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Resonant coherent excitation of 94 MeV/u Ar^{17+} ions channeling through a Si crystal

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Abstract

The resonant coherent excitation from a 1s state to $n = 2$ states of 94 MeV/u Ar^{17+} ions channeling in the $(2\bar{2}0)$ plane of a Si crystal was observed as the decrease of the survival fraction of Ar^{17+}. Three resonance dips of survival fraction were clearly seen. The resonance profile is attributed to the spin–orbital interaction, the position-dependent Stark effect, the position-dependent transition probability and the position-dependent ionization probability of excited states. The estimated experimental resolution of measurement of the resonance profile is comparable to the width of the narrowest resonance dip (~1.5 eV FWHM) or less.

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1. Introduction

When fast ions enter a crystal in parallel to the crystal axis or crystal plane, some of the ions pass through the crystal without suffering close collisions with atoms of the crystal. This phenomenon is called "channeling". The channeling ion feels an oscillating electric field since it passes through a periodic lattice of the crystal. When the energy difference between two levels of the ion matches with the energy of "quasi-photon" of the oscillating field, the ion is resonant-coherently excited. Such an excitation process is referred to as a "resonant coherent excitation (RCE)".

The RCE process was predicted by Okorokov [1]. The clear observation of RCE was reported by Datz et al. They observed the RCE through the decrease in transmission of fixed-charge-state channeling ions as a function of the ion energy [2]. Since then, the dynamics of the RCE phenomena have been intensively studied both experimentally [3–8] and theoretically [9,10]. Recently, Azuma et al. have performed a series of RCE experiments using planar-channeling of relativistic heavy ions, where the RCE was observed by rotating the

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target crystal instead of varying the projectile energy [5–8]. It was found that the resonance was quite sharp, which suggests an interesting possibility to use the RCE as a new scheme of high-precision spectroscopy of highly charged ions. In order to improve the accuracy of the in-plane rotation angle of the crystal, a high-precision goniometer was newly developed [11]. As the first experiment, the RCE of the 1s–2p transition was measured for 94 MeV/u Ar^{17+} ions.

2. Experiment

Fig. 1 shows a schematic drawing of the experimental setup. A beam of 94 MeV/u Ar^{17+} ions was provided at RIKEN ring cyclotron (RRC). The transport elements of the beamline from the RRC to the target chamber were tuned so that the angular divergence of the Ar beam was minimum. A beam optics calculation predicts that the horizontal and vertical divergences were ± 5.4 μrad and ± 10.5 μrad, respectively, which are consistent with the experimental observation of less than several tens μrad in full width. The beam was collimated with a 3 mm thick tungsten plate with a 0.5 mm ∅ hole about 45 cm upstream of the Si target. The beam optics calculation also shows that the momentum spread of the incident beam was ∼100 ppm in full width. The beam intensity was about one thousand particles/s.

A Si(0 0 1) crystal of 7 μm in thickness was used as a target, which was mounted on the high-precision goniometer [11]. The crystal orientation was checked by X-ray diffraction in advance. The ions passed through the crystal were deflected by an analyzing magnet downstream of the Si target in order to separate the final charge states. A two-dimensional position sensitive detector (2D-PSD) (DLD40: RoentDek Handels GmbH) was located at 8 m downstream of the analyzing magnet. Survived Ar^{17+} ions and charge-changed Ar^{18+} ions were detected there. The position information of the 2D-PSD was collected in a list-mode data acquisition as a function of the orientation of the Si crystal.

Electrons in excited states are much more easily stripped in the target crystal than those in the ground state. Therefore, the survival fraction of Ar^{17+}, $f(17+) = N(17+)/[N(17+) + N(18+)]$, should decrease when the Ar^{17+} ions are resonantly excited, where $N(q+)$ is the number of emerging $q+$ ions.

3. Results and discussion

We observed the RCE under the planar-channeling condition in the $(2\,\bar{2}\,0)$ plane. The resonance condition in this case is given by

$$\frac{k\cos\theta}{A} + \frac{l\sin\theta}{B} = \frac{E_{\mathrm{trans}}}{hc\gamma\beta}, \tag{1}$$

where θ is a rotation angle from the [0 0 1] axis in the plane, E_{trans} is the energy difference between two ionic levels, $\beta = v/c$, v is the ion velocity, c is the light velocity, $\gamma = 1/\sqrt{1-\beta^2}$ and h is the Planck constant. (A, B) is $(a, a/\sqrt{2})$ and a is the lattice constant. k and l are integers.

Under the planar-channeling condition in the $(2\,\bar{2}\,0)$ plane, the survival fraction of Ar^{17+} was ∼68%. Fig. 2 shows the survival fraction $f(17+)$ around the resonance condition with $(k, l) = (3, 1)$ as a function of rotation angle from the [0 0 1] axis.

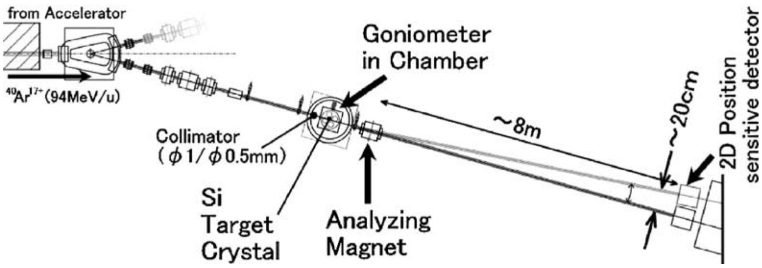

Fig. 1. Schematic drawing of the experimental setup (top view).

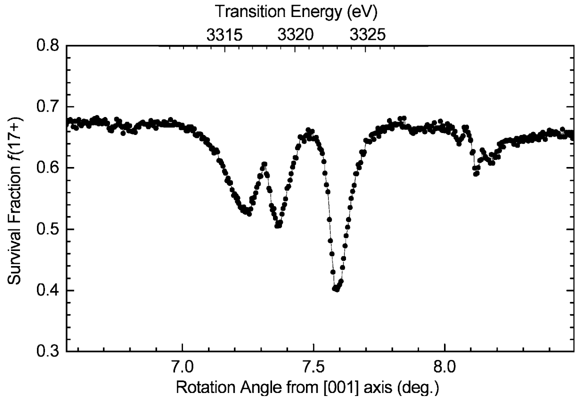

Fig. 2. Survival fraction $f(17+)$ around the resonance condition for $(k, l) = (3, 1)$ as a function of the rotation angle from [0 0 1] axis. The corresponding transition energy for the $(k, l) = (3, 1)$ resonance is shown in the upper scale. The small dip around 8.1° is thought to correspond to the resonance with $(k, l) = (4, -4)$.

RCE's with other indices such as $(k, l) = (3, 2)$, (3,3) and (3,4), were also clearly observed. Three clear dips are seen in Fig. 2. The two dips around 7.3° and the dip around 7.6° are attributed to the transition to $(j = 1/2)$-like states and $(j = 3/2)$-like states, respectively, as is explained later. The resonance width of the $(j = 3/2)$-like states is considerably narrower than that of the first order resonance for 390 MeV/u Ar^{17+} [7]. The corresponding transition energy for $(k, l) = (3, 1)$ is also shown in the upper scale of Fig. 2, which was determined assuming that the bottom of the resonance dip for the $(j = 3/2)$-like states corresponds to 3323 eV, the transition energy of 1s–$2p_{3/2}$ transition in vacuum. This assumption is more or less reasonable because the energy shift of the $(j = 3/2)$-like states from the transition energy of 1s–$2p_{3/2}$ transition in vacuum is very small as is discussed later (see Fig. 3(a)).

The features of the resonance dip is understood as follows [7]: (1) The Stark effect due to the static crystal potential results in splitting of $n = 2$ states into four individual states (Level 1–4 in Fig. 3). Two of them are the $(j = 1/2)$-like states (Level 1 and 2) and the other two are the $(j = 3/2)$-like states (Level 3 and 4). Because the electric field varies as a function of the distance from the channel center, the transition energy varies accordingly. The calculated transition energies [8] for 94 MeV/u Ar^{17+} are shown in Fig. 3(a). It is seen that the splitting of the $(j = 1/2)$-like states is much larger than that of the $(j = 3/2)$-like states. Therefore, the resonance dip of the $(j = 1/2)$-like states are more broadened than that of the $(j = 3/2)$-like states. The observed full-width of the $(j = 1/2)$-like states was ~4.5 eV, which is

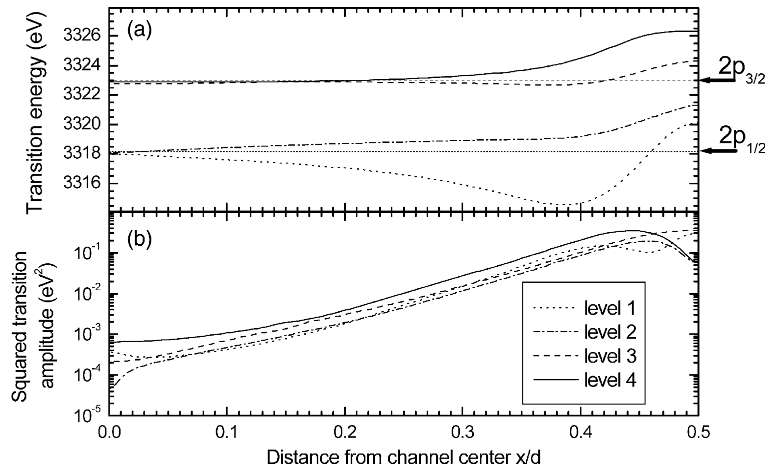

Fig. 3. (a) Transition energies from a 1s state to $n = 2$ states of planar-channeling Ar^{17+} as a function of the distance from the $(2\,\bar{2}\,0)$ channel center. The distance x is normalized by d, where $d = 1.92$ Å is the inter-planar distance. The thin horizontal dotted and dashed lines show 1s–$2p_{1/2}$ and 1s–$2p_{3/2}$ transition energies in vacuum, respectively. (b) Squared transition amplitudes as a function of the distance from the channel center.

consistent with the calculated splitting of $\sim$4.5 eV (see Fig. 3(a)). (2) The transition amplitudes to induce RCE also depend on the distance from the channel center. The squared transition amplitudes are shown in Fig. 3(b) for the $(k, l) = (3, 1)$ resonance of 94 MeV/u Ar^{17+} [8]. As a consequence, the RCE hardly takes place near the channel center even when the resonance condition is fulfilled. On the other hand, the RCE is induced effectively near the channel wall with the transition energy shifted by the Stark effect. Indeed, the $f(17+)$ increases at the resonance condition corresponding to the RCE to the $(j = 1/2)$-like states at the channel center, which is about 3318 eV. This increase of $f(17+)$ seen here is more prominent than that observed in the $(k, l) = (1, 1)$ resonance for 390 MeV/u Ar^{17+} (this resonance corresponds to $\theta \simeq 88.2°$ for our crystal orientation) [7]. This difference may be attributed to the fact that the squared transition amplitudes of the $(k, l) = (1, 1)$ resonance for 390 MeV/u Ar^{17+} are about one order magnitude larger than those of the $(k, l) = (3, 1)$ resonance for 94 MeV/u Ar^{17+} at the channel center. Regarding the $(j = 3/2)$-like states, the level splitting is too small to be observed as a splitting, but the bottom of the resonance dip for the $(j = 3/2)$-like states is rather flat. (3) The ionization probability of the $n = 2$ states becomes larger with approaching the channel wall. Therefore, the decrease of $f(17+)$ at the transition energy corresponding to the transition near the channel wall should be enhanced.

The energy loss of Ar ions in the crystal causes a broadening of the resonance width. The energy loss of channeling ions is roughly a half of that in the random incidence condition [12] and gradually increases as the oscillation amplitude of the ion trajectory increases. Assuming that the energy loss is as large as that in random incidence for a large amplitude transmission and that the resonance takes place uniformly along the whole path, the broadening of the resonance width is estimated to be $\sim$2 eV for the transition energy around 3320 eV. The actual broadening arising from the energy loss is thought to be somewhat smaller than this value. The spread of the initial beam momentum ($\sim$100 ppm) also causes a broadening of the resonance width. The corresponding width is estimated to be $\sim$0.3 eV for the transition energy around 3320 eV. The resonance width broadening caused by the beam angular divergence (several tens μrad or smaller) is much smaller than that caused by the initial momentum spread. The uncertainty of angle setting of the goniometer is negligibly small [11]. Thus, the experimental resolution considered here are comparable to the dip width corresponding to the $(j = 3/2)$-like states ($\sim$1.5 eV FWHM) or less.

As described above, the resonance dip for the $(j = 3/2)$-like state observed in the present experiment was unexpectedly narrower than that observed for 390 MeV/u Ar^{17+} ions [7]. Although the reasons of this observation are not known at the moment, we could list up a few possibilities as follows: (1) A relative initial velocity spread of the 94 MeV/u Ar^{17+} beam here is narrower than that of the 390 MeV/u Ar^{17+} beam. (2) The angular divergence of the 94 MeV/u Ar^{17+} beam is smaller than that of the 390 MeV/u Ar^{17+} beam. (3) According to Eq. (1), the relative width of transition energy due to the beam angular divergence $\Delta\theta$ is given by

$$\frac{\Delta E_{\mathrm{trans}}}{E_{\mathrm{trans}}} = \frac{-k\sin\theta/A + l\cos\theta/B}{k\cos\theta/A + l\sin\theta/B}\Delta\theta, \tag{2}$$

where $\Delta E_{\mathrm{trans}}$ is the resonance dip broadening due to beam angular divergence $\Delta\theta$. The $\Delta E_{\mathrm{trans}}/E_{\mathrm{trans}}$ at the present $(k, l) = (3, 1)$ RCE is about a half of that at the $(k, l) = (1, 1)$ RCE of the 390 MeV/u Ar^{17+} even for the same $\Delta\theta$. As a consequence of these three reasons, it is reasonable that the resonance width in the present experiment is narrower than that observed for 390 MeV/u Ar^{17+} ions. However, there may be other important reasons to cause the large difference of the resonance widths between the present experiment and the experiment using 390 MeV/u Ar^{17+}. A more detailed quantitative analysis is in progress.

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