Impact Parameter Dependent Resonant Coherent Excitation of Relativistic Heavy Ions Planar Channeled in Crystals

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Resonant coherent excitation of a $1s$ electron to $n = 2$ states in relativistic 390 MeV/nucleon hydrogenlike Ar^{17+} ions has been observed through measurements of the surviving charge state of Ar^{17+} ions planar channeled in a Si crystal. We experimentally demonstrate trajectory-dependent, i.e., impact parameter dependent resonant-coherent-excitation phenomena by measuring the energy deposition in coincidence with the charge state of emerging ions. The resonant-coherent-excitation transition energy reflects spin-orbit ($\mathbf{l} \cdot \mathbf{s}$) interaction and Stark effect originating in the static crystal field, which is in good agreement with calculations.

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Ions passing through a periodic lattice (ordered rows or planes) of a crystal feel a time dependent perturbation of the potential. When one of the frequencies of the perturbation corresponds to the difference of internal energy levels of the ions, resonant coherent excitation (RCE) occurs.

The RCE process and the possibility of radiative deexcitation were first predicted by Okorokov [1]. The first observation of RCE through the exit charge state distribution of low-Z heavy ions was reported by Datz *et al.* in 1978 [2]. Since then, much progress in understanding RCE in experiments [3,4] and theories [5,6] has been made.

Here we report the observation of trajectory, i.e., impact parameter dependent RCE of heavy ions. The relativistic ion energy is very important to this observation. The reasons are as follows: (1) The first-order Fourier component of the crystal periodic potential leads to a large excitation probability. (2) The contribution of the electron capture process is much reduced, so that we can extract the resonance phenomenon without it being obscured. (3) This situation allows us to adopt a relatively thick Si surface barrier detector as a crystal target for probing the energy deposition in the target. The observed energy deposition of a channeled ion relates to an amplitude of the ion trajectory. Thus, trajectory, i.e., impact parameter dependent information of RCE is obtained.

We investigated the RCE of a $1s$ electron to $n = 2$ states in hydrogenlike Ar^{17+} ions through measurements of the surviving fraction of 390-MeV/nucleon Ar^{17+} ions planar channeled in a Si crystal. Argon is the heaviest ion with the highest transition energy ever reported in experiments on RCE.

A well-collimated (an angular divergence of less than 0.15 mrad) beam of Ar^{17+} ions of 390 MeV/nucleon, was supplied at the Heavy Ion Medical Accelerator at Chiba (HIMAC). The detailed experimental setup was described elsewhere [7,8]. We adopted totally depleted Si surface barrier detectors of 78.5 and 94.7 μm thickness as crystal targets [9]. The electrons in the excited state are more easily stripped off by the target atom than those in the ground state, which results in a decrease in the survival probability of resonantly excited hydrogenlike Ar^{17+} ions. The charge state of emerging ions was measured with a combination of a charge separation magnet and a 2D position-sensitive Si detector located downstream of the Si crystal target. The charge state, q, and the energy deposition, ΔE, were simultaneously accumulated in "list mode" as a function of the crystal orientation, θ, to obtain the number distribution, $N^q(\theta; \Delta E)$, for $q = 17$, 18.

The incident ion velocity cannot be readily scanned for the synchrotron-type accelerator. Therefore, we observed RCE under planar channeling by changing the angle from the direction of the $[110]$ axis in the $(2\bar{2}0)$, (004), or $(1\bar{1}1)$ planes [10]. The resonance condition in this case is given by

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

where k and l are integers, θ is an incident angle from the $[110]$ axis in the plane, E_{trans} is an energy level difference, $\beta = v/c$, v is the ion velocity, c is the light velocity, and $\gamma = 1/\sqrt{1 - \beta^2}$. (A, B) is $(a/\sqrt{2}, a)$, $(a/\sqrt{2}, a/\sqrt{2})$, and $(a/\sqrt{2}, \sqrt{3}a/\sqrt{2})$ for the $(2\bar{2}0)$, (004), and $(1\bar{1}1)$ planes, respectively, and a is the lattice constant. The surviving fraction of Ar^{17+} ions passing through the present Si crystal of about 100 μm thickness in a random direction was less than 1×10^{-3}. Under channeling conditions, however, it amounts to several tens of percent. While varying the incident angle from the $[110]$ axis in the $(2\bar{2}0)$ plane, resonances of the electronic transition from $1s$ to $n = 2$ states in Ar^{17+} ions corresponding to $(k, l) = (1, 1)$, $(1, 2)$, $(1, 3)$, $(1, 5)$, and $(1, 6)$ were very clearly observed as a decrease in the surviving Ar^{17+} fraction,

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$f^{17}(\theta)$, which is defined as $f^q(\theta) = \int f^q(\theta; \Delta E) d\Delta E$. $f^q(\theta; \Delta E)$ is normalized by the total number of emerging ions, i.e., $f^q(\theta; \Delta E) = N^q(\theta; \Delta E)/N^T(\theta)$, where $N^T(\theta) = \Sigma_{q=17,18} \int N^q(\theta; \Delta E) d\Delta E$. Note that $\Sigma_{q=17,18} f^q(\theta) = 1$. $f^{17}(\theta)$ for $(k, l) = (1, 1)$ is shown in Fig. 1. The transition energy which is associated with the varied angle in Eq. (1) is given as the lower scale in Fig. 1. The experimental resolution of θ is 0.0046° corresponding to a transition energy of 0.18 eV.

The peak profile consists of several lines; a single peak at the higher energy side and a doublet peak at the lower energy side. The single peak skews to the higher energy side, and the doublet also has a tail in the lower energy side. These features are common to all observed resonance lines for the $(2\bar{2}0)$ plane, and also to those corresponding to $(k, l) = (1, 1)$, $(1, 2)$, $(1, 3)$, $(1, 4)$, and $(1, 5)$ for the (004) plane, and $(k, l) = (1, 1)$, $(1, 3)$, and $(1, 5)$ for the $(1\bar{1}1)$ plane [8].

Two arrows in Fig. 1 show the resonance positions for $1s$-$2p$ transition energies in vacuum, 3.3182 keV ($j = 1/2$) and 3.3230 keV ($j = 3/2$) [11]. The observed split results from the removal of the degeneracy of $n = 2$ states primarily due to the $\mathbf{l} \cdot \mathbf{s}$ interaction which is stressed for a heavy nucleus such as Ar. It was not observed in other RCE measurements reported for low-Z ions. In addition, the Stark effect originating from the static crystal field also contributes to the skewed profiles and tail structures as well as the doublet feature in the lower energy peak. Note that an induced wake field, which would play an important role in the lower ion energy region, contributes very little at the present high ion energy since the field is about 0.5 V/Å. It is evaluated from the relation $F_{\text{wake}} = S/Z$, where F_{wake} is the wake field, S is the stopping power, and Z is the projectile charge. On the other hand the typical crystal field, for instance, the (110) planar continuum field at 0.5 Å distance from the channel center, is about 20 V/Å.

An energy loss and an amplitude of a specific ion trajectory are related uniquely when the crystal is thick enough for channeled ions to oscillate many times. An ion passing at the center of the channel has a small possibility of colliding with the target electrons, which leads to lower energy loss. The energy deposition of surviving Ar^{17+} ions under planar channeling conditions is reduced to 8.8 MeV at the peak, compared to 17.6 MeV for emerging Ar^{18+} ions in a random orientation.

For the RCE peak of $(k, l) = (1, 1)$ in $(2\bar{2}0)$ planar channeling, $f^{17}(\theta; \Delta E)$ which is a differential with respect to the energy deposition in the crystal target ΔE is shown in Fig. 2 as a contour plot. We show the amplitude of trajectories corresponding to ΔE also in Fig. 2 [12]. Accordingly, $f^{17}(\theta; \Delta E)$ is expressed as functions of E_{trans} and the amplitude. It is to be noted that ejected high energy secondary electrons from the crystal target reduce the energy deposition in the detector. We take this contribution into account for evaluation of the energy loss from the deposited energy [13]. The ion charge dependence of the energy loss is disregarded, because the difference of the 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 complete bound-electron screening [14]. The experimental resolution of the energy deposition is less than 100 keV. However, the straggling width of the energy deposition is estimated to be about 1.0 MeV,

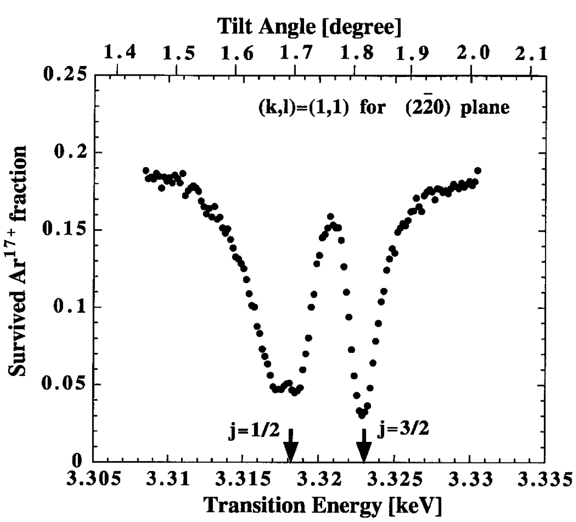

FIG. 1. The RCE peak of $(k, l) = (1, 1)$ in $(2\bar{2}0)$ planar channeling. The surviving Ar^{17+} fraction, $f^{17}(\theta)$, passing through a 94.7-μm Si crystal as a function of the tilt angle from the [110] axis, θ, in the $(2\bar{2}0)$ plane is shown. The transition energy, E_{trans}, is shown on the lower scale. Two arrows represent the resonance positions for $1s$-$2p$ energy levels ($j = 1/2$ and $j = 3/2$) of Ar in vacuum including the Lamb shift.

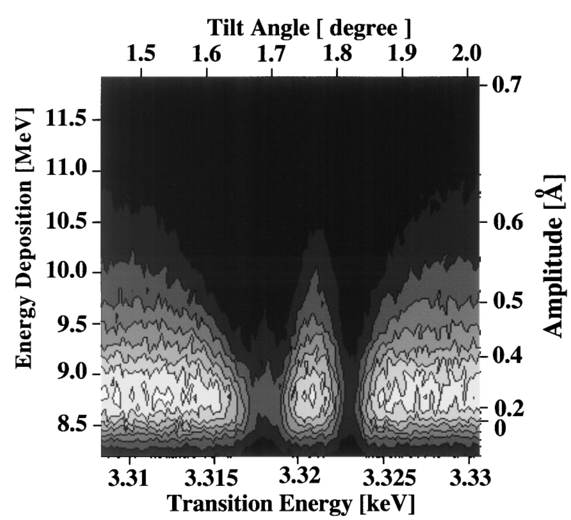

FIG. 2. A contour map of the surviving Ar^{17+} fraction, $f^{17}(\theta; \Delta E)$, at the incident angle, θ, differential with respect to the energy deposition, ΔE, for the RCE peak of $(k, l) = (1, 1)$ in $(2\bar{2}0)$ planar channeling. The transition energy, E_{trans} is inserted as the lower scale.

which obscures the absolute resolution of the amplitude of trajectories.

$f^{17}(\theta;\Delta E)$ reflects the contribution both from coherent excitation of a $1s$ electron with sequential ionization and from incoherent ionization by the target electron impact. The populations in excited states of the ions are governed by electron loss/capture, resonant coherent excitation/deexcitation, and incoherent excitation/deexcitation by target electron impact. This situation, to be exact, requires us to solve a time dependent Schrödinger equation [6].

However, we adopt a simple analysis in extracting the fraction ionized solely through RCE for each trajectory, $F_{\rm RCE}^{17\to18}(\theta,\Delta E)$, from the observed surviving fraction, $f^{17}(\theta;\Delta E)$, based on the following equation as a crude approximation, even though the uncertainty in absolute values must be kept in mind [6]. That is,

$$F_{\rm RCE}^{17\to18}(\theta,\Delta E) = 1 - f_{\rm RCE}^{17}(\theta;\Delta E) = 1 - f^{17}(\theta;\Delta E)/f_{\rm inco}^{17}(\theta;\Delta E). \quad (2)$$

Here, $f_{\rm RCE}^{17}(\theta;\Delta E)$ is the surviving fraction from coherent excitation of a $1s$ electron with sequential ionization. $f_{\rm inco}^{17}(\theta;\Delta E)$ is the surviving fraction from incoherent ionization. It is independent of θ, and replaced by $f^{17}(\theta = \theta_{\rm off};\Delta E)$ in the region of off-resonance condition. Electron capture is neglected, since it is less probable compared with ionization at the present ion energy. $F_{\rm RCE}^{17\to18}(\theta,\Delta E)$ is shown in Fig. 3 as a contour plot together with sliced sections at several regions of ΔE.

It is noteworthy that $F_{\rm RCE}^{17\to18}(\theta,\Delta E)$ is the ionized fraction at specific θ and ΔE, i.e., for a specific ion trajectory with corresponding transition energy, $E_{\rm trans}$, and trajectory amplitude, while $f^{17}(\theta;\Delta E)$ is the ΔE dependence of the surviving fraction for a specific θ. We note in Fig. 3 that $F_{\rm RCE}^{17\to18}(\theta,\Delta E)$ is rather small at the minimum ΔE, compared to the region of larger ΔE. This is not apparent in $f^{17}(\theta;\Delta E)$ shown in Fig. 2, because most of the surviving Ar^{17+} ions pass close to the center of the planar channel and lose less energy.

We calculated shifts in transition energies between perturbed $1s$ and $n = 2$ states of Ar^{17+} ions under the present experimental condition with respect to those in vacuum as a function of the distance from the center of the channel to compare with the observed features.

The details of the calculations have been described elsewhere [8]. Energy eigenvalues of $n = 2$ states in vacuum were obtained by the Dirac equation. A Hartree-Fock type (Doyle-Turner) potential for the crystal static field was adopted, and the perturbation of the Stark field was calculated using a basis set of a combination of nonrelativistic wave functions of $2s$, $2p_x$, $2p_y$, and $2p_z$ taking spin states into account. This resulted in eight sublevels. These are almost degenerate with respect to spin states, and thus four individual levels were obtained. The result is shown in Fig. 4. By comparing Fig. 3 with Fig. 4, we notice that in the region of the minimum ΔE in

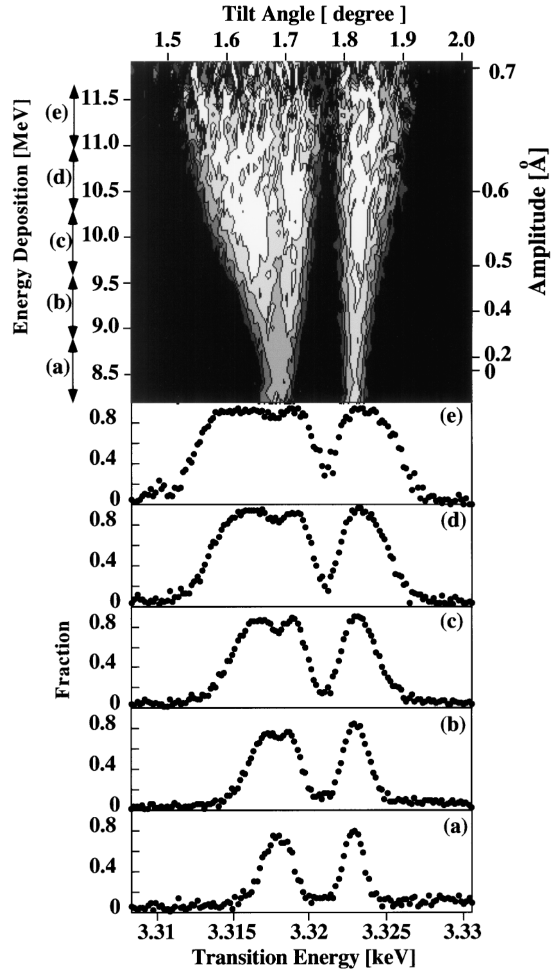

FIG. 3. A contour map of the fraction ionized solely through RCE, $F_{\rm RCE}^{17\to18}(\theta,\Delta E)$ at the incident angle, θ, and the energy deposition, ΔE, for the RCE peak of $(k,l) = (1,1)$ in $(2\bar{2}0)$ planar channeling together with sliced sections at the region of (a) $\Delta E = 8.21-8.78$ MeV, (b) $8.78-9.36$ MeV, (c) $9.36-9.93$ MeV, (d) $9.93-10.51$ MeV, and (e) $10.51-11.09$ MeV, respectively. The transition energy is inserted as the lower scale, and the corresponding amplitude of trajectories for ΔE is inserted as the right scale.

Fig. 3, two sharp peaks exist. The minimum ΔE region corresponds to the case where the ions pass close to the center of the planar channel, where the crystal field is also a minimum, and the split originates solely from the $\mathbf{l} \cdot \mathbf{s}$ interaction. As ΔE increases, the two individual peaks split further, shift and broaden to a plateau shape, which originates from Stark splitting by the position dependent crystal field.

The oscillatory ion trajectory with a finite amplitude results in various transition energies depending on the position where RCE occurs, and this induces the plateau shape. The edge of the plateau in the transition energy gives the transition energy at the position of the largest amplitude of the trajectory as understood from Fig. 4. It is expected from the position dependence of the periodic

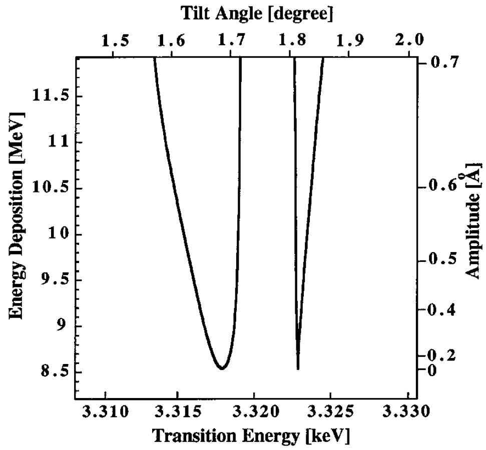

FIG. 4. Calculated transition energies (the lower scale) from $1s$ to $n = 2$ states as a function of the distance from the center of the channel (the right scale). The distance between the $(2\bar{2}0)$ planes is 1.92 Å. The corresponding ΔE for the amplitude is also shown (the left scale).

field amplitude that the RCE probability increases with increasing distance from the center of the channel. This agrees with the fact that $F_{\mathrm{RCE}}^{17\rightarrow18}(\theta, \Delta E)$ is rather large at the large ΔE as already described. Our calculation also proved the higher transition probability of RCE for positions away from the channel center. In addition, for the case of larger ΔE, this dependence leads to dip formation at the energy region, where the peak would exist at the minimum ΔE. That is, RCE at the center of channel is less preferred. This is clearly seen in the doublet feature in Fig. 3. Moreover, channeled ions spend a longer time at positions of larger amplitudes than at the center of the channel, and this also contributes to the dip formation.

Finally, the transition energy as a function of the position in the crystal in our calculation including the $1s$ Lamb shift of 1.1 eV, agrees excellently with the experimental results. The measured resonance energies are reproduced within an uncertainty of 0.2 eV. The decrease of the beam energy by energy loss in the crystal target affects the transition energy. The energy loss of about 10 MeV corresponds to a 1.2-eV shift in the transition energy. However, RCE occurs for the most part in the region close to the entrance of the crystal, so that the shift due to the energy loss would be much smaller. The present experiment has a potential possibility for precise measurement of the Lamb shift of mid-Z heavy ions. An improvement in the method of determination of the absolute beam energy is needed.

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[13] The total energy carried away by ejected secondary electrons was estimated by a Monte Carlo simulation to be 1.4 MeV for random incidence. This contribution was neglected in the preliminary analysis [7].

[14] We had measured the difference of energy loss between charge-frozen Ar^{17+} and Ar^{18+} for a Si crystal detector of 4 μm for random incidence, which amounts to only several percent.