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X-ray emission of Xe^{30+} ion beam impacting on Au target

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Abstract

X-ray emission from Xe^{30+} ions at 350–600 keV impacting on an Au target was investigated at the Heavy Ion Research Facility at Lanzhou. Characteristic X-rays of Xe ions at energy of about 1.65 keV were observed. This X-ray emission is induced by the decay of very high Rydberg states of Xe ions. It was also found that the yield of such characteristic X-rays is decreasing with increasing the projectile kinetic energy. Simultaneously, the yield of the characteristic Au X-rays from the M shell increases also. These phenomena are qualitatively analyzed with the classical Coulomb over the Barrier Mode (COBM) for highly charged ions interacting with solid state surfaces.

Keywords: Classical Coulomb over the Barrier Mode; ECR- ion source; Heavy ion beams; Rydberg state; X-rays

1. INTRODUCTION

The interaction laser beams or of multi-charged heavy ions with solid targets has drawn considerable interest, not only from fundamental physics, but also from many applications such as material modification, X-ray source devices, ion-wall interaction in magnet confinement fusion, heavy ion driven plasma, fusion energy research, and other areas as well (Bock *et al.*, 2005; Hoffmann *et al.*, 2005, 2007; Tahir *et al.*, 2005; Piriz *et al.*, 2006; Logan *et al.*, 2005; Sharkov, 2001; Golubev, 2001; Sigmund, 1969; Pikuz *et al.*, 2010; Xin *et al.*, 2010; Zavestovskaya, 2010). Accelerator physics and technology has made remarkable progress during recent years. Laser accelerated particle beams as well as conventional laser plasmas that are used as powerful ion sources have contributed to this development (Adonin *et al.*, 2009; Renk *et al.*, 2008; Ter-Avetisyan *et al.*, 2008). However, there still remains the necessity to investigate the details of the charge state effect on ion beam energy deposition in targets. Charge exchange effects in slow collisions of highly charged ions interacting with a surface still need to be explored in more detail.

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Highly charged heavy ions are efficient carriers of energy, due to their kinetic energy and potential energy due to the high ionization state as well. When such a highly charged ion approaches a metallic surface at low speed (close to the Bohr velocity, 2.9×10^6 m/s), there is a high probability for electron capture processes, due to the high dynamic and static electric field of the ion that interacts with a surface constituent atom. Capture processes are most probable to populate high Rydberg states at a large distance to the surface. This is followed by a complex cascade of processes including recombination, Coulomb ionization, photon emission, Auger electron, and fast electron emission, when the ion crosses into the surface. At the same time most of the huge potential energy will be deposited into a small volume (of nanometer scale in diameter) close to the surface (Winter *et al.*, 1999; Schenkel *et al.*, 1998; Burgdörfer *et al.*, 1991). The physics mechanism is still unclear and the X-ray spectroscopy can provide important information to understand the dynamic of these processes. For example, Briand *et al.* (1990, 1996) used X-ray spectroscopy with high energy resolution to investigate the decay of the very slow and highly charged argon ions approaching a surface, and Rosmej (2005*a*, 2005*b*) and colleagues (Rzadkiewicz *et al.*, 2010) recently measured the X-ray emission with spatial resolution to analyze the stopping and ionization processes, and charge state evolution of swift heavy ion in dense matter.

In this paper, we present some recent experimental results on X-ray measurements originating from $^{129+}Xe^{30+}$ ions beams impacting on an Au surface, the projectile initial kinetic energy ranged from 350 keV to 600 keV. Primary emphasis will be given to the investigation of projectile X-ray emission. The initial kinetic energy dependence of the X-ray yield will be discussed.

2. MAIN PERFORMANCE OF THE ECR ION SOURCES AT HIRFL

As shown in Figure 1, the Heavy Ion Research Facility in Lanzhou (HIRFL) is an accelerator complex consisting of heavy ion cyclotrons and cooling storage rings. The research activities at HIRFL cover a wide-range including nuclear physics, astrophysics, atomic physics, plasma physics, hadron physics and the applications of heavy ion beams in material science, heavy ion cancer therapy, and so on (Xu, 2009, 2010; Zhao *et al.*, 2009).

In order to enhance HIRFL performance of beam intensity and energy, two electron cyclotron resonance (ECR) ion sources, LECR3 and SECRAL, were built during the past decade (Zhao *et al.*, 2004; Sun *et al.*, 2010). LECR3 is the third ECR ion source at Lanzhou, which was commissioned in 2003. Very highly charged ion beams such as Ar^{18+} and Xe^{30+} were produced by this ion source. However, the intensity of such highly charged ion beam was quite limited, for instance, the beam current for Ar^{17+} and Xe^{30+} beam was much less than 1 μA.

After the completion of the SECRAL (a fully superconducting compact ECR ion source at Lanzhou), the beam intensity was increased by a factor of more than 30 as compared to the intensity of the same beam from LECR3. Figure 2 shows the spectrum of the highly charged Xe beams from SECRAL (Sun *et al.*, 2010).

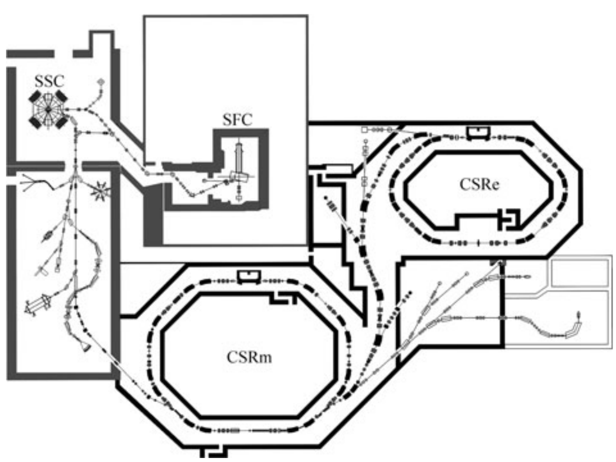

Fig. 1. The layout of the HIRFL complex. SFC: Sector Focusing Cyclotron (K = 69, ion beams with energy up to 10 MeV/u); SSC: Separated Sector Cyclotron (K = 450, ion beams with energy up to 100 MeV/u); CSRm: the main ring of CSR (Bρ < 12.1 T × m); CSRe: the experimental ring of CSR (Bρ < 9.4 T ×m).

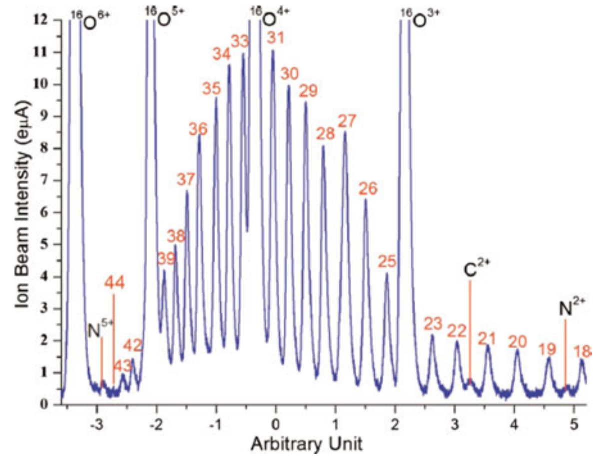

Fig. 2. (Color online) Optimized spectrum of highly charged xenon ion beams from SECRAL (the numbers upon the peaks are standing for the charge state of the xenon beams).

3. EXPERIMENTAL SETUP

The experiment was performed at LECR3. Highly charged Xe ion beams impacted onto a clean and pure (99.99%) Au target with an incident angle of 45° to the surface. The target area was about 19×24 mm that is much larger than the beam spot, which is 5×5 mm. The vacuum in the chamber was on the order of 10^{-8} mbar.

In this work, the X-rays were measured by a Si(Li) detector, which observed the target at an angle of 90 . Between the detector and the target was a beryllium vacuum window with thickness of 0.05 mm. The Si(Li) detector used in this experiment had an effective energy range of 1–60 keV and the energy resolution was 190 eV at 5.9 keV. It was calibrated with standard radioactive sources 241Am and 55Fe, for details please see our formal publication (Zhao *et al.*, 2007). The geometrical solid angle was about 0.013 ± 0.001 sr ($\sim$ 0.1% of 4π). The spectrometer efficiency and the ion beam current were determined so that absolute values for the X-ray yield could be measured. Assuming that the X-ray emission is isotropic and taking the solid angle into account, the X-ray yield per ion can be given as

$$Y = \frac{C}{N} = 2.7 \times 10^{-6} \times \frac{q \times \omega \times A}{I_{beam} \times \Delta t}, \quad (1)$$

where C is the total X-ray yield, N is the total projectile ion number, q is the projectile charge state, I_{beam} is the beam current (unit: nA), ω [keV] is the full width at half maximum of the spectral line, A is the peak value.

4. RESULTS AND DISCUSSION

The spectra shown in Figures 3 and 4 were taken during the experimental run $^{129}Xe^{30+}$ impacting on the Au surface. The initial kinetic energy was 350 keV and 600 keV, respectively. Two lines can be identified in the spectra. The line at

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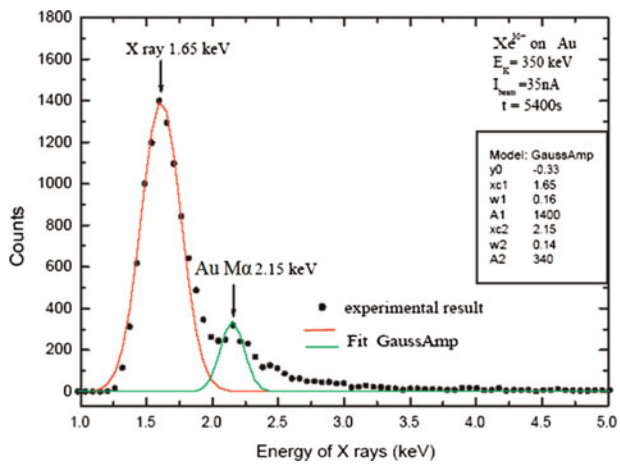

Fig. 3. (Color online) X-ray spectra for Xe^{30+} ions with kinetic energy 350 keV impacting on Au target.

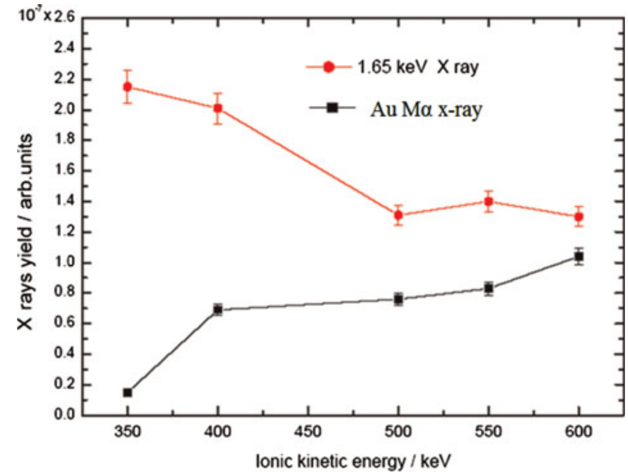

Fig. 5. (Color online) The X-ray yields per ion *vs*. the projectile initial kinetic energy.

1.65 keV has been identified as the characteristic X-ray M-shell radiation. It is observed with other targets in the same condition as well. The line at 2.15 keV has unambiguously been identified as Au Mα radiation (McMaster *et al.*, 1969).

However, according to the same publication (McMaster *et al.*, 1969), the energy of the Xe Mα X-rays should not extend beyond 1 keV, and should therefore be out of the sensitive range of our detector. We proposed earlier, that this line may possibly be induced by two-electron-one-photon (TEOP) transition of Xe ions. One may get details from our former publication [Zhao *et al.*, 2007]. The probability for such TEOP transition is very low (Salem *et al.*, 1984; Zou *et al.*, 2003). But here we observed a very high X-ray yield of about 10^{-7} per injected ion. Therefore, we propose a different mechanism where radiation originates from the high Rydberg state of the Xe ions.

It is well-known that, a highly charged ion can capture many electrons from the metallic target into high Rydberg states at a very large distance. According to the classical over-barrier model, this critical distance R_c from the ion to the surface can be given as

$$R_c = \frac{1}{2W}\sqrt{8q+2}, \qquad (2)$$

where q is the projectile charge state and W is the work function of the metal target; and the captured electrons will be located in the state with primary quantum number

$$n = \frac{q}{\sqrt{2W}}. \qquad (3)$$

Therefore in the present experiments, the Xe ions will capture the electrons into the level of n near to 10, which has a very low binding energy, about 10–100 eV. If we take into account that the inner most vacancy of the Xe^{30+} has a binding energy of about 1.71 keV, the X-rays with energy about 1.65 keV can be expected, if the transition from such Rydberg state takes place.

Furthermore, as shown in Figure 5, the yield of such X-rays is decreasing with the increasing of the initial projectile energy. It can be explained with this mode as well: Since the critical capture distance is the same, the ions with lower approaching velocity will have more time to decay through such Rydberg transition than the ions with higher velocity.

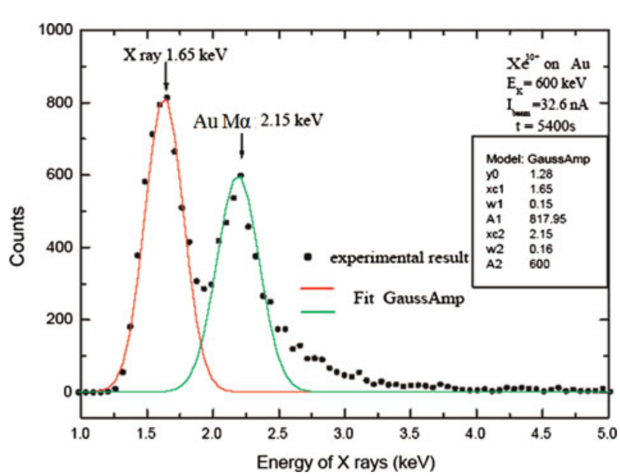

Fig. 4. (Color online) X-ray spectra for Xe^{30+} ions with kinetic energy 600 keV impacting on Au target.

5. CONCLUSION AND REMARKS

Recent experimental results on X-ray measurement during the $^{129+}Xe^{30+}$ ions beams impacting on an Au surface are reported. The characteristic X-rays of the Xe ions with energy about 1.65 keV were observed. Based on the classical over-barrier model, the characteristic X-rays were proposed to be induced by the decay of very high Rydberg state of the Xe ions. The decreasing of this characteristic X-ray yield with the increasing of the projectile initial kinetic energy matches the model as well.

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