Resonant Coherent Excitation of Li-like Ar$^{15+}$ Ions in a Thin Si Crystal

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Abstract. We investigated resonant coherent excitation (RCE) of 445 MeV/u Li-like Ar$^{15+}$ under the planar channeling and non-channeling conditions. The K-shell and L-shell excitations are observed as decreases in the survival fraction of the Ar$^{15+}$ ions after passing through a thin Si crystal. RCE under the planar channeling condition provides the opportunity to study a strong static Stark effect on the Li-like system with K-shell or L-shell vacancy. Under the non-channeling conditions, the observed excitation energies and the reported theoretical calculations were in reasonable agreement.

1. Introduction

When energetic ions are in flight through a crystal, they experience a temporally-oscillating field originating from the periodic crystalline structure. This oscillating field induces resonant coherent excitation (RCE) of the ions if the frequency matches their internal energy difference. It was predicted by Okorokov in 1965 [1] and extensively studied with H-like or He-like systems due to their simple atomic structures [2, 3, 4, 5, 6]. RCE of the L-shell electron in Li-like Fe$^{23+}$ was observed under the planar channeling condition, where the ions travel parallel to an array of atomic planes [7]. The channeling conditions have been generally preferred for the observation of RCE taking advantage of reducing the non-resonant collisional processes with the target atoms [8, 9]. On the other hand, study of RCE under the non-channeling conditions has greatly progressed in recent years with use of a relativistic ion beam and a thin crystal [10, 11]. RCE under the planar channeling and non-channeling conditions are referred to as two-dimensional and three-dimensional RCEs (2D- and 3D-RCEs), respectively. Here we report on 2D- and 3D-RCE of L-shell and K-shell electrons in Li-like Ar$^{15+}$ ion (Fig. 1).

The resonance condition of 3D-RCE is written as

$$\Delta E = \frac{h\gamma v}{a} \left\{ \sqrt{2} (k \cos \phi + m \sin \phi) \cos \theta + l \sin \theta \right\},$$  (1)
where \( h \) is Planck's constant, \( v \) is the ion velocity, \( \gamma \) is the Lorentz factor, \( (k, l, m) \) is the Miller index, \( \theta \) and \( \phi \) are the rotation and tilt angles used to describe the orientation of the crystal with respect to the ion beam [10]. When \( \phi = 0^\circ \), the (220) planar channeling condition is satisfied and the index \( m \) vanishes, leading to the 2D-RCE condition. In this condition, the ions experience not only the oscillating fields but also the static field due to the (220) atomic planes, which induce the static Stark effect [10]. In contrast, since the (220) planar potential is experienced as an oscillating field by the non-channeling ions, 3D-RCE is free from the static Stark effect. Note that ac Stark effect by the oscillating field remains in 3D-RCE [11].

2. Experiment

The experiments were performed at the heavy ion medical accelerator in Chiba (HIMAC). The 445.43 MeV/u \( \text{Ar}^{15+} \) ion beam was charge-analyzed after passing the thin Si crystal mounted on a high precision goniometer. The path length in the crystal was 1.0 \( \mu \text{m} \). We monitored the survival fraction (fraction of \( \text{Ar}^{15+} \) in the emerged ion beam) as a function of the incident angle \( \theta \) while fixing \( \phi \). Since the cross-section of the collisional ionization in the crystal is larger for the excited states, RCE is observed as a decrease in the survival fraction. In the K-shell excitation, the KLL Auger process also contributes to the decrease of the survival fraction. Note that the electron capture cross-section is negligibly small in the present high-energy region. The beam velocity was determined by the well-known transition of \( \text{Ar}^{16+} \) \( 1s^22s\,1s^22p(1^P) \) (3139.55 eV) by 3D-RCE, which was produced by the collisional ionization of \( \text{Ar}^{15+} \) in the crystal.

3. Result and Discussion

3.1. L-shell excitation

We observed 2D- and 3D-RCEs of the 2s electron to the \( n = 3 \) states using the frequency components of the oscillating field specified by \( (k, l) = (0, 1) \) and \( (k, l, m) = (0, 1, -1) \), respectively. Figure 2(a) shows the survival fractions of \( \text{Ar}^{15+} \) under the (220) planar channeling, where the tilt angle \( \theta \) was converted to the transition energy using Eq. (1) with \( (k, l) = (0, 1) \) and \( \phi = 0 \). The dip positions of 2D-RCE did not agree with the theoretical transition energies from \( 1s^22s \) to \( 1s^23s(2S) \), \( 1s^23p(2P) \) and \( 1s^23d(2D) \) in vacuum [12], which are indicated by arrows in the figure. This is mainly due to the static Stark mixing between the \( n = 3 \) states induced by the (220) planar potential.

By contrast, in 3D-RCE observed at \( \phi = -0.17^\circ \) (Fig. 2(b)), the dip positions reasonably agreed with the theoretical transition energies, since 3D-RCE is free from the static Stark effect. Note that the 2s-3s and 2s-3d transitions were observed, although the electric dipole transition is dominant in 3D-RCE [13]. These forbidden transitions can be explained as a result of the ac Stark mixing between the 2s and 2p states induced by other harmonics of the oscillating fields near the 2s-2p resonance, that is, \( (k, l, m) = (0, 0, 2) \) and \( (0, 0, 4) \). In the frame work of
survival fractions of Ar$^{15+}$ under the (a) planar channeling and (b) non-channeling conditions as a function of the transition energy. The arrows indicate the transition energies to $2S_{1/2}$, $2P_{1/2}$, $2P_{3/2}$, $2D_{3/2}$ and $2D_{5/2}$ of the 1$s^23l$ states in ascending order.

Figure 3. Survived fractions of Ar$^{15+}$ under the (a) planar channeling and (b) non-channeling conditions as a function of the transition energy. The arrows indicate the transition energies to $2P_{1/2}$, $2P_{3/2}$, $2P_{1/2}^+$ and $2P_{3/2}^+$ of the 1$s$2$s2$p$ states in ascending order.

The perturbative treatment, the maximum mixing is evaluated to be 5% and the corresponding energy shift is less than 0.2 eV.

3.2. K-shell excitation

Excitation of the 1$s$ electron to the 2$p$ states was also observed. Figures 3(a) and (b) show the 2D- and 3D-RCE spectra induced by the frequency components $(k,l)=(1,-1)$ and $(k,l,m)=(1,-1,0)$, respectively. The theoretical transition energies of the $1s(2S)2s2p(1P)$ and $1s(2S)2s2p(3P)$, i.e., $2P^+$ and $2P^-$, calculated by Chen et.al. [14] are indicated in the figures. Since the energy differences between the mixable states are large in the $n=2$ states compared to the $n=3$ states, the positions of resonance dips in 2D-RCE are close to those in 3D-RCE. However, the intensity ratio of the two dips is apparently different between 2D- and 3D-RCEs, which sensitively reflect the static Stark mixing in 2D-RCE.

In 3D-RCE, as well as the L-shell excitation, the observed excitation energies reasonably
agreed with the theoretical transition energies. It is noted that the ac Stark mixing between
the $2s$ and $2p$ states discussed above does not affect the excitation energies of 3D-RCE by
$(k, l, m) = (1, 1, 0)$ due to the fact that the polarization direction of the oscillating field specified
by $(k, l, m) = (1, 1, 0)$ and $(0, 0, m)$ are orthogonal. Therefore, the ions are not excited to the
magnetic substates of the $1s2s2p$ states mixed with other states by the ac Stark effect.

4. Summary
We observed 2D-RCE and 3D-RCE of Li-like $\text{Ar}^{15+}$ in a thin Si crystal. In the L-shell excitation
under the planar channeling condition, we observed strong static Stark effect in the 2D-RCE
spectrum, which was not observed under the non-channeling condition. Furthermore, we
succeeded in observing RCE of the K-shell electron in Li-like system for the first time. The
intensity ratio of K-shell excitation to $2P^+$ and $2P^-$ was affected by the static Stark effect in
2D-RCE. In both cases, the transition energies observed by 3D-RCE well agreed with theoretical
calculations. This work points the way toward the production of triply excited Li-like system
in combination with the double resonance technique [11, 15]. The experiment for successive
excitations of the $1s$ electrons in Li-like system are now in progress.

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