Inner bremsstrahlung accompanying β decay of ^{147}Pm

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The inner bremsstrahlung spectrum associated with the nonunique first-forbidden β decay of ^{147}Pm was measured employing the magnetic deflection method with a 4.5×5.1 cm^2 NaI(Tl) scintillation spectrometer in the energy region 30—200 keV. The contribution due to the 121 keV source gamma ray line was subtracted by normalizing its peak with that of the 122 keV ^{57}Co gamma ray pulse height distribution recorded in the same experimental setup. The raw spectrum was unfolded following Liden and Starfelt and compared with theoretical spectral distributions. The measured spectral distribution does not match any of the theories in any part of the investigated energy region.

I. INTRODUCTION

Inner bremsstrahlung (IB) is a weak continuous energy electromagnetic radiation associated with β emission and electron capture. When a nucleus emits an electron the dipole moment of the nucleus-electron system changes due to the sudden creation and separation of an electron from a proton causing the emission of an IB photon. This should be contrasted with the external bremsstrahlung (EB) produced when the outgoing electron interacts with a nucleus other than the one from which it originates.

The importance of IB studies, both from an experimental and theoretical standpoint, is highlighted in a detailed survey by Persson.[1] Several discrepancies exist, not only between the theory and the experiment, but also among the individual measurements. Extensive investigations have been carried out with allowed as well as forbidden transitions. Disagreement between the theory and the experiment is more conspicuous in the case of forbidden transitions.[2] The divergence between the measurement and the theory is found to increase with increasing energy. Attempts to include Coulomb effects[3,4] and detour effects[5] also have not yielded satisfactory results.

^{147}Pm is a nonunique first forbidden β-emitting isotope with an end point energy of 225 keV. IB from this isotope has been measured by Boehm and Wu,[6] Langevin-Joliot,[7] Starfelt and Cederlund,[8] Singh and Al-Dargazelly,[9] and Prasad Babu *et al.*[10] Boehm and Wu reported good agreement with the Knipp-Uhlenbeck-Bloch (KUB) theory in the energy range 35—100 keV. Langevin-Joliot measured IB in the range 20—160 keV and her results were found to deviate from the KUB theory. Starfelt and Cederlund observed excess over the KUB-Nilsson theory in the energy range 15—160 keV, with the excess being higher, the higher the photon energy. Singh and Al-Dargazelly reported large deviations up to two orders of magnitude between theory and experiment in their measured energy range 50—220 keV. Prasad Babu *et al.* observed good agreement in shape with the Lewis-Ford (LF) theory in the range 50—160 keV. The disagreement between the measurement and the theory observed by Singh and Al-Dargazelly is attributed to the neglect of EB produced in the source encasement. Apparently the measurements of Prasad Babu *et al.*[10] appear to be satisfactory from the point of view of comparison with the LF theory. Considering the above discrepancies, it was thought worthwhile to reinvestigate the IB from ^{147}Pm by employing a different experimental technique. For comparison, the detour theory is also considered in the present work.

II. EXPERIMENTAL TECHNIQUE

A carrier-free ^{147}Pm source of strength 10 μCi, procured from the Bhabha Atomic Research Centre (BARC), Bombay, India, was used in the present investigation. The decay scheme[11] is shown in Fig. 2(a).

^{147}Pm decays with three branching ratios: 99.994% decay events lead to the ground state of ^{147}Sm; 0.0057% and 4×10^{-7}% decay events lead to the first and second excited states of ^{147}Sm, respectively. The events leading to the formation of the second excited state are not observed in the present investigation because of their extreme low intensity. IB associated with the β decay of the 0.0057% branch is negligible and it is confined to an energy region below 103 keV.

IB measurements are usually made following three methods, which are the following: (i) beta stopper method, (ii) coincidence method, and (iii) magnetic deflection method. In the beta stopper method the electrons are stopped in a low-Z material and then the correction is applied for EB production in the absorber material. This introduces an extraneous source of error to the measured spectrum. The main disadvantage of the coincidence method is that the number of coincidences recorded per beta disintegration is very small. Therefore one requires large time periods demanding the high stability of the electronic equipment. To improve the counting rate one can use strong sources. But in that case the chance coincidences increase in proportion to the square of the activi-

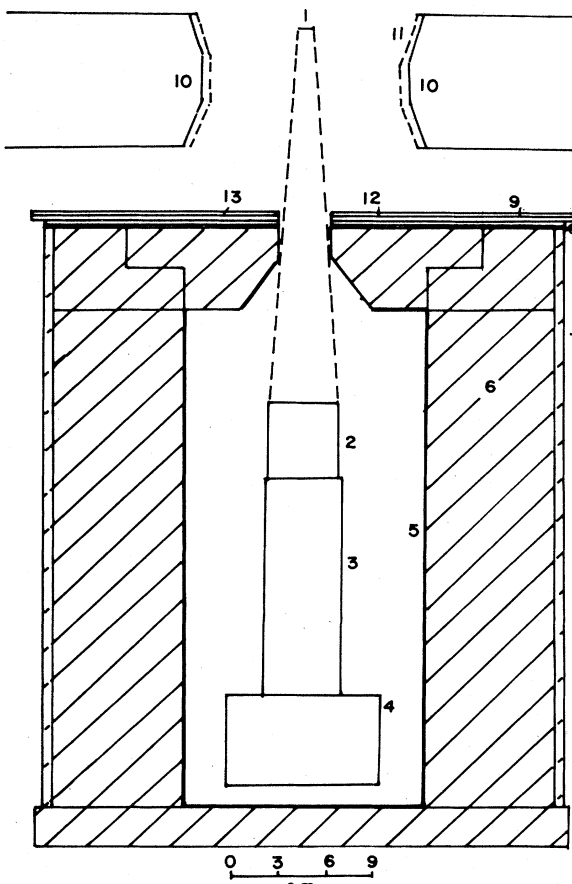

FIG. 1. Experimental setup: (1) source, (2) NaI(Tl) crystal, (3) photomultiplier, (4) cathode follower and preamplifier, (5) aluminum lining, (6) lead, (7) mild steel, (8) mild steel cover plates, (9) aluminum cover plate, (10) magnet pole piece, (11) Perspex lining, (12) aluminum ring, (13) Perspex ring, and (14) Perspex cover plates.

ty. In the case of thick sources, source scattering introduces an additional error.

Renard[12] was the first to use the magnetic deflection method in IB measurements. Berenyi and Varga[13] undertook a detailed study of the various experimental methods and their measurements proved the efficacy of the magnetic deflection method beyond a doubt. Later, this method was used by Sanjeeviah, Venkataramaiah, and Gundu Rao.[14] In the present measurement, the magnetic deflection method is used. The experimental arrangement is shown in Fig. 1. A 4.5×5.1 cm^2 NaI(Tl) scintillation detector coupled to an RCA 8053 photomultiplier was employed. The data were recorded with an EG and G ORTEC 7150 1K MCA.

The magnetic field intensity was adjusted such that no beta particles reached the detector. First a lead foil of 1 mm thickness was placed below a Perspex sheet of thickness 6 mm at the entrance of the collimater, and the counts were recorded in the integral mode. Then the positions of the foil and the Perspex sheet were interchanged and the counts were recorded again for the same time.

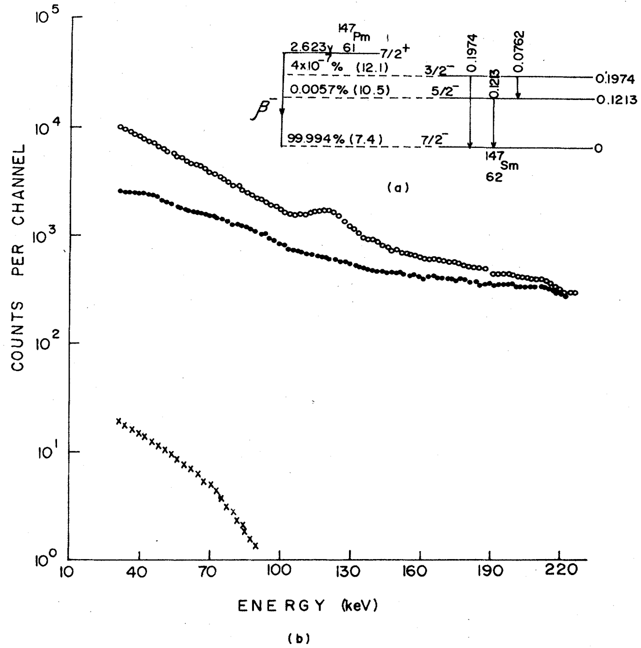

FIG. 2. (a) Decay scheme of ^{147}Pm; (b) measured spectral distribution, background, Compton electron distribution.

Had the field been insufficient, the counts in the second measurement would have been more than those in the first one due to the production of EB. The field intensity was adjusted until the equality of the two counts, within statistical error, was obtained. This confirmed the absence of EB, which in turn ensured that the beta particles are not reaching the detector. The spectrometer was calibrated using ^{125}I (35 keV), ^{170}Tm (84 keV), ^{57}Co (122 keV), ^{22}Na (511,1274 keV), and ^{137}Cs (662 keV), gamma ray lines. The stability of the amplifier gain was ensured by checking it every 20 h with the 662 keV gamma ray line. The IB data were collected for a total period of 200 h. Since the IB is of very low intensity the background was also recorded for the same time. The data were accumulated over several runs of 20 h each, and a total of ten such consistent readings was taken for the final analysis. Figure 2(b) shows the measured spectrum with the corresponding background. The Compton correction is also shown in that figure.

III. UNFOLDING PROCEDURE

In any gamma ray spectral measurement, what one records is the pulse height distribution of the counts resulting from the interaction of the incident radiation in the detector medium. Retrieval of the original information from the measured counts is called spectral unfolding, and in the present investigation the step by step procedure due to Liden and Starfelt[15] was followed.

As a first step, the background was subtracted from the measured spectrum. Since the count rate was quite low, the pileup effects were neglected. The contribution due to low intensity 121 keV gamma rays, due to the deexcitation of the first excited state of ^{147}Sm, was eliminated[10,16] by recording the spectrum of photons of 122 keV from ^{57}Co. The photopeak due to 137 keV gamma rays (12.1%) in the measured spectrum, is not resolved. Its contribution, being very small, is neglected in the normalization of the peaks. The two peaks were normalized before the contribution of the 122 keV line was subtracted from the total IB spectrum. The energy difference of 1 keV between these two lines is considered negligible. The spectrum thus obtained was corrected for finite energy resolution using the equation,

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

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

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

In order to get the resolution corrected spectrum, the observed pulse height distribution was substituted in place of $N^1(E_r)$ in the equation, and integration was carried out numerically. The output spectrum is corrected and substituted for $N^1(E_r)$, and the processes repeated until the convergence of the substituted number is achieved. The resultant spectrum is then corrected for Compton electron distribution using the equation,

$$(\Delta Nc)_{E_r}=\frac{1}{E_r^*} N(E_r)[1-K(E_r)]\Delta E_r \ , \quad (2)$$

where $(\Delta Nc)_{E_r}$ is the Compton electron distribution from 0 to E_r^* due to photons of energy E_r and $E_r+\Delta E_r$, $K(E_r)$ is the peak-to-total ratio, and E_r^* is the maximum energy of the Compton scattered electron. The resultant spectrum is then corrected for the K-x-ray escape using the equation,

$$N_5(E)=\frac{N_4(E)-N_5(E+E_k)F(E+E_k)}{1-F(E)} \ , \quad (3)$$

where $F(E)$ is the escape correction factor given by Liden and Starfelt,[15] $N_5(E)$ is the distribution corrected for the K x ray, and $N_4(E)$ is the experimental data after Compton distribution correction. The spectrum is then corrected for the absorption in the aluminum can covering the crystal, and in the air medium between the source and the detector. Finally, the spectrum was corrected for geometry and detection efficiency. The percentage errors involved in the present measurement and the various corrections applied to the measured spectrum are found to be about 4% in the energy range below 80 keV, and less than 10% below 160 keV, and it is found to be 14% around 200 keV.

IV. COMPARISON WITH THEORY

Knipp and Uhlenbeck[17] and Bloch[18] were the first to make theoretical estimates of IB and this is usually known as the KUB theory. These calculations were later extended by Chang and Falkoff[19] and Madansky *et al.*[20] to first and second order forbidden transitions. Lewis and Ford[4] and Nilsson[3] included the Coulomb effects. Ford and Martin[5] extended the theory to include the so-called "detour effects."

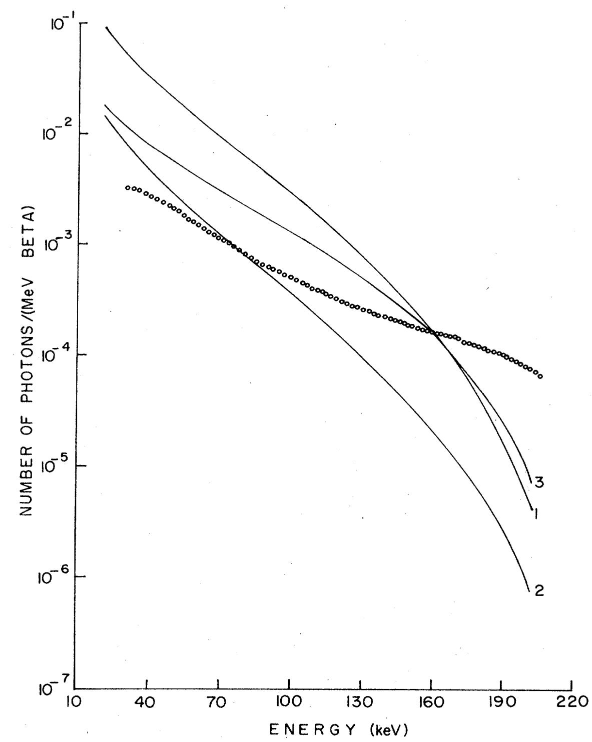

FIG. 3. (1) KUB, (2) LF, and (3) FM theoretical spectral distributions; ○○○ (linked circles), experimental spectral distribution.

The theoretical calculations of KUB, LF, and Ford-Martin (FM) were carried out using the Mysore University Computer TDC 316. The theoretical distributions, along with the unfolded measured spectrum expressed as the number of photons/MeV/beta, are shown in Fig. 3. The measured spectral distribution does not agree with any of the theoretical predictions. Comparing the measured spectra with the LF distribution, it can be seen that the former lies below the latter in the energy range 39—80 keV, with maximum deviation of 173% at 39 keV. The trend is reversed after 80 keV. At 160 keV the positive deviation is 95%. Above this energy the measured spectrum lies above all the theoretical distributions. This trend is found to be similar to many of the earlier measurements,[21–29] contrary to general expectation.[21] Therefore it is felt that more measurements are still needed to come to a possible conclusion.

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