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Inner bremsstrahlung accompanying $\beta$ decay of $^{86}$Rb

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Abstract. Inner bremsstrahlung accompanying the first-forbidden beta decay of $^{86}$Rb was measured using the magnetic deflection technique with a 4.5 $\times$ 5.1 cm$^2$ NaI(Tl) crystal in the energy range 200–1660 keV. The raw spectrum was unfolded using the step-by-step process of Starfelt and Liden and compared with KUB, LF and FM theories. The measured spectrum is found to show fairly good agreement with LF theory in the energy range 200–1500 keV and it is found to deviate thereafter from all three theories.

1. Introduction

Beta decay is associated with the emission of weak inhomogeneous electromagnetic radiation called Inner Bremsstrahlung (IB). The IB is emitted by the changing dipole moment of the electron–nucleus system due to the creation and separation of electron and proton. IB has to be contrasted with External Bremsstrahlung (EB), which is emitted when the electron is deflected by a nucleus other than the one from which it emerges.

Persson (1968) has given a detailed review of the IB field from both the experimental and theoretical points of view. Although several experimental and theoretical works have been devoted to understanding the process underlying the IB phenomenon, there is still disagreement not only between theory and experiment but also among individual measurements themselves, and the disagreement between theory and experiment is conspicuous for first-forbidden transitions. The divergence between theory and experiment increases with increasing energy (Narayana et al 1977, Prasad Babu et al 1976).

Attempts to include Coulomb effects could only lessen the divergence but could not eliminate it altogether. Even the inclusion of the so called 'detour' transitions could not account for the observed excess over theory.

With the above considerations in view it was decided to study the IB spectrum of $^{86}$Rb and to see whether the inclusion of Coulomb effects alone would be sufficient or whether detour transitions must also be included. This isotope was chosen because it does not appear to have been studied before.

2. Experimental details

Rubidium-86 was procured from Bhabha Atomic Research Centre, Trombay, India. The carrier-free $^{86}$Rb was supplied in liquid form. The actual experimental source was prepared on a thin Mylar film (~1.7 mg cm$^{-2}$) cemented to a thin Perspex ring of diameter 2.5 cm.
The source was prepared by evaporating the liquid drop by drop onto the Mylar film. A few drops of dilute insulin were added to the source to obtain uniform spreading on the film. It was checked for impurities by recording the gamma spectrum using a hyperpure Ge detector. No observable impurities were noticed. For $\beta$ impurities the spectrum of the source sample was recorded using a plastic scintillator and no impurities were observed.

$\beta$ measurements are usually made following three methods: (i) the beta stopper method, (ii) the coincidence method and (iii) the magnetic deflection method. Renard (1953) was the first to use the magnetic deflection method. Berenyi and Varga (1970) undertook a detailed study of the various experimental methods and their measurements proved the efficacy of the magnetic deflection method beyond doubt. This method was later used by Sanjeeviah (1978), Venkataramaiah (1978) and Gundu Rao (1983), and this method is employed in the present investigation.

The experimental arrangement is shown in figure 1. A $4.5 \times 5.1 \text{ cm}^2$ NaI(Tl) scintillation detector coupled to an RCA 8053 photomultiplier was employed in the present measurement and the data were recorded with an EG & G ORTEC 7150-MCA. The magnetic field intensity was adjusted such that no $\beta$ particle from the source reached the detector. To achieve this, a thin lead foil was placed below a Perspex sheet a few mm
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Figure 2. (a) Measured spectral distribution (A), background (B) and Compton electron distribution (C). (b) Decay scheme of $^{86}$Rb.

thick and the integral counts were recorded. Next the positions of lead foil and Perspex sheet were interchanged and again the integral counts were noted for the same time interval. The equality of the two counts within statistical error indicated that no β particles were reaching the detector. The spectrometer was calibrated using $^{57}$Co (122 keV), $^{203}$Hg (280 keV), $^{22}$Na (511 keV, 1.27 MeV), $^{137}$Cs (662 keV) and $^{54}$Mn (835 keV). The data were accumulated for several runs of 20 h each and a total of ten consistent runs was considered for the final analysis. The background was also recorded for the same time. The raw experimental spectrum and the corresponding background together with the Compton correction are shown in figure 2(a). The decay scheme (Lederer and Shirley 1977) is shown
in figure 2(b). The dominant peak at 1076 keV is due to the source-dependent gamma. The small hump at 1300 keV is due to the corresponding peak in the background.

3. Spectral unfolding

What one usually measures is the pulse-height distribution due to the folding of the incident spectrum with the detector response. In order to get the true spectrum the raw spectrum should be unfolded and in the present investigation the step-by-step process due to Starfelt and Liden (1953) was employed.

After subtraction of the background from the measured spectrum, the 1076 keV peak due to the decay of $^{86}$Rb to the first excited state of $^{86}$Sr is eliminated following the procedure of Prasad Babu et al (1974). For this purpose the spectrum of the 1115 keV peak due to the decay of $^{65}$Zn was recorded under the same experimental conditions. After subtracting the IB distribution in the region of the 1076 keV peak, the two peaks were normalised and the contribution due to 1076 keV was then subtracted at every channel from the background-subtracted IB spectrum. A small difference of 39 keV between these two lines is ignored. The resultant spectrum is next subjected to a correction for finite energy resolution using the equation

$$N(E) = \int_{0}^{\infty} \frac{N'(E_t)}{(2\pi KE_t)^{1/2}} \exp \left( -\frac{(E_t - E)^2}{2KE_t} \right) dE_t$$

(1)

where the FWHM, $2W$ and $K$ are related by

$$K = \frac{W^2(E_t)}{2 \ln 2}$$

In order to get the resolution-corrected spectrum, the observed pulse-height distribution was substituted for $N'(E_t)$ in equation (1) and the integration was carried out numerically. The output spectrum is corrected and substituted for $N'(E_t)$ and the process repeated till convergence is obtained.

The resolution-corrected spectrum is then corrected for the Compton electron distribution. The photons which are involved in Compton collisions in the crystal give rise to a continuum from zero to $E_r^*$, the maximum energy of the recoil electron. If the number of photons of energy $E_r$ absorbed in the crystal is $n_a(E_r)$, then the number of Compton electrons ranging in energy from zero to $E_r^*$ is $n_a(E_r)(1 - K(E_r))$, where $K(E_r)$ is the fraction of photons detected with full energy. This factor is sometimes referred to as the peak-to-total ratio. The total number of Compton electrons at an energy $E$ due to all incoming photons from zero to $E_{max}$ is given by

$$n(E) = \int_{0}^{E_{max}} C(E, E_r)n_a(E_r)(1 - K(E_r)) dE_r$$

(2)

where the function $C(E, E_r)$ is the probability that a photon of energy $E_r$ gives rise to an electron of energy $E$ in a Compton event. On the assumption that the Compton electron distribution for any $\gamma$-ray energy is approximately constant over the energy range from zero to $E_r^*$ the following approximations are made:

$$C(E, E_r) = C(E_r) = 1/E_r^* \quad \text{for } 0 < E < E_r^*$$

$$C(E, E_r) = C(E_r) = 0 \quad \text{for } E > E_r^*.$$
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In order to obtain the Compton electron distribution the integration in equation (2) is performed numerically. The observed pulse-height distribution is first extrapolated to the end-point. By starting at the highest energy $n_\text{s}(E_r)$ is taken. Next the corresponding $(1 - K(E_r))$ is calculated. Then by choosing a suitable value for $\Delta E_r$ the ordinate $(\Delta n_\text{c})_r$ of the Compton distribution from zero to $E^*_r$ due to photons of energy between $E_r$ and $E_r + \Delta E_r$ is calculated from the relation

$$(\Delta n_\text{c})_r = (1/E^*_r)n_\text{s}(E_r)(1 - K(E_r))\Delta E_r.$$ (3)

This process is repeated to cover the entire energy region. Finally the Compton electron distribution is obtained by adding up all the contributions. This is subtracted from the background, from the 1076 keV peak and from the pulse-height distribution corrected for finite energy resolution.

The values of $K(E_r)$ are determined by recording the pulse-height distributions of a number of monoenergetic $\gamma$-ray lines to cover the entire energy region of present interest (Sanjeeviah and Sanjeevaiah 1978). They are displayed as a function of photon energy. The required values of $K(E_r)$ are then obtained from the resulting graph and used in equation (3).

Corrections for the detection efficiency and geometry were made following the procedure given by Wolicki et al (1956). The geometric efficiency is defined as

$$e_\text{Ge}(E) = \frac{G_E}{G_p} \times e_\text{abs}(E)$$ (4)

where

$$e_\text{abs}(E) = \frac{\text{Number of pulses recorded per second}}{\text{Number of radiations emitted by source per second}}$$

$$= \frac{N}{N_0}$$

and $G_E$ and $G_p$ are the extended-source and point-source geometry factors (Burt 1949). For a point source along the axis of the crystal $e_\text{abs}$ is given by Wolicki et al (1956) as

$$N = \frac{1}{2}N_0 \left( 1 - \cos \theta_1 - \int_{\theta_1}^{\theta_2} \sin \theta \exp(-M\sigma b \sec \theta) d\theta 
- \int_{\theta_1}^{\theta_2} \sin \theta \exp[-M\sigma(R \cosec \theta - a \sec \theta)] d\theta \right)$$ (5)

with

$$\theta_1 = \tan^{-1}(R/a)$$ and $$\theta_2 = \tan^{-1}[R/(a + b)],$$

where $M$ is the density of NaI crystal, $\sigma$ is the gamma absorption cross section, $a$ is the distance from source to detector, $b$ is the thickness of the crystal and $R$ is its radius. Using these values of $e_\text{abs}$ the geometric efficiency is evaluated.

The values of $e_\text{abs}$ tabulated by Wolicki et al (1956) are available. These values were computed using the old $\sigma$ values of White (1957). The values of $e_\text{abs}$ used in the present work have been calculated using equation (3) with recent values of the absorption cross sections (Hubbell 1969).
Because of the presence of the 1076 keV γ-ray line the pile-up contribution to the recorded 18 spectrum has been considered. The pile-up consists of the random coincidences of two uncorrelated radiations being detected within the resolving time 2τ of the detector system. The pile-up at an energy E is given by (Van Lieshout et al 1968)

\[ N_{pu}(E) = 2\tau \int_{0}^{\infty} N(E-X)N(X) \, dX \]  

where \( N_{pu}(E) \) represents the number of pulses per second at the energy E due to the combined contribution of pairs of pulses at energies \( E-X \) and \( X \) occurring within a time interval 2τ. The pile-up spectrum will have a sum peak at an energy of 2152 keV with a total intensity of 2\( \tau N^2 \) where \( N \) is the count rate at the photopeak. Using the experimental spectrum of 86Rb the contribution due to pile-up at each channel was calculated by using equation (5). It was found to be low since the source strength used was low (110 μCi). It was hardly seen in the recorded spectrum.

4. Comparison with theory

Knipp and Uhlenbeck (1936) and independently Bloch (1936) were the first to make the theoretical calculation of the 18 spectral distribution in allowed β decay and this is known as Kub theory. Wang Chang and Falkoff (1949) and Madansky et al (1951) extended these calculations to the first- and second-forbidden transitions. Lewis and Ford (1957; LF) and Nilsson (1956) accounted for the Coulomb effects on the 18 spectrum. Ford and Martin (1969; FM) included the ‘detour transitions’.

The isotope 86Rb has two branches with different end-point energies. 91.2% of the decay events lead to the ground state (2−→0+). This transition is classified as first-forbidden unique. The remaining 8.8% of the decay events lead to the first excited state (2−→2+) and this transition is characterised as first-forbidden non-unique. The 18 theoretical calculation was carried out separately for the two branches with appropriate branching ratios and the corresponding numbers were added to get the total spectrum. The contribution to the total 18 spectrum comes predominantly from the ground-state transition (91.2%). The contribution due to the decay in the other branch is very small (8.8%). As the calculations in the two cases are found to be not very different (Ford and Martin 1969; the 18 distributions due to the two branches are calculated using the same theory. Figure 3 shows the corrected total spectrum together with the theoretical spectra of Kub, LF and FM. The spectra are represented as number of photons per MeV per β disintegration as a function of energy. No normalisation of theory to experiment has been made. Error bars are shown in representative points at 500 keV and 1500 keV. Below 500 keV the overall error is less than 1%. At 500 keV it is about 5% and at higher energies the error becomes considerable, being 20% at 1500 keV.

5. Results and discussion

From figure 3 it is clear that the measured spectrum is close to LF theory (within 5%), the deviation being negative in the energy range 200–1500 keV, and beyond 1500 keV the measured experimental spectrum shows positive deviation from all three theories. From the present measurement it may be concluded that 18 accompanying β decay of 86Rb can
be adequately explained by the Coulomb-corrected theory of Lewis and Ford over a major portion of the measured spectrum. The positive deviation beyond 1500 keV cannot, however, be explained on any grounds.

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