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Simultaneous K plus L shell ionized atoms during heavy-ion collision process

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Abstract. The fraction of simultaneous K plus L shell ionized atoms is estimated in Fe, Co and Cu elements using carbon ions at different projectile energies. The present results indicate that the fraction of simultaneous K plus L shell ionization probability decreases with increase in projectile energy as well as with increase in the atomic number of the targets atoms.

Keywords. K plus L shell ionization probabilities; Si(Li) detector; carbon ions.

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1. Introduction

Several studies indicate that when heavy ions are used as projectiles, K shell ionization is usually accompanied by multiple vacancies in L shell [1–5]. This multiple ionization phenomenon causes a shift in K X-ray energies towards higher energy side [6–10]. Due to these energy shifts in X-rays, satellite lines are observed at higher energies in addition to diagram lines. The X-ray components under the satellite lines correspond to energy shifted K X-rays emitted from multiply ionized atoms, while the X-ray components under the diagram lines correspond to the X-rays emitted from singly ionized atoms. The ratios of the intensity of X-rays under satellite lines to the total intensity of X-rays under the diagram lines and the satellite lines represent the fraction of multiply ionized atoms that are produced during the heavy-ion collision process. The energy difference between the satellite lines and the diagram lines is of the order of a few electron volts. Hence, they cannot be resolved with Si(Li) detector. Hence, it is not possible to estimate the fraction of multiply ionized atoms arising due to heavy-ion collision process by employing

Si(Li) detector. Li *et al* [11] have suggested a method to estimate the fraction of simultaneous K plus L shell ionized atoms employing a Si(Li) detector. They have estimated the fraction of multiply ionized atoms in Ca, Ti and Fe using deuterons and helium ions as projectiles at different energies. In that method, Li *et al* [11] considered the critical absorption of energy shifted K_β X-rays while passing through an external absorber of the same material. The energies of normal K_β X-ray components (arising due to singly ionized atoms) should lie below the K absorption edge of the same target atoms, while the energies of the shifted K_β X-ray components (arising from multiply ionized atoms) should lie above the K absorption edge of the same target atoms. As a result, the energy shifted K_β X-ray components will be absorbed much more than the normal K_β X-ray components while passing through an external absorber of the same target materials.

In the present work, the fraction of multiply ionized atoms is estimated using the method described by Li *et al* [11] in Fe, Co and Cu elements with carbon ion projectiles at energies of 6, 7 and 8 MeV.

2. Experimental details

Thin targets of Fe, Co and Cu were prepared on Al mylar backing material by vacuum deposition technique. The thickness of the foils lies between 20 and 30 μg/cm^2. The experiments were carried out at the Institute of Physics, Bhubaneswar using 3 MV pelletron accelerator. The targets were kept at an angle of 45° to the beam direction and exposed to a beam of carbon ions. The X-rays emitted from the targets are recorded with a high resolution Si(Li) detector whose FWHM is 160 eV at an energy of 5.9 keV. The detector is kept at an angle of 90° to the beam direction. The beam current is maintained between 2 and 5 nA. For a particular target, and at a particular beam energy, the K X-ray spectrum of a target is recorded for sufficiently long time to ensure good statistics. The same K X-ray spectrum is recorded by placing the absorber of the same material externally between the target and the detector. The same experiment is repeated for different targets at different projectile energies. The normalized overlapped K X-ray spectrum of cobalt obtained with and without external absorber due to 8 MeV carbon ions is shown in figure 1. From the overlapped spectrum, it is evident that the intensity of K_β X-rays with external absorber is reduced compared with the intensity obtained without absorber. This is due to the critical absorption of the energy shifted K_β X-rays while passing through the external absorber.

3. Method and data analysis

Let g_{KL} represent the fraction of simultaneous K plus L shell ionized atoms due to heavy-ion collision process. According to Li *et al* [11], g_{KL} is given by

$$g_{\mathrm{KL}} = \frac{f_n^\beta - R \cdot f_n^\alpha}{f_n^\beta - f_s^\beta},$$

where

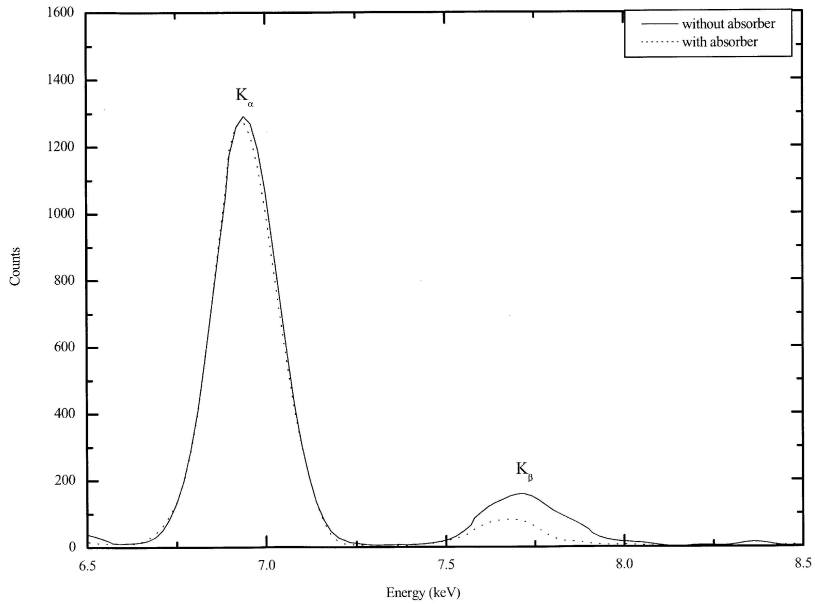

Figure 1. Normalized overlapped K X-ray spectrum of Co obtained with and without external absorber due to 8 MeV carbon ion projectiles.

$$R = \frac{I_\beta/I_\alpha(\text{with absorber})}{I_\beta/I_\alpha(\text{without absorber})}.$$

f_n^α and f_n^β represent the transmission probability of normal K_α and K_β X-rays and f_s^β represents the transmission probability of the shifted K_β X-ray components. From the observed spectra, the intensities of K_α and K_β X-ray components with and without absorber are estimated using peak fit software package. From the intensity values obtained with and without absorber, the values of R were estimated at different projectile energies. The values of f_n^α, f_n^β and f_s^β were estimated using the attenuation coefficients. The attenuation coefficients corresponding to the energies of the normal as well as energy shifted X-ray components were estimated from the tables of Storm and Israel [12]. The energies of shifted X-ray components were estimated from the corresponding measured energy shifts.

Tribedi *et al* [13,14] and Dhal *et al* [15,16] have carried out extensive studies and reported the dependence of K X-ray energy shifts and K X-ray intensity ratios on the energy and charge state of the projectiles. Their results indicate that the K X-ray energy shifts produced in a target by a projectile at different energies do not vary appreciably. In the present work, the energy shifts measured by our group [17] in one of our earlier experiments with carbon projectiles were employed in calculating the energies of the shifted X-ray components. Substituting the values in the above equations, the g_{KL} values are estimated in Fe, Co and Cu elements employing carbon ion projectiles at different energies. The g_{KL} values thus obtained in the present work are given in table 1.

Table 1. Experimental g_{KL} values obtained with carbon ion projectiles with different energies.

Energy of the projectile (MeV)	$g_{KL} \times 100$		
	Fe	Co	Cu
6	49±2.9	47±2.8	33±2.0
7	46±2.8	41±2.5	30±1.8
8	37±2.2	38±2.3	24±1.4

4. Results and discussion

The experimental g_{KL} values thus obtained for Fe, Co and Cu elements with carbon ion bombardment at three different projectile energies are presented in table 1. The uncertainties associated with the experimental values are also shown in the same table. The statistical error in the intensity of K_β X-ray component is about 3% and in K_α X-ray component is about 2%. Hence, the overall uncertainty in the parameter R was around 5%. The errors associated with other parameters are about 3%. Hence, the overall error in the experimental g_{KL} value is about 6%. If the K_β fluorescence yield does not change significantly as a result of the presence of an L shell vacancy and if the lifetime of the L shell vacancy is long compared to the lifetime of K shell vacancy, then [11]

$$g_{KL} = P_{KL},$$

where P_{KL} is the probability of simultaneous K plus L shell ionization. Boschung *et al* [18] have pointed out that the effect of simultaneous vacancies in the M, N, O,... shells do not affect the K X-ray energies appreciably. It is true that the spectator vacancy may occur in any of the different L sub-shells. But, Boschung *et al* [18] have also pointed out that the energy shift of the satellite line does not vary appreciably with a change in the position of the spectator vacancy among the L sub-shells.

It is not possible to compare our experimental data with the data of Li *et al* [11]. Fe is the only common element between the two works. But there is no common projectile energy. Also the projectiles that are employed in both these works are different. However, in the present work, it is observed that g_{KL} values decrease with the increase of projectile energy and also with increase of the atomic number of the target material. Similar trend was also observed by Li *et al* [11] while using deuterons and helium ions as projectiles. We have planned some more such experiments with different projectile–target combinations at different projectile energies. Meanwhile, we thought the present experimental data though undertaken with only one projectile at different energies with different targets, would contribute to the existing data on this aspect which further helps to arrive at some general conclusions in this aspect.

5. Conclusion

In the present work, the fraction of simultaneous K plus L shell ionized atoms are estimated in Fe, Co and Cu targets using carbon projectiles. From the present results, it is concluded that the fraction of simultaneous K plus L shell ionized atoms decreases with increase in projectile energy as well as with the increase in atomic number of the target.

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