X-Ray-Induced Fluorescence Spectroscopy with EBIT

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Abstract. Highly charged ions have a great potential for further insight into atomic physics or nuclear physics. We are planning an x-ray-induced fluorescence spectroscopy of highly charged ion trapped in EBIT. In the present paper we report an estimation of the feasibility of the experiment with EBIT and the present status of the demonstration experiment with synchrotron radiation and highly charged ion beam produced by a laser ion source.

INTRODUCTION

The EBIT is one of the best tools to study the physics of highly charged ions. Highly charged ions represent a very peculiar possibility to test electromagnetic interactions because the bound electrons in the highly charged ions are in exceedingly large field. As a result, small effects of atomic energy levels are enhanced, and it allows QED test or measurement of hyperfine interaction easily compared to the experiment with neutral atoms or lower charged ions. To measure atomic transitions precisely, laser spectroscopy experiment based on the technique of laser-induced fluorescence (LIF) method is quite useful. The researches of atomic spectral lines by the method have contributed greatly to the studies of not only atomic physics but also nuclear physics [1], and we developed experimental apparatus for laser spectroscopy with highly charged ions [2-4]. However the laser spectroscopic experiment is limited by energy oscillated by lasers (up to 5 eV). On the other hand, excitation energies of highly charged ions increase to 280 eV such as the 1s²2s²S⁰½ - 1s²2p²P¹₂ transition of U⁸⁹⁺ ion. In order to measure transitions of highly charged ions, we are developing a new experimental technique which uses x rays (up to several hundreds eV) instead of laser light to measure atomic transitions of highly charged ions.

For the above objective, highly charged ion beam and x-ray source are necessary. In the present situation, a high-quality x-ray beam that has a high resolution and high intensity is only available in the facility of synchrotron radiation (SR). So far, x-ray
beams provided by SR sources have been applied to experimental works on the photoionization of atomic ions [5-7], but x-ray-induced fluorescence spectroscopy with SR, which is based on LIF method, was not done previously. It is because the intensity of the x-ray beam by SR sources is several orders of magnitude less than that of laser. Therefore intensity of ion beam or number of trapped ions is quite important to compensate for the intensity of SR.

The laser ion source has been developed for use as an injector of accelerators [8], and it is suitable for the experimental setup of x-ray-induced spectroscopy with SR. Because it can supply high current beams of highly charged ions by a simple structure and is small-sized ion source; experimental apparatus requires to be moved instantly and easily at a public beam line, such as SR facility. Moreover, a laser ion source has can be made at a moderate price. In the present paper, we report a feasibility of the x-ray-induced fluorescence spectroscopy with EBIT and the present status of the demonstration with SR and highly charged ions (C4+) generated by laser ion source.

**ESTIMATION OF EXPERIMENT WITH EBIT**

The scheme of the x-ray-induced fluorescence spectroscopy with EBIT is shown in Fig. 1. In the present paper, a measurement of the 1s²2s² ²S₁/₂ - 1s²2p² ²P₁/₂ transition of lithium-like uranium ion (U⁸⁹⁺) is estimated. X-ray beam injects perpendicularly to the trapped region of the EBIT and excites ions in the 1s²2s² ²S₁/₂ state (ground state). The ions excited by the x-ray beam decay immediately to the ground state with emitting fluorescence photons. Then the photons are detected by the x-ray detectors. The resonance spectrum is obtained by scanning the x-ray energy, and making 2D plot of the photon counts versus the x-ray energy. The resonance energy is obtained from the spectrum.

**FIGURE 1.** Functional scheme of the x-ray-induced fluorescence spectroscopy with EBIT. T, ion-trap region of EBIT; X, x-ray beam; F, fluorescence photon; D, x-ray detector.

**Count Rate of Fluorescence**

The parameters for estimation of the fluorescence count rate are summarized in Table 1. The count rate of the fluorescence (R_signal) is calculated by,

\[
R_{\text{signal}} = \frac{C \cdot f \cdot A \cdot E_{\text{beam}} \cdot \eta}{t}
\]
\[ R_{\text{signal}} = B_{12} \frac{\rho_x}{\Delta V} N_i \cdot t \cdot f_i \cdot \epsilon_d \cdot \Omega_d. \] (1)

![Diagram](image)

**FIGURE 2.** Schematic diagram of the interaction of two-level system.

Figure 2 shows the schematic diagram of the interaction of two-level system. The spontaneous transition probability (\(A_{21}\); the Einstein coefficient of spontaneous emission) of the target transition is calculated by the GRASP code [9], and it is evaluated to be 8.873 x 10^{11} /s. The Einstein coefficient of induced emission (B) is calculated from the spontaneous transition probability as follows [10],

\[ B_{12} = \frac{g_2}{g_1} B_{21}, \] (2)

\[ B_{21} = \frac{c^3}{8 \pi \hbar \nu} A_{21}. \] (3)

The power density of the x ray beam in Table 1 corresponds to 3 x 10^{10} photons/s in the diameter of 0.1 mm. As a result, \(R_{\text{signal}}\) is estimated to be 0.1 cps. Although it is difficult to estimate the count rate of the noise, it goes without saying that the low-rate of noise is the best thing to come off.

| TABLE 1. Parameters for estimation of signal count rate. |
|--------------------------------------------------------|
| **Ion**                                                |
| **Excitation energy (eV)**                             | 280 |
| **Spontaneous transition probability (/s)**             | \(A_{21}\) 2.243 x 10^{10} |
| **EBIT**                                               |
| **Trapped region of EBIT [\(\phi\) (mm) x \(L\) (mm)]**  | \(\phi\) 0.1 x 10 |
| **Number of trapped ions**                             | 10000 |
| **X ray**                                              |
| **Power density (J/m^3)**                              | \(\rho_x\) 3.85 x 10^{3} |
| **Band width (Hz)**                                    | \(\Delta V\) 6.83 x 10^{12} |
| **Others**                                             |
| **Quantum efficiency of x-ray detector**               | \(\epsilon_d\) 0.4 |
| **Solid angle of detector**                            | \(\Omega_d\) 0.05 |
| **Interaction rate (Frequency of SR)**                 | \(f_i\) 5 x 10^{8} |
| **Pulse width of SR (s)**                              | \(t\) 1 x 10^{10} |
Resolution and Accuracy

There are three factors which cause the spectrum line width; (1) energy spread of the x-ray beam, (2) Doppler width caused by ion motions, (3) natural width of the target transition. They are summarized in Table 2. Resolution of the x-ray beam for the estimation is 10000, and the energy of the ions trapped in EBIT is supposed to be 100 eV [11]. The line width of the resonance spectrum is estimated to be 0.032 eV in consequence. The result indicates that the excitation energy can be obtained in the accuracy of less than 0.001 eV if the statistics of the spectrum are sufficient. And the accuracy is one order higher than that in the previous experiment [12].

| Table 2. Parameters for resolution estimation. |
|-----------------------------------------------|
| Energy width of x-ray (eV)                     |
| Doppler width (eV)                             |
| Natural width of the transition (eV)           |
| Total width (eV)                               |
| 0.028                                         |
| 0.016                                         |
| 1.5 x 10^{-5}                                 |
| 0.032                                         |

EXPERIMENT WITH LASER ION SOURCE

The experimental setup is shown in Fig. 3. The ion beam produced by the laser ion source is extracted by an acceleration voltage and focused by the einzel lens. Then the charge states of the ions are selected by the dipole magnet, and the ion beam propagates to the fluorescence detector. The ion beam is focused on the fluorescence detector by the electrostatic quadrupole lens. In the detector, the ions excited by the x-ray beam decay to the ground state with emitting fluorescence photons. The resonance
spectrum is measured by scanning of the x-ray energy. The C^{4+} ion is chosen for the target because this ion has an excitation energy of 300 eV which is suitable for synchrotron radiation. The level scheme of the C^{4+} ion is shown in Fig. 4.

**FIGURE 4.** Level scheme of C^{4+} ion.

Figure 5 shows the design of the laser ion source and the extractor. Ions are extracted from laser plasma produced by focusing the laser radiation on the target surface. The target is a solid carbon which has a cylindrical form with a size of \( \phi 60 \times \phi 50 \times 200 \text{ mm} \). The target is mounted on the drum revolved from 1/1000 to 3 rpm by an electric motor. It corresponds to the surface speed from 0.5 mm/s to 20 mm/s. The motor speed was continuously controllable. One of the alignment laser guides the point of the laser injection. The Nd:YAG laser, which has a maximum power of 450 mJ/pulse and a pulse duration (FWHM) of 6 ns, is used for production of plasma. The laser beam is transported to the entrance window of the plasma source chamber by three dichroic mirrors and focused on the surface of the target by the lens of \( f = 400 \text{ mm} \). The power density of the laser radiation flux on the target is estimated to be \( 1.2 \times 10^{13} \text{ W/cm}^2 \). The turbo molecular pump, which has a pumping speed of 820 l/s for \( \text{N}_2 \), is mounted on the plasma chamber. The repetition rate of the Nd:YAG laser is limited up to 3 Hz during operation, though the laser has a repetition ability of 10 Hz. It is because the operation with 10 Hz causes the vacuum of the ion source worse. The ion source is applied with a maximum bias voltage of 100 kV. After the plasma drift of 41 cm, ions are extracted from plasma and accelerated by the applied voltage. The aperture located in the end of the plasma drift has a diameter of 30 mm. It covers a
solid angle of $4 \times 10^{-3}$ sr from the focal point on the target. The dipole magnet has 150 mm radius and a bending angle of 60 degrees. At the entrance and exit of the magnet, xy slits are located. The detector has a cryopump system for achieving high vacuum ($4 \times 10^{-6}$ Pa) for the suppression of noise coming from the collisions of ions and residual gas molecules [3]. Four micro channel plates (MCPs) of 30 mm aperture (Hamamatsu 2224-21SFX) is mounted in the detector. A faraday cup with 10 mm aperture, and the beam profile viewer made of ZnS are also located in the detector.

**Ion Beam**

Figure 6 shows the plasma shape at the end of the dipole magnet without acceleration and magnetic field. The distance from the target of the ion source to the faraday cup is 1.43 m. The voltage of -1000 V was applied to the suppressor of the faraday cup. Ions are extracted by the voltage from the plasma.

![Figure 6](image)

**FIGURE 6.** Ion current in the laser plasma. At this time, Slit was fully opened.

Figure 7 shows the ion current at the end of the straight line. This signal was measured under acceleration voltage of 26 kV and the Einzel lens of +20 kV. Ions current. The distance from target to the faraday cup is the same as Fig. 4. This signal was measured under acceleration voltage of 26 kV and the Einzel lens of +20 kV.

![Figure 7](image)

**FIGURE 7.** Ion current at the end of the straight line. This signal was measured under acceleration voltage of 26 kV and the Einzel lens of +20 kV.
Figure 7 shows the time structure of the ion bunch with an acceleration voltage of 26 kV and it contains whole charge state of carbon ions. The faraday cup of Fig. 7 is positioned just after the dipole magnet with no magnetic field. The apertures of the slits located in the entrance and the exit of the dipole magnet are 20 x 20 mm and 6 x 6 mm, respectively. Figure 8 shows the signal from the faraday cup mounted on the fluorescence detector.

**Estimation of Signal Count Rate**

From Fig. 8, the number of ions with a size of 10 mm is $1.3 \times 10^8$ ions/pulse. The count rate of the fluorescence ($R_{signal}$) is calculated as,

$$R_{signal} = B_{12} \cdot \frac{\Delta x}{\Delta V} \cdot N_i \cdot t \cdot f_i \cdot f_{laser} \cdot \alpha_{cap} \cdot \Omega \cdot \mu.$$

The formula is based on the same logic with formula (1). However, the above formula contains the parameters of the ion beam because ions are pulsed beam. The parameters for the demonstration experiment are summarized in Table 1. The spontaneous transition probability (the Einstein coefficient of spontaneous emission) of the target transition is $8.873 \times 10^{11}$ s$^{-1}$ [13]. As a result, $R_{signal}$ is estimated to 0.3 cps. The x-ray intensity used for estimation is $1.0 \times 10^{12}$ photons/s/0.1%bw with a repetition rate of 500 MHz, and it is a realistic value for synchrotron radiation [14, 15]. The result indicates the ion beam current is enough to carry out an x-ray-induced spectroscopy experiment with SR. Under the present condition, the count rate of the noise was measured to be 3 cps. As compare to the noise from the ion beam, the noise from the x-ray beam is negligible. The count rate of the noise from SR was measured at the beam line (BL-16B) of the Photon Factory [15]. To improve a signal to noise (S/N) ratio, the noise rate must be decrease. It will suppress by improving the vacuum of the detector, because the noise is caused by the collisions of the ions and the residual gas in the detector.
TABLE 3. Values of each parameter for estimation of the signal count rate.

| Parameter                          | Value          |
|------------------------------------|----------------|
| Spontaneous transition probability (s) | $A$           | $8.873 \times 10^{11}$ |
| Power density of x ray (J/m$^3$)    | $\rho_x$      | $1.6 \times 10^{-5}$   |
| Repetition rate of laser (s)        | $f_{\text{laser}}$ | 3                     |
| Bandwidth of x ray (Hz)             | $\Delta \nu$  | $7.4 \times 10^{13}$  |
| Quantum efficiency of MCP           | $\varepsilon_{\text{mcp}}$ | 0.4                |
| Solid angle of detector             | $\Omega_d$    | 0.063                 |
| Interaction rate                    | $f_i$         | 250                   |
| Number of ions (/bunch)             | $N_i$         | $1.3 \times 10^8$    |
| Interaction time (s)                | $t$           | $2 \times 10^{-9}$   |

CONCLUSION

We verified the possibility of an x-ray-induced fluorescence spectroscopy with EBIT. To carry out the experiment, the EBIT only for the experiment should be designed. The estimation of the noise level is difficult at this moment. However, if a low-noise level compared to the signal is achieved, the experiment will be carried out. In an experiment with x rays which has a resolution of 10000, excitation energy will be obtained in the accuracy of more than $10^{-5}$. It corresponds to 0.001 eV in case of the $1s^22s^22S_{1/2} - 1s^22p^22P_{1/2}$ transition of U$^{89+}$. And the accuracy is one order higher than the previous measurement [12]. If an x-ray source that can oscillate a high-resolution and high-intensity as a visible laser is made for practical use, such as a free electron laser, it will enable to do the experiment with EBIT much easier.

The demonstration experiment with the laser ion source make off as expected in the near future. By improving the noise level, we can increase the number of incident ions to the fluorescence detector. And it allows decrease the photon number at the same time. Consequently, we can use x rays with higher-resolution because a high-resolution beam has a low-intensity. The experimental apparatus reported in this paper is designed for an x-ray-induced fluorescence spectroscopy; it is naturally suitable for LIF spectroscopy.

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