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L-shell X-ray production of molybdenum and niobium induced by 1500–3500 keV Xe^{26+} ions

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ABSTRACT

L-shell X-ray production cross sections are measured for molybdenum and niobium target induced by Xe^{26+} ions. The incident energy range varies from 1500 to 3500 keV. The experimental results are well reproduced by the binding-energy-modified binary encounter approximation model in the united-atom limit. In addition to target L-shell X-ray spectra, we also observe a weak spectrum which corresponds to the forbidden transition 3d → 2s from the projectiles.

1. Introduction

Ions impacting on the solid surface have been of continuous interest for about one hundred years because ion–solid collisions have important significances not only for fundamental researches, such as atomic structure and level life, but also for technical applications, like ion-beam modification and analysis of surfaces [1]. For the inner-shell ionization during collisions, three mature theories have been given by the previous work: direct Coulomb ionization (DCI) [2], electron capture (EC) [3], molecular orbital (MO) promotion [4]. In general, for fast ions colliding with the solid, DCI agrees well with the experimental results [5]. For the fully stripped ions, if considering both EC and DI, one also could obtain a good agreement between the theory and experiment [6]. Besides, for slow ion–solid encounter, in terms of electron promotion, a reasonable explanation would be got within the MO framework [7]. Radiative de-excitation of the inner-shell vacancy results in the X-ray emission. The validity of the above theories has been tested and verified through many experiments. However, most experimental work in this field was focused on measuring X-ray production from the light ion–solid collisions. Work done for the interaction between heavy ions and solid at low energy is relatively rare, especially for projectiles with nuclear charge Z_P larger than target nuclear charge Z_T.

In this work, we extend the measurements of X-ray production to the slow heavy-ion system with $Z_P > Z_T$. In the present experiment, L-shell X-ray production from the target and a weak spectrum from the incoming ions are simultaneously measured during 1500–3500 keV Xe^{26+} ions bombarding Mo and Nb surface. The experimental data are in a good agreement with the calculated values by binding-energy-modified binary encounter approximation (BEA) model in the united-atom (UA) limit, within the frame of MO.

2. Experiment apparatus and method

The experiment was carried out at the 320 kV High Voltage Platform which used a novel permanent magnet electron cyclotron resonance ion source (ECRIS) [8], located in the Institute of Modern Physics (IMP), CAS. A schematic diagram of the experimental arrangement is shown in Fig. 1. During the experiment, Xe^{26+} ion beams were accelerated to 1500–3500 keV, extracted and selected by a 90° analyzing magnet. Then the beams in single charge state passed a quadrupole and were collimated highly through two sets of four jaw slits. After entering the chamber, the energetic ions impinged on the target surface at 45° direction. Finally, the emitted X-ray was counted with a Si (Li) detector mounted at 90° relative to the beam incident direction. The detector has a solid angle of 23.8 msr and an energy resolution of 165 eV at 5.9 keV from ^{55}Fe radioactive source. The base pressure of the target chamber was maintained at 2×10^{-8} mbar. In addition, both the targets had a same purity of 99.99%, a same size of 20×21 mm^2, a same thickness of 0.5 mm and a polished surface.

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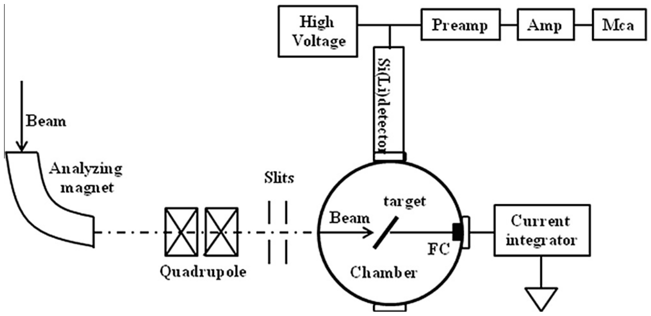

Fig. 1. Schematic diagram of the experimental set-up.

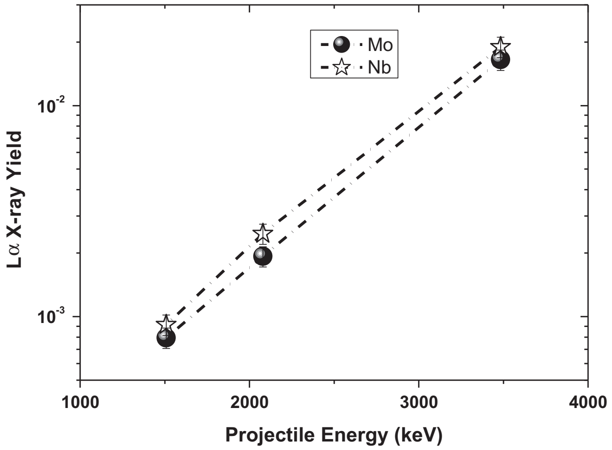

Fig. 3. Mo and Nb Lα X-ray yield induced by Xe^{26+} ions versus the incident energy (*E*). Filled circle: Mo; Open star: Nb. The dashed lines are drawn to guide the eyes. Error bars have the same size with the symbols.

3. Results and discussion

Typical X-ray spectra following the interactions of Xe^{26+} ions with Mo and Nb target are shown in Fig. 2(a) and (b). On the basis of energetics, the Lα and Lγ X-ray arise from the target (Mo and Nb) 3d → 2p and 4p → 2s transitions, respectively. Besides, the interesting observation here is that the generation of the projectile Lβ X-ray spectrum which is contributed to forbidden transition 3d → 2s.

If one assumes X-ray isotropic emission, the X-ray yield can be deduced from the following expression [9]:

$$Y(E) = \frac{N_X}{N_P}\frac{4\pi}{\Omega}\frac{1}{\varepsilon\mu} \qquad (1)$$

where N_X is the total detected X-ray counts for each spectrum, which is determined by integrating the X-ray peak using Gaussian Fitting in OriginPro8; N_P is the total number of the incident particles, which is estimated by the equation $N_P = N_{\text{target}}/(1+\gamma/q)$ [10,11]; Ω is the solid angle seen by the detector from the target, which is 23.8 msr in the present experiment; ε is the Si(Li) detector efficiency calculated using manufacture's specifications; μ is the photon filter transmission coefficient in 2 cm air and a 50 μm beryllium window [12]. Mo and Nb Lα X-ray yield excited by Xe^{26+} ions as an incoming energy function are shown in Fig. 3. The errors of X-ray yield are about 11%, including statistical and systematic errors.

Supposed Xe^{26+} ions slow down along a straight trajectory and neglected the energy loss straggling, target Lα X-ray production cross sections could be extracted from the X-ray yield Y(*E*) using the standard formula [1]

$$\sigma_X^e(E) = (n)^{-1}[dY(E)/dE](dE/dR) + (\overline{\mu}/n)Y(E) \qquad (2)$$

where *n* is the target atom density; *dY(E)/dE* is extracted by fitting the X-ray yield as a function of the projectile energy; *dE/dR* describes the stopping power for the incoming ions in the target, calculated using the SRIM-2008 program [13]; $\overline{\mu}$ represents the absorption coefficient of the target for photon of different energies and is acquired from the NIST [14]. The experimental values $\sigma_X^e(E)$ for Mo and Nb as an incident energy function are plotted in Figs. 4 and 5, respectively. However, the uncertainty of the X-ray production cross sections is slightly larger than that of the yield, because the experimental data are not smooth.The experimental results illustrate that Mo (Nb) Lα X-ray production cross sections ($\sigma_{X:Mo}^e(E)$, $\sigma_{X:Nb}^e(E)$) increase with the increasing impact energy. Moreover, $\sigma_{X:Mo}^e(E)$ and $\sigma_{X:Nb}^e(E)$ are of the same order of magnitude as target atomic numbers are neighboring. Besides, the theoretical production cross sections $\sigma_X^t(E)$ calculated by the binding-energy-modified BEA model [15] are also plotted in Figs. 4 and 5. The detail of this model will be discussed in the following.For slow collisions ($v_p \leqslant v_e$, v_p is the projectile velocity; v_e is the orbital velocity of the bound electron), using the modified BEA, the direct ionization of target atom has been interpreted successfully by several groups [16,17]. According to this model, the inner-shell ionization cross sections are given by [15]

$$\sigma_I(E) = (Nz^2\sigma_0/U^2)G(V) \qquad (3)$$

where *N* is the number of the equivalent electrons with the binding energy *U*; *Z* is the projectile charge and $\sigma_0 = 6.56 \times 10^{-14}\ \text{cm}^2\ \text{eV}^2$. The term *G(V)* expresses a scaled velocity ($V = v_p/v_e$) function, which has been given in Ref. [15].

As we know, the binding-energy modification to BEA is based on the model that a transient quasi-molecule [4,9] will be formed

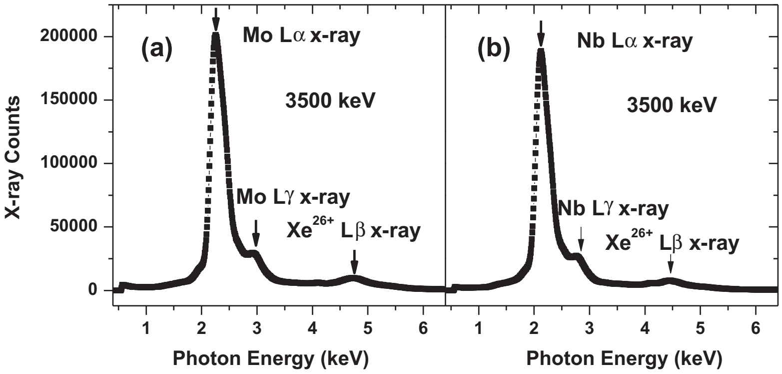

Fig. 2. (a) X-ray spectra emitted in collisions Xe^{26+} + Mo at 3500 keV and (b) X-ray spectra emitted in collisions Xe^{26+} + Nb at 3500 keV.