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Resonant Coherent Excitation of Hydrogen-Like Ar Ions to the $n = 3$ States

T. Azuma[1]*, T. Ito[2], Y. Takabayashi[2], K. Komaki[2], Y. Yamazaki[2,3], E. Takada[4] and T. Murakami[4]

[1] Department of Physics, Tokyo Metropolitan University, Hachioji, Tokyo 192-0397, Japan
[2] Institute of Physics, Graduate School of Arts and Sciences, University of Tokyo, Komaba, Meguro, Tokyo 153-8902, Japan
[3] Atomic Physics Laboratory, RIKEN, Wako, Saitama, 351-0198, Japan
[4] National Institute of Radiological Sciences, Inage, Chiba 263-8555, Japan

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Abstract

We have succeeded in observing resonant coherent excitaion (RCE) of 1s electrons to the $n = 3$ states in 390 MeV/u hydrogen-like Ar^{17+} ions planar channeled in a silicon crystal through measurements of the charge-state distribution of ions transmitting the crystal. Furthermore, we directly confirmed RCE to the $n = 3$ states by observing the enhancement of the de-excitation X-rays, i.e., K_β X-rays under the resonance condition. The resonance profiles of the charge-state distribution as functions of the incident angle to the crystal, which uniquely relates with the transition energy, have a characteristic structure consisting of several peaks. Compared with the profile of RCE to the $n = 2$ states, the present profiles show a large peak shift from the $j = 1/2$ and 3/2 levels in vacuum, and the profiles are much wider than those expected from the Stark-split level structure of the $n = 3$ manifolds due to the position-(distance from the channel center in the planar channel) dependent strong static field in the crystal.

1. Introduction

Energetic ions are guided by a lattice to travel along a crystal axis or plane in a ‘‘crystal channeling’’ condition. The ion trajectory is determined by the static continuum potential in a crystal. In addition the ions traveling across a periodic array of atomic strings or ordered planes experience an oscillating field in the projectile frame. When one of the frequencies of the oscillation matches with an atomic transition energy of the ion, it will be resonant coherently excited (RCE) [1–9].

When we consider RCE of 1s electrons to the excited states of hydrogen-like ions, the excited ions through RCE decay in two complementary ways. They are more easily ionized by the target electron impact in the crystal than those in the ground state, and are observed as a decrease of the surviving fraction of hydrogen-like ions among the transmitted ions. Otherwise, the excited states are radiatively de-excited to the ground state. We succeeded in observing the trajectory-, i.e., impact parameter-dependent RCE of relativistic heavy ions through the ionization of the excited ions, and demonstrated that the RCE transition energy reflects spin-orbit ($l \cdot s$) interaction and Stark effect originating from the static continuum potential [7,8]. Furthermore, we observed the X-ray emission from the excited heavy ions through RCE [9].

In this article we report a recent observation of RCE of 1s electrons to the $n = 3$ states in 390 MeV/u hydrogen-like Ar^{17+} ions planar channeled in a Si crystal (i.e., ions travel in an open space between two adjacent crystal planes) through measurements of the charge-state distribution of transmitted ions from the crystal. Generally, the ionization cross sections by the target electron impact of low-Z ions in the high n-states are larger, and the resulting short lifetime of the excited states tends to lead a broad resonance width to be observed. Accordingly, high-Z ions with a large velocity are advantageous to the observation of RCE to the higher n-states. The large ion velocity is very important also for the precise determination of the transition energy, since the high coherency is attainable by ions passing a number of atomic strings without disturbance by the target electron impact excitation or ionization. The observation of RCE of Si^{13+} ions to the $n = 3$ states was previously reported [10], however, we for the first time found a striking structure with several peaks in the resonance profiles.

2. Experimental

A beam of 390 MeV/u Ar^{17+} ions was supplied at the Heavy Ion Medical Accelerator at Chiba (HIMAC). The experimental setup was the same as that for RCE to the $n = 2$ states described elsewhere [7–9]. The beam of Ar^{17+} ions passed through a 21 μm-thick Si crystal, whose $(2\bar{2}0)$ plane was placed horizontally, and the charge-state distribution of the transmitted ions was measured with a combination of a charge separation magnet and a 2D-position sensitive Si detector located at the downstream end of the beam line. The X-rays emitted from Ar ions were also measured by a Si(Li) detector located at an angle of 41° with respect to the beam direction on the horizontal plane.

We observed RCE in a planar channeling by changing the tilt angle, θ, successively from the direction of the [110] axis in the $(2\bar{2}0)$ plane up to about 10° to cover both resonance conditions of the $n = 2$ and 3 excitations.

From the resonance condition, the transition energy, E_{trans}, for a specific pair of k and l uniquely relates with the tilt angle by the equation

$$k \cos\theta/(a/\sqrt{2}) + l \sin\theta/a = E_{\mathrm{trans}}/\gamma h v, \tag{1}$$

where a is the lattice constant of a Si crystal, and the 2D Miller index (k, l) specifies the direction of atomic strings to be passed by the ions on the channeling plane [2,8].

*e-mail: azuma@phys.metro-u.ac.jp

3. Results and discussion

In the $(2\bar{2}0)$ planar channeling, the surviving fraction of Ar^{17+} ions passing through the crystal is about 25% as seen in Fig. 1. It is noted that this fraction sensitively reflects the quality of crystal samples reflecting the small critical angle of relativistic channeling. As shown in Fig. 1, resonances of the electronic transition from 1s to the $n = 3$ states corresponding to $(k, l) = (1, 2)$, (1,3), (1,5), and (1,6) were clearly observed as decreases in the surviving Ar^{17+} fraction in transmitted Ar ions, together with resonances from 1s to the $n = 2$ states corresponding to $(k, l) = (1, 1), (1,2), (1,3), \cdots$, when we change the tilt angle. We note that a resonance for $(k, l) = (1, 4)$ is not expected because of the extinction rule originating from the diamond structure of a Si crystal [8,11].

It is apparent that all of the observed profiles in the resonance conditions have a characteristic structure with peaks. With use of the relation of Eq. (1), we can obtain the transition energy from the tilt angle, and thus we made resonance profiles as functions of the corresponding transition energy as shown in Fig. 2 for $n = 2$ states and Fig. 3 for the $n = 3$ states, respectively.

First, as seen in Fig. 2, the resonance profiles of RCE to the $n = 2$ states for all pairs of (k, l) consist essentially of two peaks for $j = 1/2$ and $j = 3/2$ split by $l \cdot s$ interaction, as was demonstrated [7,8]. Two arrows in Fig. 2 show the transition energies to these levels in vacuum. The skewed shape of the two peaks and the doublet structure of the $j = 1/2$ peak are understood by Stark-split levels of the $n = 2$ states and by the position-dependent RCE and ionization probabilities. That is,

(1) The Stark effect due to the static continuum potential depends on the position (as functions of the distance from the channel center), and results in four individual levels (see Fig. 4 in [7]). The $j = 1/2$ peak splits into two levels (Level 1 and 2), and the $j = 3/2$ peak into two levels (Level 3 and 4) in the field.
(2) The RCE probability of each level also depends on the position reflecting a Fourier component of the corresponding oscillating potential, $\phi_{k,l}$, due to the (k, l) string, as well as the composition of the Stark-mixed wavefunctions.
(3) The ionization probabilities of the excited states are larger in the region close to the wall because of higher target electron densities.

The position dependence of the Stark-mixed levels tells us that the central positions of the $j = 1/2$ and $j = 3/2$ peaks in the resonance profile correspond to RCE at the channel center where both RCE and ionization probabilities fall to minimum. This is the origin of the dip formation of the $j = 1/2$ peak. The channeled ions spend longer time at the position of the larger amplitude along their oscillatory trajectories than at the channel center, which also contributes to the dip formation. The position-dependent level shift of Level 3 and 4 is too small to form a dip for the position integrated $j = 3/2$ peak. The (k, l) dependence of the resonance profiles is understood by the difference of each $\phi_{k,l}$. (see Fig. 4 in [8]). The transition matrix element which gives the transition probability depends on the intensity of the oscillating field, i.e., the gradient of the potential, $\phi_{k,l}$. A pair of (k, l) of the higher order generally corresponds to the smaller Fourier component of the oscillating field.

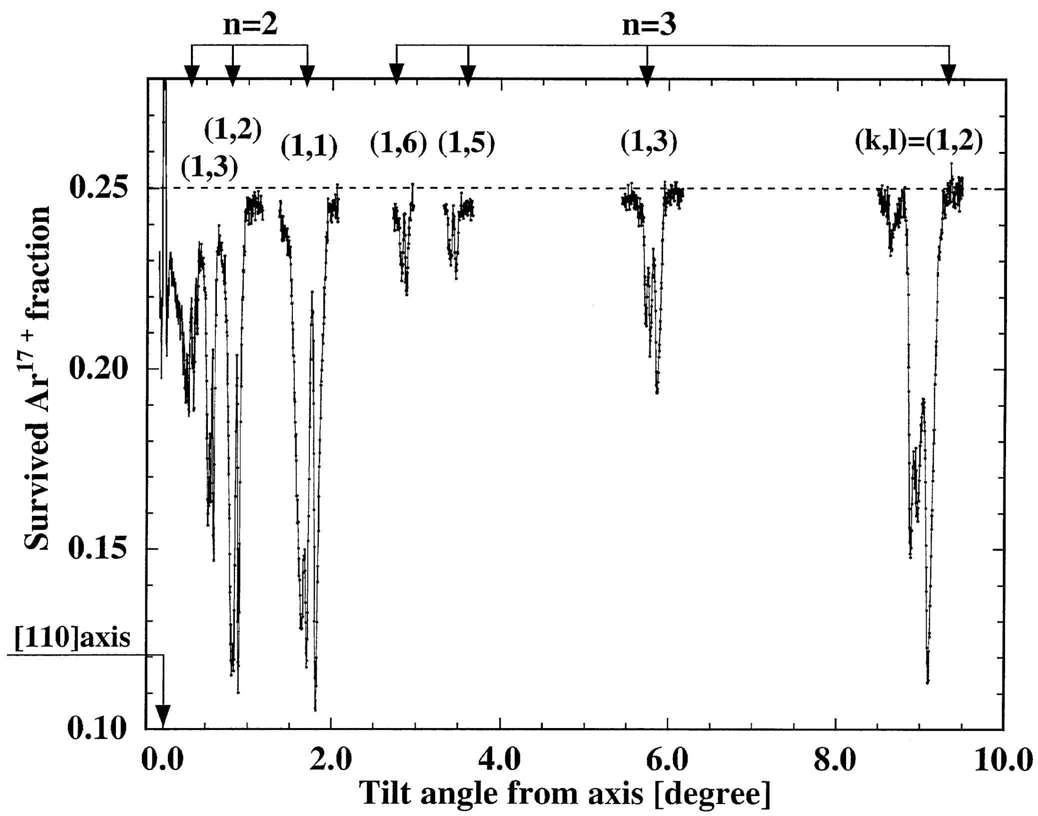

Fig. 1. The RCE profiles of the transitions from 1s to the $n = 3$ states for $(k, l) = (1,2)$, (1,3), (1,5), and (1,6), together with those from 1s to the $n = 2$ states for $(k, l) = (1,1)$, (1,2), (1,3), ..., in the $(2\bar{2}0)$ planar channeling for the surviving Ar^{17+} fraction among transmitted Ar ions through a 21 μm-thick Si crystal as functions of the tilt angle from the [110] axis in the $(2\bar{2}0)$ plane.

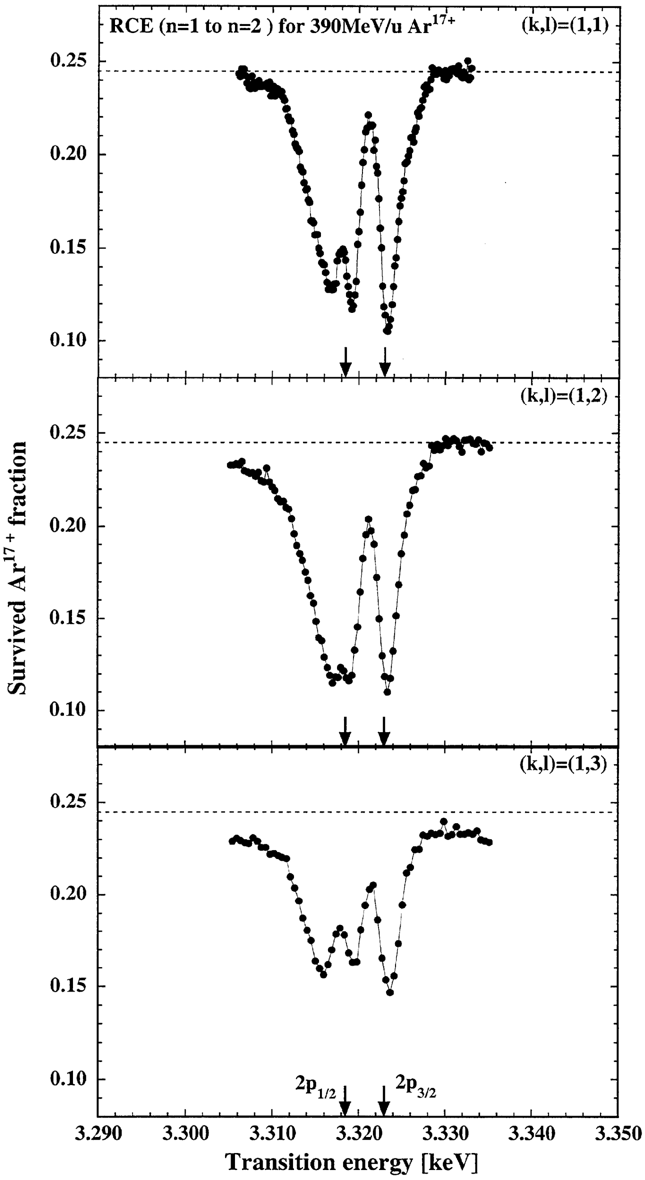

Fig. 2. The RCE profiles of the transitions from 1s to the $n = 2$ states for $(k, l) = (1,1), (1,2), (1,3)$ plotted as functions of the transition energy, E_{trans}. Two arrows indicate the resonance position for $2p_{1/2}$ and $2p_{3/2}$ in vacuum.

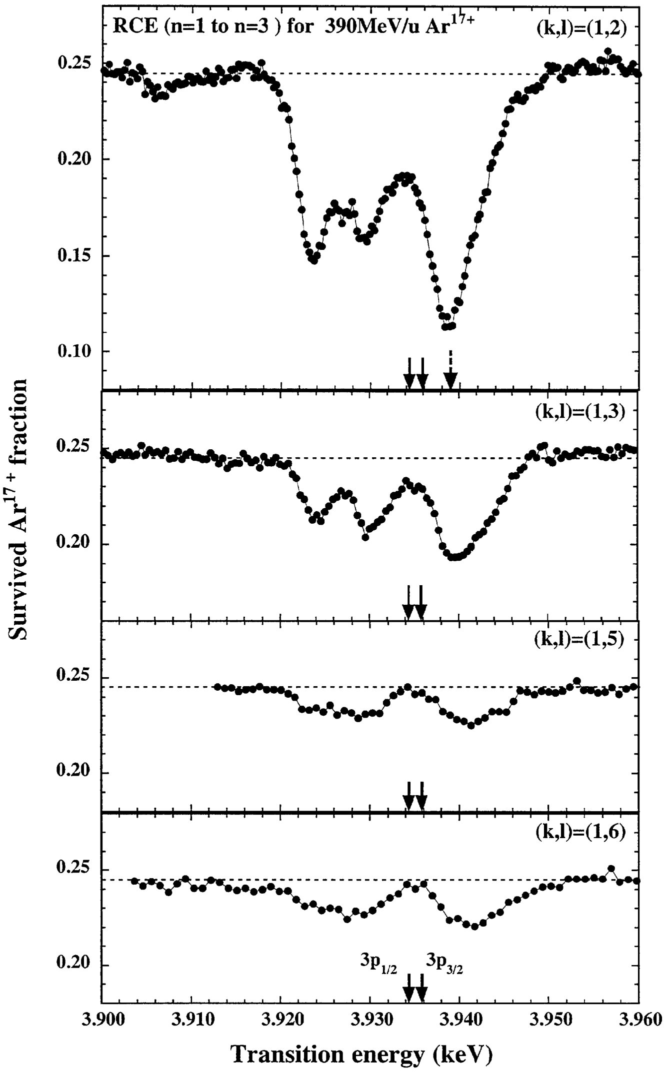

Fig. 3. The RCE profiles of the transitions from 1s to the $n = 3$ states for $(k, l) = (1,2), (1,3), (1,5)$, and $(1,6)$ plotted as functions of the transition energy, E_{trans}. Two arrows with solid lines indicate the resonance position for $3p_{1/2}$ and $3p_{3/2}$ in vacuum, and an arrow with a dashed line shows the position for the X-ray measurements.

The resonance profiles of RCE to the $n = 3$ states shown in Fig. 3, at a glance, have a similar structure with comparable intensities to those of RCE to the $n = 2$ states. However, they are quite different in reality. We can compare the resonance profiles for the $n = 2$ and the $n = 3$ states for an identical (k, l), i.e., an identical Fourier component of the potential, $\phi_{k,l}$, and the observed differences in the resonance profiles are attributed to the properties of the ions themselves. Two arrows in Fig. 3 again show the transition energies to the $j = 1/2$ and $j = 3/2$ levels in vacuum. The split due to $l \cdot s$ interaction is smaller than that for the $n = 2$ states, and these positions are obviously different from the observed peaks, which is a striking contrast with the case of the $n = 2$ states where the peak position matches quite precisely with the theoretical value as already described. Furthermore, the resonance profiles are more broadened than the case for the $n = 2$ states. When we consider the Stark-mixed $n = 3$ manifolds, the corresponding energies are split into nine individual levels in the field, and extended widely. However, the observed broadening of the resonance profiles are much wider than the energy width expected from the Stark-split level structure, which is considered to be roughly proportional to $n(n - 1)$ for the linear Stark effect.

In order to directly confirm RCE to the $n = 3$ states, we measured the de-excitation X-rays emitted from Ar ions under the resonant condition for $(k, l) = (1, 2)$. That is, we measured them at the point of the transition energy of 3.939 keV, where we observed the strongest resonance in the charge-state resonance profile as is indicated by a dashed arrow in Fig. 3.

In the $(2\bar{2}0)$ planar channeling under the non-resonant condition, we observed K_α X-rays of Ar ions at 5.0 keV Doppler-shifted due to the present large ion velocities. Under the RCE condition, we found an evident enhancement of K_β X-ray of Ar ions at 5.9 keV corresponding to the $n = 3$ excitation. The present enhancement is, however, smaller than that of RCE to the $n = 2$ states, i.e., K_α X-ray enhancement [9]. This is reasonable partly because the

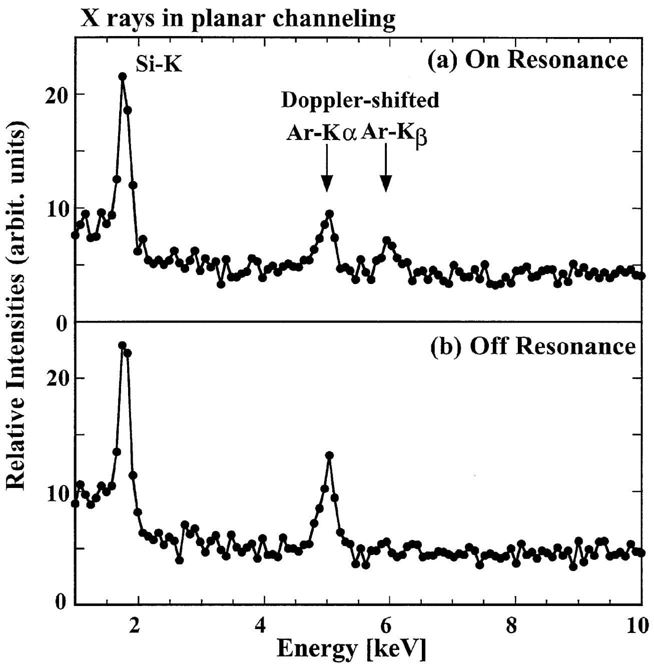

Fig. 4. **(a)** The X-ray energy spectra under the RCE condition at $E_{\rm trans} = 3.939$ keV, and **(b)** those for in the $(2\bar{2}0)$ channeling but not under the RCE condition.

ionization probability by the target electron impact is larger for the ions excited to the $n = 3$ states than those to the $n = 2$ states by ~ 2.3 times, when we crudely scale it by $\ln(T/E_{bin})/(T \cdot E_{\rm bin})$ (T: electron energy at the equivalent velocity to a projectile, $E_{\rm bin}$: an electron binding energy of a projectile), and partly because the de-excitation lifetime is ~ 3.3 times longer [12]. These features result in the ionization channel favored as the decay mode, and lead to the large RCE intensities observed in the charge-state distribution. The K_α X-ray intensity is rather weak under the RCE condition. This is explained by the fact that the excitation of 1s electrons to the $n = 2$ states by target electron impact is suppressed by RCE to the $n = 3$ states. We also note that the 3p state decays not only to the ground state but also to the 2s state, however, its decay rate is slower by ~ 7.5 times [12].

4. Conclusions

In conclusion, we observed resonant coherent excitation (RCE) of 1s electrons to the $n = 3$ states in 390 MeV/u hydrogen-like Ar^{17+} ions planar channeled in a silicon crystal through measurements of the charge-state distribution of transmitted ions from the crystal. We also confirmed RCE to the $n = 3$ states by the observation of enhancement of the de-excitation K_β X-rays. We for the first time found a characteristic broad structure with peaks in the resonance profiles of the charge-state distribution. Compared with the profile of RCE to the $n = 2$ states, the present profiles show a large peak shift from the $j = 1/2$ and $3/2$ levels in vacuum, and the profiles are much wider than those expected from the Stark-split level structure of the $n = 3$ manifolds due to the position-dependent strong static field in a crystal.

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