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Recent Experiments on Resonant Coherent Excitation of Heavy Ions at HIMAC

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Abstract: When energetic ions penetrate into a crystal in a channeling condition, they travel across a periodic array of the atomic strings or ordered planes. These ions feel an oscillating field in the projectile frame. If the energy corresponding to this frequency matches with the transition energy of the electronic states of the ions, the ions have a chance to be excited. It is called Resonant Coherent Excitation (RCE). We have succeeded in observing resonant excitation of $1s$ electron to the $n=2$ states in H-like Ar^{17+} with relativistic velocities in 1998. Since then, much progress has been made. The observation of the RCE to the higher electronic states, RCE of heavier ions, and RCE of He-like ions in our lab allowed us to understand the resonance phenomena in detail. We also recognized its potentiality as a tool for high-precision atomic spectroscopy.

Key words: channeling; heavy ion; coherent excitation

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1 Introduction

When energetic ions of more than hundreds keV/u penetrate in a single crystal parallel to a crystal axis or plane, the ions travel in an open space without colliding with atoms in atomic strings or planes guided by the static field, which is generally called "channeling". In addition, the channeling ions feel a time-dependent oscillating field in the projectile frame, since they pass across a periodic array of the atomic strings or ordered planes. If an energy, $h\nu$(h: Planck constant), corresponding to the frequency, ν, of this oscillating field matches with a transition energy of an internal degree of freedom of the ions, excitation called Resonant Coherent Excitation (RCE) takes place.

In order to excite an innershell electron of heavy ions with a few bound electrons, the oscillating frequency corresponding to the energy of the order of keV is required. Then, heavy ions of several 100 MeV/u is in need, because a spacing between atoms is of the order of several Å. As for the intensity of the oscillating field, it amounts to as large as several tens of V/Å, i. e., several GV/cm at maximum, since a derivative of a crystal potential is of the same order as the Coulomb field in an atom.

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In 1998 we started experiments of RCE using a heavy ion accelerator for medical treatments in Japan, Heavy Ion Medical Accelerator in Chiba (HIMAC) in National Institute of Radiological Sciences. The accelerator covers up to several hundreds MeV/u for the maximum attainable velocity.

There are other advantages of the relativistic velocity for the incident channeling ions to observe RCE of heavy ions. First, the channeling ions pass through the crystal without much experience of incoherent atomic collisions with target electrons, which results in the sharp resonance in RCE. Second, we can adopt the transmission type surface barrier silicon detector (SSD) as a target crystal. With use of it, we measure the deposited energy of the channeling ions into the crystal simultaneously, and we can extract the impact parameter-dependent information of RCE.

2 Observation of RCE

There are several processes accompanying RCE between the ground and excited states. After the resonant excitation, the excited state proceeds to one of three channels: resonant de-excitation to the ground state, de-excitation by emitting X-rays to the ground state, and ionization by the collision with the target electrons. We have several observation methods to detect RCE experimentally: (1) The ions in the excited state are more easily ionized through the collision with the target electrons compared with those in the ground state. Therefore, the fraction of the higher charge state in the charge-state distribution of the emerging ions from the crystal increases under the resonance condition. (2) At the same time, the yield of electrons stripped from the ions (loss electrons) also increases under the resonance condition. (3) When the ions escape from ionization, X-rays are emitted. Increase of the de-excitation X-ray yield under the resonance condition confirms RCE. The methods (1) and (2) are based on the same process, which compete with the process in the method (3). As the atomic number of the heavy ion becomes larger, the ionization cross section is reduced, and the lifetime of the excited state is shortened. Therefore, the method (3) becomes efficient. We have observed RCE through all of these three methods.

At first we observed resonant coherent excitation of the $1s$ electron to the $n=2$ state of 390 MeV/u hydrogen-like Ar^{17+} ions in planar channeling in a Si crystal. We varied the angle of the crystal with respect to the beam direction in the $(2\,\bar{2}\,0)$ plane including the [110] axis to observe the 1st-order resonance, where the ions travel through the periodic array of atomic strings whose direction is defined by the 2D reciprocal vector of $(\boldsymbol{k}/A,\ \boldsymbol{l}/B)$, $(k,\ l$: integer$)$. The resonance condition in this case is derived as, $(k\cos\theta/A)+(l\sin\theta/B)=E_{\mathrm{trans}}d/\gamma\beta hc$. $(A,\ B)=(a/\sqrt{2},\ a)$ for the $(2\,\bar{2}\,0)$ plane, a is a lattice constant, θ is the angle of the incident beam direction with respect to the [110] axis, and E_{trans} is the transition energy. By scanning the incident angle θ, from the direction of the [110] axis in the $(2\,\bar{2}\,0)$ plane, the resonant excitations corresponding to the electronic transition of Ar^{17+} ions were observed in the several conditions of the incident angle θ, corresponding to combinations of $(k,\ l)$, like (1,1), (1,2) ... as increases of the fraction of Ar^{18+} ions. The resonance spectrum has a complicated structure and basically consists of two peaks corresponding to the excitation from the $1s$ state to $2p_{1/2}$ and $2p_{3/2}$. Each peak is not symmetric and has a tail. The $2p_{1/2}$ peak has a doublet structure with a dip. The split into two peaks originates from removal of the degeneracy of $n=2$ states mainly due to the spin-orbit $(\boldsymbol{l}\cdot\boldsymbol{s})$ interaction, which is stressed for heavy ions. The asymmetric tail and the doublet features are resulted from the Stark effect due to the static crystal electric field.

Then, in order to obtain the detailed information of these complicated structures, we measured the deposited energy of Ar^{17+} ions by the SSD and the charge-state distribution of the emerging ions simultaneously, and obtained the fraction of Ar^{18+} ions with respect to the total incident ions, $f^{18}(\theta; \Delta E)$ as a function of the deposited energy, ΔE. It is possible to extract the information of the ion trajectory, because this deposited energy keenly reflects the ion trajectory in the crystal. The deposited energy of the channeling ions to oscillate many times is uniquely related with an amplitude of the ion trajectory in the planar channeling condition. From comparison of the obtained data and calculated shifts in transition energies between perturbed $1s$ and the $n=2$ states of Ar^{17+} ions under the present experimental condition, we conclude that we experimentally showed the energy levels of the ion with one electron in the case where perturbation due to spin orbital ($\boldsymbol{l} \cdot \boldsymbol{s}$) interaction and that due to Stark effect are effective to a similar extent.

3 Recent progress

Soon after the above measurements, we observed enhancements of both yields of de-excitation X-rays and loss electrons produced by ionization of H-like ions using the 390 MeV/u Ar^{17+} ions. We further extended our observation of RCE to a variety of systems and conditions.

● RCE to the $n=3$ and higher states

We observed resonant coherent excitation (RCE) of $1s$ electron to the $n=3$ states in 390 MeV/u hydrogen-like Ar^{17+} ions through measurements of the projectile charge states. 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 have a characteristic structure consisting of several peaks. Compared with the profile of RCE to the $n=2$ states, they show a large peak shift from the $j=1/2$ and 3/2 levels in a vacuum, and the profiles are broadened due to the Stark-split level structure of the $n=3$ manifolds depending on the static field in the crystal. We further succeeded in observing RCE to $n=$ 4 and 5 states.

● RCE of heavier ions

We observed RCE of 460 MeV/u H-like Fe^{25+} ions under the resonance condition of $(k,l)=(2,-1)$ through measurements both of the projectile charge state and de-excitation X-rays. The observed charge-state spectra show smaller skewness of the peaks, which indicates the smaller contribution of the Stark effect due to the small size of the ions compared with Ar^{17+} ions. The de-excitation X-rays yield is larger than that for Ar^{17+} ions.

● RCE of He-like ions

We observed RCE of 383 MeV/u He-like Ar^{16+} ions under the resonance condition of $(k,l)=(1,-1)$ and 423 MeV/u He-like Fe^{24+} ions under $(k,l)=(2,-1)$ through measurements both of the projectile charge state and de-excitation X-rays. We clearly observed peaks corresponding not only to $1s^2 \rightarrow 1s2p\ ^1P_1$ but also to $^3P_1$.

Through these observations we have realized that the transition energy is determined in very high precision. With use of the deposited energy or the scattering angle of the ions, we are able to extract the data for "best channeling ions" passing just in the center of the planar channel and not affected by the static crystal field because of its absence. Their resonance energy corresponds to the intrinsic transition energy from the ground state to the excited states in vacuum. In the case of 390 MeV Ar^{17+} ions in channeling through the SSD, the observed width of the $2p_{3/2}$ resonance is 1.1 eV, and the natural resonance width is determined to be about 0.9 eV, i. e., a few 100 ppm (FWHM) of the transition energy taking the energy width of the incident ions and their angular spread into accounts. This narrow width suggests that the ions travel keeping their phase of wave functions without being perturbed by incoherent collisions for a long distance, which is one of the advantages of the relativistic velocity. Thus, the transition energy is determined in a very high precision in principle, however, the beam energy is difficult to be determined precisely by operating parameters of the accelerator.

Now we are trying to determine the absolute transition energies of $1s^2 \rightarrow 1s2p$ of $^1P_1$, and $^3P_1$ in the two-electron He-like ions. In advance, we measure RCE of H-like ions, which are produced by electron stripping of He-like ions by inserting a thin foil at the upstream position of the crystal, and we determine the beam energy from the observed transition energy of the $2p_{3/2}$ state adopting the theoretical value of the $1s$ ground state Lamb shift of H-like ions.

From a view point of atomic physics, spectroscopy of highly-charged ions with few-electrons is an intriguing subject in QED effect involving the intense electromagnetic field (high-Z QED). This RCE technique is a completely new method of spectroscopy in principle compared with traditional wave length measurements with a Bragg crystal spectrometer, or energy measurements with a semiconductor detector. We consider that the "RCE spectroscopy" is one of promising candidates for spectroscopy of highly-charged ions.

4 Summary and outlook

We have succeeded in observing resonant excitation spectra of RCE in high precision using heavy ions with relativistic velocities. We obtained the information of the spin-orbit ($l \cdot s$) interaction and Stark effect for the excited levels due to the crystal electric field in high precision. Following the first experiments with H-like Ar^{17+} ions, a variety of experiments were performed both by observing the charge-state distribution and de-excitation X-rays. Moreover, we recognized its potentiality as a novel tool for high precision atomic spectroscopy.

Finally it is noted that the excited states proceed to the RC-De-excitation (RCD) as well as ionization or X-ray emission. Under the present condition of heavy ions with relativistic velocities, RCE and RCD take place with a large probability and the ions are regarded to be in the coherently mixed-up state of two levels of the ground and excited states in the Rabi oscillation. We plan to extend our research from this point of view.

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共振相干激发的最新实验研究

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摘　要：在满足沟道效应条件下，高能离子在穿过晶体时，离子穿过的是周期性的原子序列或者有序平面阵列．在入射离子的坐标系中，离子感受到一种振动场的作用．如果与此振动频率相关的能量与离子的电子态跃迁能量相匹配，则离子有可能被激发，这种现象就称为共振相干激发(RCE)．1998 年，成功地观测到了类氢 Ar^{17+} 离子以相对论速度穿过 Si 晶体时，其 1s 电子到 $n=2$ 态的共振激发．此后，有关出射离子电荷态分布以及退激 X 射线谱的实验研究取得了很大进展，近期的实验研究还观测到了类氢离子的 1s 电子到更高电子态($n=3$，4，5)的 RCE 和更重离子的 RCE，以及类氦离子的 RCE．这些实验结果有助于详细研究这种共振现象．实验结果表明，RCE 也能够作为研究高精度原子谱学的一种潜在的工具．

关 键 词：沟道；重离子；相干激发