does not hold for other RCE measurements reported for low-Z ions. In the calculation, the higher transition probability of RCE is indeed expected for the position away from the channel center. It is consistent with the

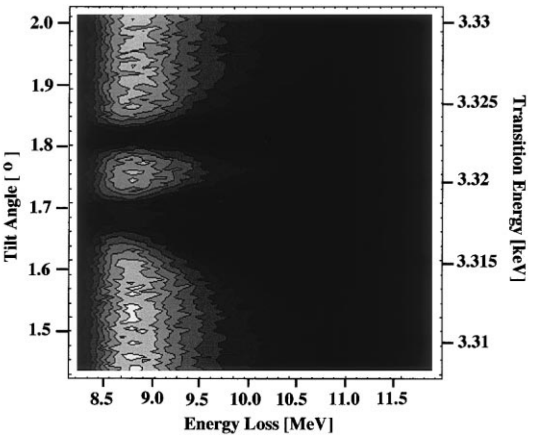

Fig. 2. The intensity of the survived Ar^{17+} fraction as functions of the incident angle, θ, and the energy deposition, ΔE, for the RCE peaks of $(k,l) = (1,1)$ in the $(2\,\bar{2}\,0)$ planar channeling. The corresponding transition energy to θ are inserted in the right scale. The experimental condition is the same as that for Fig. 1.

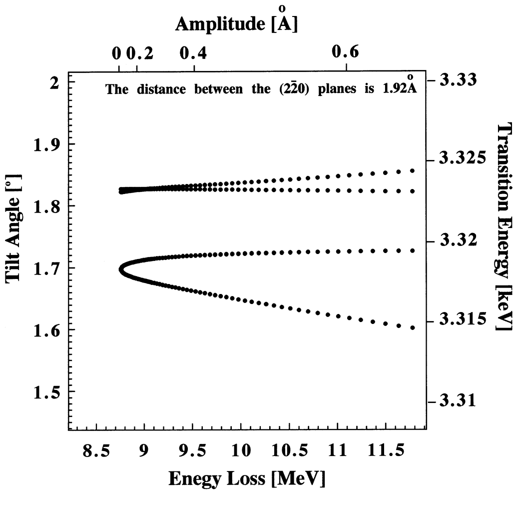

Fig. 3. Calculated transition energies from 1s to $n = 2$ states as a function of the amplitude of the trajectory, which is regarded to be equivalent to the distance from the center of the channel (the uppper scale). The distance between the $(2\,\bar{2}\,0)$ planes is 1.92 Å. The corresponding ΔE for the amplitude is also shown (the lower scale).

fact that the amplitude of the periodic field increases with increasing distance from the center of the channel. Thus, the transition energy and probability as a function of the position in the crystal in our calculation agree quite well with the experimental results.

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