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K-shell X-ray production in Silicon ($Z_2 = 14$) by ($1 \leqslant Z_1 \leqslant 53$) slow ions

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ABSTRACT

K-shell X-ray emission of Silicon induced by near-Bohr-velocity ions was systematically investigated in collision systems for which the ratio of projectile-to-target atomic numbers (Z_1/Z_2) ranged from 0.07 to 3.79. The results show that, in asymmetric collisions, the measured K-shell X-ray production cross sections of Silicon fit very well with the predictions of different direct ionization models depending on the atomic number of projectile. In the case of near-symmetric collisions ($Z_1/Z_2 \sim 1$), an obvious enhancement of the X-ray production cross section was observed, which can be attributed to the vacancy transfer within the framework of quasi-molecular model.

1. Introduction

The inner-shell ionization of atoms induced by the ion–solid collision has been extensively studied in the last decades. In these studies, tabulations and more recent reviews of the status for light ions impacting show that the direct ionization is the main mechanism responsible for K-shell vacancy production of target atom [1,2], and most of the available experimental data, spanning a large range of relative velocities and target atomic numbers, are accurately described in a consistent way by ECPSSR theory [3]. Nevertheless, K-shell vacancy production of target atom becomes more complicated for the heavy-ion collisions, additional mechanisms, such as molecular-orbits (MOs) model at low velocity and electron capture have to be taken into account [4–7]. In general, the atomic model is applicable for the target X-ray production in asymmetric collisions, and yet the target X-ray production is usually discussed via the molecular model in symmetric or near-symmetric collisions. Watson et al. investigated Cu and Al K-shell vacancy production cross sections as a function of projectile atomic number for the same 10-MeV/u incident ions [8,9]. However, only a few experimental studies for the heavy-ion collision near Bohr velocity have presented the systematic behavior. In the energy region, the incident ions not only have enough energy to approach target atom, but also have enough time to form the molecular orbits and transfer inner-shell vacancies or electrons. Hence, under the circumstance, both the direct ionization and the vacancy transfer or sharing of the formed MOs may active play. Our previous work reported target Z dependence of Xe L X-ray emission in heavy ion–atom collisions near Bohr velocity, in which an obvious resonant phenomenon was discussed by level matching of quasi-molecular model [10].

The primary objective of the present work is to obtain projectile Z dependence of Si K-shell X-ray production cross section in ion–solid collision near Bohr velocity. The cross sections were measured in near-symmetric and asymmetric collisions and compared with some theoretical models. The emphasis is given the systematical trend for the variety of the cross sections and the enhancement of the cross sections in the near-symmetric collisions.

2. Experimental setup

The experiment was performed at the 320 kV high voltage experimental platform at Institute of Modern Physics, Chinese Academy of Sciences (IMP, CAS) in Lanzhou [11,12]. Ions (H^+, He^{2+}, Ne^{7+}, Ar^{11+}, I^{20+}) near Bohr velocity were extracted from the Electron Cyclotron Resonance (ECR) ion source. The experimental system has been fully described in the previous work [3]. The ion beam with spot size of about Φ3 mm impacts perpendicularly onto the Si solid target surface which has a purity of 99.99%, a area of

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6.9 cm^2 and a thickness of 1 mm which can stop all incident ions in our energy range. The emitted X-rays were detected at 45° to the normal of the target by a Si drift detector (XR-100SDD), which has a detective area of 7 mm^2 and 12.5 μm Beryllium (Be) window in the front of the detector. An effective energy range of the detector is 0.5–14.3 keV when the gain is selected at 100, and an energy resolution of about 136 eV at 5.9 keV when the peaking time is set at 9.6 μs. The solid angle of the detector which is calibrated using the standard radioactive sources ^{55}Fe and ^{241}Am is 0.0011 sr. Its efficiency was determined by the transmission measurements.

3. Results and discussion

A typical Si K-shell X-ray emission spectrum induced by 5.0-MeV I^{20+} ions is shown in Fig. 1. To obtain the Si K-shell X-ray yield $Y(E)$ per incident particle, it is assumed that the X-ray emission is isotropic. Taking into account the solid angle and the detection efficiency of the detector, X-ray yield is given by

$$Y = \frac{N_x}{N_p \eta (\Omega/4\pi)} \tag{1}$$

where N_x is the X-ray counts which is extracted from the Gaussian fitting of the spectrum. N_p is the total number of incident ions. η is the detection efficiency of the detector which is about 74.7% for Si K-shell X-ray. Ω is solid angle of the detector.

The experimental X-ray production cross section can be derived from the yield using the well-known formula for the thick target [13],

$$\sigma_x(E) = \frac{1}{n}\frac{dY(E)}{dE}\frac{dE}{dR} + \frac{\mu}{n}\frac{\cos\theta}{\cos\varphi}Y(E) \tag{2}$$

where n is atom density of the target (atom/g), μ is the mass absorption coefficient of the target (cm^2/g), which can be found from the NIST database [14]. θ is the incident angle to the normal direction of the target surface, φ is the observation angle to the normal direction of target surface, $Y(E)$ is the yield at the projectile energy E, dY/dE is derived from fitting the function to E and Y. dE/dR is the stopping power calculated by SRIM2010 program [15]. The total uncertainty of the cross section is about 19%, consisting of the uncertainty of stopping power about 13%, fitting of dY/dE about 10% and $Y(E)$ about 10%.

Based on BEA theory, the ionization cross section is calculated in a close form as following [16],

$$\sigma_i = \left(\frac{NZ^2\sigma_0}{U^2}\right)G(V) \tag{3}$$

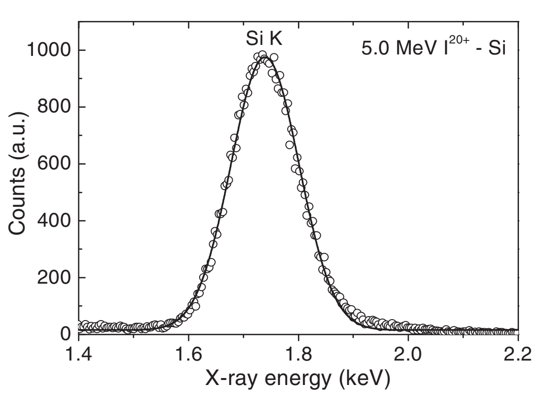

Fig. 1. Typical Si K X-ray spectrum induced by 5.0-MeV I^{20+} ions. The circle represents experimental data. The solid line represents Gaussian fitting.

where N is the number of i-shell electrons, Z is the projectile nuclear charge, $\sigma_0 = \pi e^4 = 6.56 \times 10^{-14}$ cm^2 eV^2; U is the binding energy of electron, G (V) is a universal function of the scaled velocity $V = \upsilon_p/\upsilon_i$ (υ_p is the velocity of the projectile, υ_i is the average velocity of i-shell electrons). The theoretical X-ray production cross section is obtained from the ionization cross section by the formula [17],

$$\sigma_x = \sigma_i * \omega \tag{4}$$

where σ_i is the ionization cross section of i-shell electron of target atom, ω is the fluorescence yield [18], which is about 0.0497 for Si K-shell X-ray emission.

The experimental Si K-shell X-ray production cross sections are shown in Table 1 and Fig. 2 involving projectiles with atomic numbers $1 \leqslant Z_1 \leqslant 53$. Meanwhile, theoretical calculations are also included for comparison in Fig. 2. For a given projectile, X-ray production cross sections increase with the increasing of incident energy, and at the same incident energy, monotonously increases as a function of the atomic number of the projectile, since energy loss of incident ions in target rises. A noteworthy feature is that the cross sections reach the maximum for Ar^{11+} ions impacting relative to other projectiles.

A comparison between the experimental data and the theoretical predictions shows as following: (i) for the light ions (H^+ and He^{2+}), X-ray production cross sections are well described by ECPSSR theory, which is consistent with the studies over a large range of relative velocities and target atomic numbers [3]. (ii) For the intermediate-heavy ions (Ne^{7+}), the experimental results can be reproduced by the calculations of BEA theory taking into account the effect of Coulomb Repulsion [19] and effective-charge modification [20]. At low velocities, the highly charged heavy ions carrying their residual orbital electrons interact with the target atom, the screening effect of the residual orbital electrons to the atomic nucleus can't be neglected since they acts as ions or atoms rather than point charge. Hence, the projectile

Table 1
Si K-shell X-ray production cross sections induced by different projectiles.

Projectile	Incident energy (MeV)	Cross section (cm^2)
H^+	50	4.72×10^{-26}
	100	8.86×10^{-25}
	125	2.08×10^{-24}
	150	3.90×10^{-24}
	175	6.61×10^{-24}
	200	1.04×10^{-23}
	225	2.13×10^{-23}
	250	2.58×10^{-23}
He^{2+}	100	2.41×10^{-27}
	200	8.97×10^{-26}
	300	9.23×10^{-25}
	400	2.39×10^{-24}
	600	8.25×10^{-24}
Ne^{7+}	1.0	4.56×10^{-24}
	1.1	6.83×10^{-24}
	1.2	1.10×10^{-23}
	1.3	1.36×10^{-23}
	1.4	1.58×10^{-23}
Ar^{11+}	1.0	8.68×10^{-22}
	1.5	1.12×10^{-21}
	2.0	1.33×10^{-21}
	2.5	1.53×10^{-21}
	3.0	1.72×10^{-21}
I^{20+}	2.0	1.50×10^{-22}
	2.5	1.84×10^{-22}
	3.0	2.19×10^{-22}
	3.5	2.49×10^{-22}
	4.0	2.99×10^{-22}
	4.5	3.32×10^{-22}
	5.0	3.74×10^{-22}