Study of 1s internal bremsstrahlung spectrum from ^{57}Co

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Abstract

The internal bremsstrahlung contribution from the electron capture of ^{57}Co has been measured in coincidence with K-X-ray of the residual atom. The end-point energy (EPE) is extracted from the data using the linearised Jauch plot. The transition energy obtained using the (EPE) is 842.7 keV, which is close to the value given by Audi and Wapstra. The measured intensity and shape factor from 300 to 600 keV are found to be in good agreement with the Glauber and Martin theory. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Internal bremsstrahlung radiation (IB) is a continuous electromagnetic radiation accompanying beta decay (IB beta) and orbital electron capture (IBEC) processes. IB is the result of the change in dipole moment of the nucleus–electron system. Recently, the interest in the field of IB has been renewed largely especially in the IB following EC (Zlimen et al., 1991; Hindi et al., 1994, 1995; Daszewski et al., 1995; Hindi and Kozub, 1996; Janas et al., 1991; Hornshøj et al., 1987; Pfitzner et al., 1996). The interest lies in testing the validity of the existing theories, besides determining the end-point energy (EPE), the transition energy (Q) and the shape factor. The EPE of the IBEC spectrum is the difference between the transition energy and the binding energy (B_{nl}) of the captured electron from the corresponding ‘nl’ orbit of the atom.

The EPE determination for the case of ^{57}Co decaying to 136.37 keV level of ^{57}Fe has a special problem. The ^{57}Co also decays to 706.4 keV level although with a small branching ratio of 0.18%. This second branch

leads to a weak gamma transition of 692 keV (inset of Fig. 1). This is surprisingly close to the value expected for the EPE of the 1s IB spectrum using the transition energy of 836 keV (Audi and Wapstra, 1993).

The earlier IBEC studies, however, measure the value of transition energy to be 434 ± 30 keV (Jung and Pool, 1956) and 674 ± 30 keV (Lancman and Lebowitz, 1971) which are widely different. These are also at variance with the value of 836.1 keV quoted by Audi and Wapstra (1993) in their atomic mass tables. Although a much later work (Babu et al., 1990) gives a closer value of 846.5 ± 5 keV for the transition energy, it is to be noted that even the raw spectrum obtained in that work does not show the 692 keV peak near the EPE. Further, this (Babu et al., 1990) and the previous studies (Jung and Pool, 1956; Lancman and Lebowitz, 1971) involve the measurement of the total IB spectrum only. The transition energy is measured based on the determination of the EPE. Since the total IB intensity is a sum of the contributions due to capture of 1s, 2p, 2s, etc. orbital electrons, the EPE is different in each case. As a result, the transition energy derived from the total IB spectrum is not reasonably accurate. It is, therefore, essential to separate the specific partial shell electron contribution to

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Fig. 1. Spectrum of IB photons from ^{57}Co taken in coincidence with the 6.4-keV K-X-rays of ^{57}Fe . The solid line is a guiding line through the data points. Inset: Relevant portion of the decay scheme of ^{57}Co showing the different branching ratios of EC decay (Lederer and Shirley, 1978).

the IB intensity as may be seen in Hindi and Kozub (1996), Janas et al. (1991), Hornshoj et al. (1987) and Pfutzner et al. (1996).

Morrison and Schiff (1940) predict that the IB intensity for allowed EC transition should be of the form $k(k_0 - k)^2$, where k is the energy of the emitted photon and k_0 is the EPE. Later, Glauber and Martin (1956) improved this theory by taking into account the nuclear Coulomb effect, the screening effect and relativistic effect. A detailed review on the IB accompanying the EC decay is provided by Bambynek et al. (1977). It can be noticed that the agreement between theory and experiment, in general for IBEC, is not satisfactory. Even though there is an agreement in the spectral shapes, there is a large disagreement in spectral intensities. Further, the agreement in the shape factor, which includes Coulomb, screening and relativistic effects is also not satisfactory. Bambynek et al. (1977) point out that besides the precise measurement of normalised total IB spectra, partial spectra that accompany the capture of electron from specific atomic sub shells are very much needed. It is also felt that since Z is not too low in the case of ^{57}Co , Coulomb and screening effects are expected to play an important role in the observed IB spectrum.

In the light of the above, it was felt worthwhile by us to measure the internal bremsstrahlung contribution from the electron capture of ^{57}Co in coincidence with K-X-ray of the residual atom. The EPE has been extracted from the data using the linearised Jauch plot. The shape factor is extracted from the coincidence data. The measured intensity and shape factor from 300–600 keV are compared with the Glauber and Martin (1956) theory.

2. Experimental details

^{57}Co source of strength 20 μCi in the form of a disc of diameter 5 mm was obtained from BRIT, Mumbai, India. The IB spectrum from ^{57}Co was measured using co-axial HPGe detector of diameter 53 mm and length 58 mm of ORTEC make (GMX23210). The 6.4-keV K-X-ray was detected with a high-resolution silicon PIN diode detector with an area 13 mm² and thickness 500 μm of AMPTEC make (XR100 T). The pulses from the two detectors were amplified and fed to 'start' and 'stop' gate of time-to-amplitude converter (TAC) unit via timing single channel analyser (TSCA). The resolution time of TAC was fixed at 1 μs . The TAC/SCA output was used as a gate to select IB pulses corresponding to K-capture in ADC/MCA unit. The spectrum was collected for 500 h with calibration check for every 10 h. The HPGe spectrometer was calibrated using standard gamma sources.

3. Data analysis

The IB coincidence spectrum so obtained is shown from 300 keV in Fig. 1. The region below 300 keV (not shown here) could not be used due to the presence of the strong 122- and 136-keV gamma peaks (of ^{57}Fe) and their sum peak at 260 keV. The over-riding peak at around 692 keV seen in the figure corresponds to the weak transition (0.18%) from 706.4 to 14.4 keV energy level in the residual nucleus ^{57}Fe (decay scheme—insert of Fig. 1). Since the data acquired is for 500 h, this peak appears in spite of its weak transition.

The chance spectrum is obtained by calculating the chance count rate (N_c) for each channel using the relation $N_c = 2\tau N_1 N_2$; here N_1 is the measured 'singles' count rate corresponding to IB of the same channel and N_2 that of the X-rays (area under the X-ray peak), respectively and 2τ is the resolving time of the TAC.

The chance-subtracted spectrum is shown in Fig. 2. This spectrum is then corrected for finite resolution, Compton scattering and detector efficiency by the following method (since the count rate is very low, pile up effects are not considered).

The resolution correction has been carried out assuming that a mono-energetic gamma line spreads into a Gaussian distribution due to statistical fluctuations in several processes. The resolution-corrected spectrum is calculated, by iteration, using the following expression:

$$N(E) = \int_0^\infty \frac{N^1(E_r)}{(2\pi k E_r)^{1/2}} \exp\left[\frac{-(E_r - E)^2}{2k E_r}\right] dE_r, \quad (1)$$

where $N(E)$ is the chance-subtracted counts and $N^1(E_r)$ is the actual resolution-corrected counts. The factor k is related to FWHM.

Fig. 2. Graph showing chance-subtracted spectrum (squares) and the solid line is a guiding line. The crosses indicate the Compton-correction in the energy region. Inset: The singles K-X-ray spectrum used for coincidence gate.

The FWHM of standard gamma peaks was experimentally determined and best fit to these values was used to determine FWHM at other energies. The HPGe detector has a resolution of $<1\%$ at 662 keV for a shaping time of $1\mu\text{s}$ in the amplifier. The resolution correction was found to be small.

Due to scattering of gamma photons in the detector medium, the energy of the Compton electron spreads from zero to the Compton edge. The contribution of these electrons to the pulse height was calculated by taking into account the Compton contribution from higher energy gamma photons. The required peak-to-total ratio for this calculation was experimentally determined. The Compton correction is shown in Fig. 2.

The intrinsic peak efficiency of the detector at different energies was obtained from the detector manual. The Compton- and resolution-corrected spectrum is divided by the efficiency at each bin of 10 keV width. The resulting spectrum of $1s$ IB is divided by the theoretically evaluated non-radiative EC transition probability. This ratio is compared with that based on the theory of Glauber and Martin (1956). This is presented in Fig. 3.

4. Results and discussion

As stated earlier, the 692-keV peak due to the weak transition in ^{57}Fe is over-riding on the IB continuum. The presence of this peak close to the EPE presents a special problem in ^{57}Co for the determination of the EPE. Hence, the EPE is obtained (excluding this peak region) from a linearised Jauch plot, by extrapolation of the straight line.

Fig. 3. Normalised IB yield per keV per EC decay (circles). The error bars indicate the propagated errors. The solid line is the prediction based on Glauber and Martin theory.

Fig. 4. A linearised plot (Jauch plot) of the IB yield per keV per EC decay. The solid line is a weighted least-squares fit to the data points. The dotted lines on either side represent the statistical confidence bands at a confidence level of 95%.

4.1. Jauch plot

The $1s$ -IB intensity distribution per K-capture may be written as

$$(dW_{1s}/dk)/W_k = (\alpha/\pi)k(1 - k/k_0)^2 R_{1s}(Z, k), \quad (2)$$

where $R_{1s}(Z, k)$ is the shape factor and α is the fine-structure constant. Rearranging the expression, we get

$$[(dW_{1s}/dk)/(W_k k R_{1s})]^{1/2} = (\alpha/\pi)^{1/2} (1 - k/k_0). \quad (3)$$

Using this equation, the linearised Jauch plot is then obtained by replacing (dW_{1s}/dk) by the experimental value of $(dW/dk)^{\text{exp}}$. A weighted least-squares fit is made to this data. This is shown in Fig. 4. The EPE is

obtained by determining the intercept of the straight line on the energy axis. The EPE for ^{57}Co , thus, extracted is found to be 698.6 keV.

4.2. Transition energy

The transition energy for the decay of ^{57}Co to ^{57}Fe is then calculated by adding the k-shell binding energy and the gamma-transition energy from the 136.4-keV level to the EPE. This is found to be 842.7 keV.

4.3. Error analysis

The error on each data point in the chance-subtracted spectrum arises due to the random error in IB coincidence counts and in the chance coincidence counts; the latter again is the result of statistical errors in singles measurements in IB and K-X-rays. The sources of systematic errors in the measurements are: (i) finite resolution; (ii) Compton contribution; and (iii) detector efficiency. The systematic uncertainty on each point has been estimated, keeping in view the energy-dependent effect of each of these error sources. The systematic errors were found to be small compared to the random errors. Thus, the propagated error at each stage has been estimated and is shown in the final spectrum (Fig. 3) and in the linearised Jauch plot (Fig. 4). Taking this error as weight, a least-squares fit is made for the linearised data and the EPE is obtained. The uncertainty in the EPE is estimated by drawing the statistical confidence bands with a confidence level >95%. This is also shown in Fig. 4. The uncertainty in the EPE is found to be +37 and –30 keV around 698.6 keV.

4.4. Shape factor

In the Glauber and Martin (1956) theory, Coulomb and relativistic effects are taken into account in terms of the shape factor $R_{1s}(Z, k)$. The IB intensity per 1s-electron capture is written as

$$((dW_{1s}/dk)/W_k) = ((dW_{1s}/dk)/W_k)_{\text{MS}} R_{1s}(Z, k), \quad (4)$$

where $((dW_{1s}/dk)/W_k)_{\text{MS}}$ is that based on the theory of Morrison and Schiff (1940) which does not include the corrections. The experimental shape factor R_{1s} is evaluated using this equation and then compared with the theoretical shape factor. The comparison is shown in Fig. 5 along with the errors.

5. Conclusions

The transition energy extracted for ^{57}Co , using the EPE obtained from the experiment, has yielded a value of $842.7^{+37/-30}$ keV. This value, compared to the earlier

Fig. 5. Experimental shape factor for 1s component of IB determined in coincidence measurement (squares with error bars). Solid line shows the result of Glauber and Martin theory.

experiments, is much closer to the value of 836 keV given by Audi and Wapstra (1993). However, the statistics involved in the experiment is poor in spite of the long counting time of 500 h. This is expected in a coincidence experiment with a low-counting efficiency for both the detectors. However, a fair agreement in the shape factor with the Glauber and Martin (1956) theory, within statistics, points to the validity of the theory for allowed EC transitions.

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