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K_β /K_α Intensity Ratio and Total Vacancy Transfer Probability of Cs Following Nuclear Decay of Ba^{133}

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Abstract— Characteristic K X-ray photons of Cs have been measured following nuclear decay via electron capture process. X-ray spectrometer consisting of a Si(Li) detector and a PC based MCA is used to detect and measure the K X-ray photons emitted only in an approximate 2π – geometrical configuration. From which, *K X-ray* intensity ratio is calculated and is been compared with others' values obtained by different methods and the theoretical values computed by Scofield. A deviation of less than 2% in the *K X-ray* intensity ratio and the calculated K to L shell total vacancy transfer probability for Cs is reported. The deviation is accounted for Coulomb exchange interaction between electrons and the shake processes involved in the decaying nucleus.

Keywords— K_β/K_α intensity ratio, 2π-geometry, K to L shell total vacancy transfer probability

I. INTRODUCTION

Over many years, several researchers have shown interest in the computation of K_β/K_α intensity ratio of pure elements and alloys. Characteristic K X-rays is pivotal in various fields of atomic, molecular physics, astronomy, forensic science, industry, material science and nuclear physics [1, 2]. The characteristic K X-ray emission from pure elements is possible through excitation methods, decay processes, secondary excitation and X-ray absorption techniques [3-10]. In nuclear decay processes, viz. electron capture or IC, an electron is emitted from the inner shell leaving a vacancy for the electron. The ejected electron escapes the Coulomb potential and the remaining electrons with a fewer chance of getting excited to the vacant bound states or ionize to the continuum. The former known as shakeup and the latter is shake off respectively. Studies show that the shake process depends inversely as the square of nuclear charge Z [11, 12]. Hence, the shake process in nuclear decay affects X-ray emission. Also, it is reported for a given element decaying by electron capture (EC), the K_β/K_α intensity ratio is appreciably higher than that measured by photoionization and other methods [13]. Hence, there seems more scope for further investigation.

In this work, the characteristic K X-rays of Cs emitted during the nuclear decay of the radionuclide Ba^{133} following electron capture is been measured. From which K_β/K_α intensity ratio and K to L shell total vacancy probability is calculated. Its' been established that an almost 2π-geometry configuration proposed earlier by our group [10, 13, 14] requires only a weak radioactive source and since, most of the methods involve strong radioactive sources, the risk of radiation exposure is more. An attempt is made to validate the experiment using a simple 2π-geometry configuration for the study of some K X-ray fluorescence parameters from the characteristic K X-rays emitted during the EC process in a nuclear decay process. Ba^{133} radionuclide decays via electron capture and emits Cs K X-rays. These have been detected using Si(Li) X-ray detector coupled to a PC based 8k multichannel analyzer. The details of the experimental arrangement and the methodology is been discussed in section III Methodology. In this work, necessary corrections for the characteristic K X-rays emitted is corrected for various corrections and the calculation of K_β/K_α intensity ratio and K to L shell total vacancy transfer probability for Cs K X-rays is reported. An uncertainty of less than 2% in the result of K_β/K_α intensity ratio of the experimental work to the theoretical and others' experimental values by different methods is been stated. From the K_β/K_α intensity ratio the total K to L shell total vacancy transfer probability (η_{KL}) is calculated. The uncertainty in the calculation of 'η_{KL}' is been systematically estimated and reported in the Result and Discussion section IV. From this work, since there is a good agreement between the measured values for some K X-ray fluorescence parameters between this work and others' values, it seems there appears a scope for studying other X-ray fluorescence parameters as well. This would probably bring in more insights about understanding the atomic structure and electron rearrangement mechanisms during nuclear decay.

II. THEORY

In The intensity ratio of the characteristic K X-rays is calculated as in equation (1),

$$\frac{K_\beta}{K_\alpha} = \frac{I_j^{\prime} \cdot \varepsilon_i f_{g_i} f_{Be_i} f_{Au_i} f_{d_i}}{I_i^{\prime} \cdot \varepsilon_j f_{g_j} f_{Be_j} f_{Au_j} f_{d_j}} \quad (1)$$

where $I_i^{\prime}$ and $I_j^{\prime}$ are the detected K X-ray photons of nature $i = (K_\alpha)$ and nature $j = (K_\beta)$ from the decaying nucleus respectively. ε_i and ε_j is the correction for attenuation of emitted K X-ray photons of nature *i* and nature *j* in the active volume of the detector crystal. Similarly, the correction factor for the geometry of the experimental arrangement, correction factor for attenuation of emitted K X-ray photons of nature *i* and nature *j* in the window material (beryllium) of the detector, the correction factor due to attenuation of emitted K X-ray photons in the gold layer of the detector and the correction factor due to silicon dead layer for nature *i* and nature *j* K X-ray photons are $f_{g_i} f_{Be_i} f_{Au_i} f_{d_i}$ and $f_{g_j} f_{Be_j} f_{Au_j} f_{d_j}$ respectively. The true intensity for the emitted K X-ray photons for nature *i* and nature *j* is calculated after applying suitable corrections using eqn.1.

During the process of electron capture in nuclear decay, an electron in the inner shell viz, K- shell is captured by the nucleus. This results in the creation of a vacancy in the K-shell of the atom. This vacancy is soon filled by an electron from the higher bound state or an electron from an unbound state through radiative or Auger transitions. During which, electron rearrangement process takes place and results in the transfer of vacancy creation in additional higher shell or subshell. In the process, the total number of vacancies created in the L- shell by a K- shell to L- shell transition by filling a vacancy in the K- shell is called the K to L total vacancy transfer probability, η_{KL}. The K to L total vacancy transfer probability is calculated as given by Schonfeld and Janßen [8],

$$\eta_{KL} = \left[\frac{2-\omega_K}{1+\left(\frac{K_\beta}{K_\alpha}\right)}\right] \quad (2)$$

were 'ω_K' is the K-shell X-ray fluorescence yield and $\left(\frac{K_\beta}{K_\alpha}\right)$ is the K X-ray intensity ratio.

III. MATERIALS AND METHODS

K X-ray photons of Cs is been detected and measured from weak point radioactive source of Ba^{133} that decay via electron capture (EC) with a probability close to 100%. Ba^{133} radioisotope were prepared on a Perspex disc with a thin mylar film of 1mm in thickness by the Radiopharmaceuticals Division, Therapeutic and Reference Sources Section, BARC, Mumbai. Employing a simple 2π – geometrical configuration arrangement [13], the emitted K X-ray photons have been estimated. The X-ray detector spectrometer consists of a Si(Li) detector of an active surface area of 20 mm^2, 3.5 mm thick and Be window of thickness 12.5 μm with energy resolution of 140 eV at 5.9 keV and a PC based 8K MCA coupled to the X-ray detector. The intensity of emitted K X-ray photons due to the nuclear decay of the radioactive element via electron capture is measured as follows. Placing Ba^{133} source in front of the face of the detector window, as close as possible so as to capture most of the Cs K X-ray photons emitted in the forward hemisphere and to have a nearly 2π – geometrical configuration (Fig. 1), the 'source spectrum with type *i* and type *j* K X-ray peaks, K X-ray escape peak and internal bremsstrahlung continuum' of the decaying nucleus is acquired for a small live time of 600s. A typical source spectrum with Cs K_α X- ray peak at (31.0

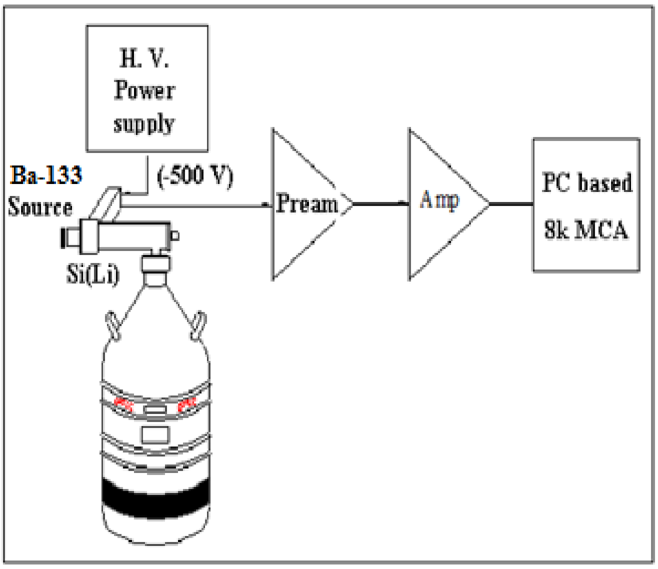

Figure 1. Experimental arrangement

keV), K_β X- ray peak at (35.7 keV), bremsstrahlung continuum is shown in (Fig. 2). The source spectrum is plotted using ORIGIN software by setting the baseline at zero. Now, to get the K X-ray spectrum from the acquired source spectrum, the source spectrum is subtracted for background radiation including internal bremsstrahlung continuum by calculating the mean background per channel under the K X-ray peak of respective type. From the background corrected K X-ray spectrum of Cs (Fig. 3), the K X-ray peaks is fitted to a Gaussian distribution function. Using the Fit-peak analysis in the ORIGIN software the area under each peak is carefully estimated. The area under each peak gives the intensity of K X-ray photons of the given type which is now corrected for the intrinsic efficiency of the detector material, geometry correction for the solid angle subtended by the active material of the detector at the source, the attenuation correction for K X-ray photons of respective type in the beryllium window of the detector, the corrections for absorption in gold layer and absorption in silicon dead layer of the detector using the method suggested by Cohen [15] and the true intensity of the K X-ray section should be concise but provide sufficient detail of the material used and equipment and the procedure followed to allow the work to be repeated by others. photon of the given type is estimated.

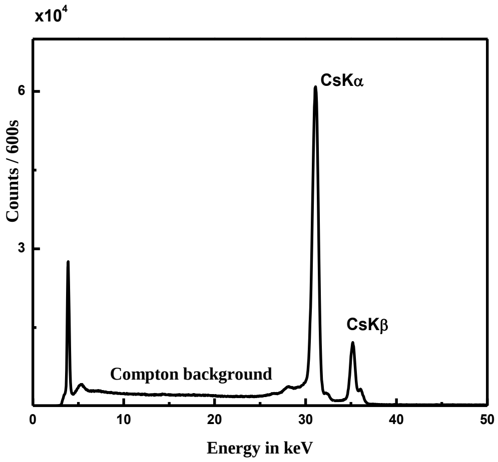

Figure 2. Ba[133] source spectrum with K X-ray peaks of Cs and Compton background

From the true intensity of K X-ray photons, the $\left(\frac{K_\beta}{K_\alpha}\right)$ intensity ratio is calculated using eq.1.

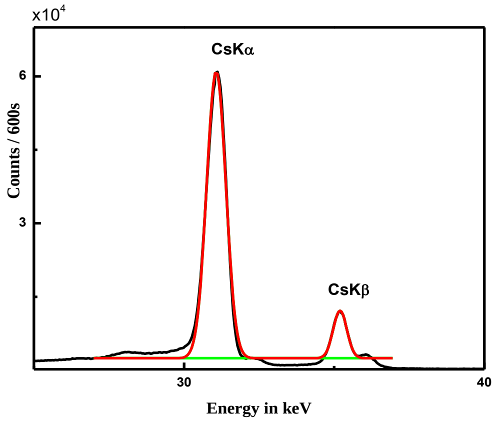

Figure 3. *Cs K X-ray Spectra after background subtraction*

For consistency of the result and to validate the methodology, the procedure is repeated four times.

IV. Results and Discussion

The characteristic K X-ray photons of Cs emitted due to electron capture (EC) process have been measured employing a simple 2π – geometrical configuration method as detailed in section III. The K_β/K_α intensity ratio in this work is compared with the theoretical values of Scofield [16] and others' experimental values obtained by the methods of photon excitation and decay processes is presented in Table 1. The this work shows a systematic increase in the measured relative intensity of K X-rays $\left(\frac{K_\beta}{K_\alpha}\right)$ with the others' experimental values involving different methods of photoionization and excitation methods and is close to the theoretical values of Scofield [16]. The $\frac{K_\beta}{K_\alpha}$ ratio of this work shows a deviation of < 1% with the theory, semi-empirical, fitted values and the others' experimental as in Table 1. An uncertainty of < 2% is reported in the measurement of K X-ray photons of nature i and nature j respectively. We, in this work have used the Hubbell [2] values for fluorescence yield (ω_K) for Cs and have calculated the K to L total vacancy transfer probability as in eqn. (2) of section II. The calculated total vacancy transfer probability (η_{KL}) of the this work is compared with the semi-empirical values computed by Schonfeld and Janßen [8], theoretical values of Ertugral et. al [23] and the others' experimental values and is presented in Table1. The calculated value for total vacancy transfer probability for Cs in this work shows a deviation of 1.2% and 1.1% with Schonfeld and Janßen [8] and Ertugral et. al [23] and < 1% with Simsek et. al [27]. An uncertainty of < 2%is estimated in the calculation of K to L shell total vacancy transfer probability. This uncertainty is found to be a cascading effect of uncertainty in the intensity ratio $\left(\frac{K_\beta}{K_\alpha}\right)$ and the fluorescence yield (ω_K).

Table 1. Comparison of measured K_β/K_α intensity ratio with theoretical values, semi- empirical and others' experimental methods and η_{KL} total vacancy transfer probability with the semi-empirical values, theoretical and others' experimental.

Atom	Z	K_β/K_α intensity ratio		
		This work	**a, b, c**	**Others' experimental**
Cs	**55**	0.2322 ± 0.0023	0.2358 [8]	0.2293 ± 0.0046* [19]
			0.2240 [16]	0.2369 ± 0.0047 [19]
			0.235 [18]	0.2328 ± 0.0073 [21]
				0.2340 ± 0.018 [24]
		η_{KL} total vacancy transfer probability		
		This work	**a, b, c**	**Others' experimental**
Cs	55	0.8830 ± 0.002	0.895(4)[8]	0.887 ± 0.013 [27]
			0.894 [23]	

a-Theory, b-semi-empirical, c-fitted

*-K X-ray intensity from Decay method

V. Conclusion and Future Scope

Using an almost simplen2π – geometrical configuration method consisting of X-ray detecting system and a weak radio source, K_β/K_α intensity ratio for Cs is been measured. The K X-ray photons emitted during the decay of Ba[133] radio isotope through electron capture is been detected in the forward hemispherical direction and is multiplied by a factor 2 in order to normalize the isotropic emission. From the measured K X-ray photons, K_β/K_α intensity ratio for Cs is first calculated. Using the fluorescence yield values from the data tables of Hubbell et. al [2], the K to L shell total vacancy transfer probability is estimated. A good agreement is been established with this work to that of the theoretical work and semi empirical fit values. However, the K_β/K_α intensity ratio for Cs is found to be slightly more in this work than the others' experimental values for K_β/K_α intensity ratio for Cs using methods other than nuclear decay method. It is found this higher value of K_β/K_α intensity ratio in Cs is due to the shake process in the electron re-arrangement process during nuclear decay. A detailed study may result in better understanding for the structure of an atom during the shake process and the electron re-arrangement process. Hence there seems a wide scope for the study as there is dearth of data in the understanding the structure of atoms and the electron re-arrangement mechanism during nuclear decay process in low and medium Z elements. Upon careful assessment and measurement of the emission lines, it is also possible to estimate many other X-ray fluorescence parameters.

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