Inner Bremsstrahlung accompanying β decay in 147Pm

S.J. Keshava, K. Gopala & A. Venkataraman

(Department of Radiation Physics, Kidwai Memorial Institute of Oncology, Hosur Road, Bangalore 560 029)

Department of Studies in Physics, Manasagangotri, University of Mysore, Mysore 570 006

Kuvempu University, Shankaraghatta, Shimoga District, Karnataka

Received 23 July 1999; revised 21 November 2000; accepted 29 December 2000.

Previous measurements of the Inner Bremsstrahlung (IB) from 147Pm, have shown serious disagreements with the theory. In the present paper efforts have been made to measure the IB of 147Pm with reasonable statistical accuracy. In addition the exact Fermi function rather than its first order approximation has been incorporated in the evaluation of the Lewis and Ford (LF) theory, for the case of first forbidden transitions. The experimental results are in good agreement with LF theory.

1 Introduction

The emission of a continuous spectrum of electromagnetic radiation simultaneously with the emission of β particles is known as Inner Bremsstrahlung (IB). The probability of emission is about 1/137, the fine structure constant. The emission is in the energy range of zero to E̅ end point energy of β particles. The intensity being higher at low energy end, decreases with increasing energy approaching zero towards the end point energy. This process is distinctly different from the external Bremsstrahlung (EB) in the fact that the IB emission takes place within the dimensions of a β emitting atom where as EB results from the retardation of emitted β particle in the Coulomb field of some other nucleus. 147Pm decays to 147Sm by β emission with a half life of 2.6 years with log f/ = 7.4 and end point energy of 225 keV. The transition is classified as non-unique first forbidden [1(7/2) → (7/2)]. Z independent theoretical calculation for the allowed transitions was given by Knipp, Uhlenbeck and independently by Bloch popularly known as KUB theory. Lewis and Ford (LF) incorporated first order Coulomb correction into the KUB theory for allowed transitions and also gave the theory for the first forbidden case with the first order Coulomb correction. Ford and Martin (FM) introduced detour transition probability in addition to direct transitions appropriate to first forbidden transitions. Chang and Falkoff (CF) developed the theory for the second forbidden transitions. The experimental results were widely varying. Boehm and Wu found agreement with KUB in the range 35-100 keV. Langwin and Joliot observed deviation from KUB between 20 and 160 keV. The results of Starfelt and Cedullund were in excess of KUB-Nilsson theory from 15 to 160 keV, the excess being higher for higher photon energy. Large deviations from the theory can be seen in the measurements of Singh and Al-Dargazelly and Babu et al. over the entire energy range. Contrary to this, Prasad Babu et al. showed good agreement with LF theory in the range 50-160 keV. Insertion of exact form of Fermi function instead of approximate forms into the theories by Keshava et al. too, failed to reduce the gap between the theory and experiment. These diversities in the experiments motivated us to re-examine the IB spectrum from this isotope. 147Pm emits a weak intensity source of energy 121.3 keV (0.0057 %) which can be easily subtracted from the IB spectrum with the knowledge of source activity, the geometric detection efficiency and the photo peak efficiency of the detector, the detector resolution and the peak to total ratio.

2 Experimental Details and Data Analysis

Carrier free 147Pm source was obtained from Bhabha Atomic Research Centre, Mumbai. The source was spread over a circular area of 1 cm diameter on a thin Mylar foil and mounted in a circular plastic ring holder of outer diameter of 2.5 cm. A NaI(Tl) crystal of size 4.445 cm diameter and 5.08 cm length was used as a detector coupled with
RCA8053 photo-multiplier tube, pre-amplifier, amplifier and FG & G ORTEC Model 7150 Multichannel Analyser. The activity at the time of conducting the experiment was 27548 Bq. The spectrometer was calibrated using the known mono-energetic gamma sources. The source to detector distance was 1.58 cm and it was positioned in the center of the detector. The spectrometer calibration was 1.26 keV per channel. First 26 channels were blocked by the lower discriminator setting to eliminate instrument noise pulses. The source and the detector system including the photo-multiplier tube and pre-amplifier assembly was shielded by lead housing which had 2 mm aluminium lining on the inner surface. The lead housing helps in reducing the background counts and the aluminium lining helps in preventing electron transport (in the case of a β emitter) to the lead housing (which may result in the production of unwanted external Bremsstrahlung and lead K-x rays). The source thickness was small enough so that the self-absorption and production of EB are neglected. The source was housed in a perspex cylindrical box which provided a minimum thickness of 0.8 cm of perspex for attenuating the source β particles. As perspex is a low Z material (mean Z = 6.5) the EB production in that also is neglected. However, the correction due to the absorption of EB in the β stopper material as well as the aluminium covering of the NaI detector is incorporated in the calculation of the geometric efficiency. Ten samples counting of 50 hr each and similar size background counting were performed.

The statistical strength of the data is determined by the statistical significance of the difference between the mean source plus background (X) and the mean background (B) counts. Noting that the nuclear counting follows Poisson distribution which approaches Normal or Gaussian distribution when the number of measurements are large, the distribution of sample means too follow the normal distribution and so also the distribution of the difference between any two sample means. In any given channel both source plus background and background counts are considered as the samples of a population for the purpose of conducting the statistical test. The standard error σ for the distribution of the difference between any two sample means is given by:

\[ \sigma = \sqrt{[X + B]} \]

Denoting the difference X-B as \( I_a \), then the statistic \( t = I_a/\sigma \) determines the confidence level of \( I_a \), which can be read from the Standard Normal Curve Area Tables (Armitage and Berry \(^1\)) for which mean = 0, standard deviation = 1 and \( t \) is the abscissa extending from -∞ (infinity) to +∞. \( p \) is the ratio of the area under the Standard Normal Curve lying between any given value of \( t \) and \( t = \infty \), to the area under the Standard Normal Curve lying between \( t = 0 \) and \( t = \infty \). The \( p \) value corresponding to \( t = I_a/\sigma \) determines the required confidence level.

(i) if \( I_a \geq 3\sigma \), then it can be considered as true; IB intensity at a confidence level of 0.3 % or less (\( p \leq 0.003 \)). The data can be considered to be excellent. (ii) if \( 2\sigma \leq I_a < 3\sigma \), then the confidence level of IB intensity lies between 5 % and 0.3 % (0.003 < \( p \leq 0.05 \)). The data can be considered to be good; (iii) if \( 1\sigma \leq I_a < 2\sigma \), then the confidence level of IB intensity lies between 32 % & 5 % (0.05 < \( p \leq 0.32 \)). The data can be considered to be fair. (iv) if \( I_a < 1\sigma \), then at a confidence level of more than 32 % (\( p > 0.32 \)), the data is considered to be statistically poor and the null hypothesis may be accepted (i.e., the difference between X and B is considered insignificant and both X and B are treated as sample means coming from the same population of counts).

If it is decided to terminate the data at any desired confidence level (for example 32 % or 5 % or 0.3 %) which may correspond to some channel number say \( N \). The counts in the \( N+1 \)th channel can be treated essentially as background only. This magnitude of counts may be subtracted from all channels. This is similar to correcting positive zero error in any measuring instrument. This procedure may also be termed as base line shift (BLS).

The data obtained from \(^{137}\text{Pm} \) was excellent up to 180 keV and good up to the end point energy. Sizable counts were present at the end point energy and beyond. Even though efforts are made to maintain the stability of the instrument, because of the long hours of counting and also the background counts and source counts being recorded at different times, the fact that the inherent fluctuations exist in both, make the difference counts \( I_a \) either positive or negative towards the end point energy where nil counts are expected. This fact also justifies the BLS described above for positive differences.
In our present experiment, the data terminated at different levels of confidence (0.3 % and 5 %) was processed with and without BLS. The unfolding of the IB intensities from the raw data was carried out adopting the step by step procedure of Liden and Starfelt\textsuperscript{14}, details of which can be found elsewhere (Basavaraju et al.\textsuperscript{15} and Babu et al.\textsuperscript{16}). After initial background subtraction and pile-up correction, the intensity spectrum is corrected for the finite energy resolution of the NaI(Tl) detector. The resolution function is taken as Gaussian. Next, the correction due to the compton electron distribution is made. Further the data is subjected to iodine K X-ray escape correction and the geometric detection efficiency of the detector-source spatial configuration including the attenuation of photons by the aluminium covering of the detector and the $\beta$ absorber (if used, as in the case of $\beta$ emitters). Finally the spectrum being corrected for the photo peak efficiency of the detector.

However, it is necessary to mention, the distortion caused by the detector resolution correction. The IB spectral data undergoing this correction tend to show false higher intensities in a few channels at the beginning and in a few channels towards the end. Due to the absence of counts on one side, the convolution procedure adds counts to the above said channels and hence the corrected data show false higher intensities. Except for this, most of the spectrum is well corrected within two or three iterations. The BLS method mentioned earlier overcomes this problem in the high energy end.

### 2.1 Uncertainties in the Experimental Data

The sources of uncertainties were: (a) The activity of the source, (b) uncertainties in the used attenuation coefficients in the calculation of the geometric efficiency of the detector, (c) uncertainties in the calculation of the peak to total ratios and compton electron distributions, iodine K X-ray corrections and resolution correction, and (d) statistical uncertainties in the counting.

The source was received in prepared condition from M/s Bhabha Atomic Research Centre, Mumbai, India with an activity tolerance specification of $\pm 10 \%$. This uncertainty was immaterial, because our aim was to study the shape of the spectrum only and not the absolute intensities. The attenuation coefficients were borrowed from Hubbell\textsuperscript{17} whose values being used universally by all experimental workers. Uncertainties in the calculation of peak to total ratios arise from the elimination of back-scatter part from the spectrum. In the present study, the end point energy was only 225 keV and the dominant mode of interaction being photo electric interaction, the compton back scatter probability is quite low and does not add much error into the calculation. The error in this measurement cannot exceed 3.4 %. Since the peak to total ratios are used in the estimation of the Compton electron distribution, the magnitude of error in this part of the calculation too, remains the same. Further, the magnitude of the compton electrons itself is quite small as can be seen in the illustrations and does not add any significant error into the estimations. Similarly, the corrections associated with the iodine K X-ray escape too are very small. The resolution correction errors are negligible in the major portion of the spectrum and the errors introduced at either ends of the spectrum are discussed in the text.

### 2.2 Comparison of the Experiment with the Theory

The authors have used the end result of Lewis and Ford, and Ford and Martin calculations for the case of unique first forbidden transitions even though the transition in $^{14}\text{I}$Pm belongs to the category of non-unique first forbidden class containing additional matrix elements. Almost all previous workers also used the same calculations for comparison with theory. The reason being that the Inner Bremsstrahlung photon intensities were normalized with respect to the $\beta$ intensities. The matrix elements which appear in the IB photon intensity calculation, will also appear in the $\beta$ emission probability calculations. Our belief is that when the integrated probability of IB photon emission is divided by the integrated probability of the beta emission, the effect of the additional matrix elements may not be visible in the ratio and hence the shape of the normalized IB intensity curve for the unique as well as non-unique first forbidden transitions remains almost the same.

### 3 Results and Discussion

The results of the IB spectral studies in $^{14}\text{I}$Pm are shown in Figs 1-3. The uncorrected experimental IB spectrum and the background are shown in Fig. 1. Fig. 2 shows: (i) The raw experimental spectrum after background and pile-up
Fig. 1 — Uncorrected raw experimental photon spectrum and the corresponding background

Fig. 2 — A: Background and pile-up corrected. τ line eliminated experimental spectrum of $^{147}$Pm terminated at the end point energy. B: Spectrum after resolution correction to A. C: Compton electron distribution in B and D: Resolution correction for the data terminated at 0.3% confidence level with base line shift

corrections and 121.3 keV line subtraction, (ii) spectrometer resolution correction showing the distortion produced at the extreme ends, (iii) the compton electron distribution which is small in magnitude, (iv) the resolution correction performed by taking the count data at a confidence level of
Fig. 3 — Comparison of experimental result with theoretical spectrum. A: Lewis and Ford (first forbidden with exact Fermi function replacing its approximation); B: Ford and Martin (with exact Fermi function); C: Experimental IB spectrum using raw data at a confidence level of ≤ 0.3% with base line shift (normalized to LF at 110 keV); D: Experimental IB spectrum using raw data up to end point energy without base line shift; E: Experimental IB spectrum using data as in D with base line shift; F: Experimental IB spectrum from published literature [Babu et al., Phys Rev C, 32 (1985) 1010]

≤0.3% with BLS. Fig. 3 shows the IB intensities obtained by different statistical considerations. Theoretical distributions based on LF and FM theories are also shown. For the purpose of direct comparison with the past experimental results, one such result from Babu et al. is also shown. The IB intensities calculated by terminating the raw data at the end point energy position: (i) without BLS, (ii) with BLS, both deviate from the theories. The shape of intensity curve whose calculation is based on terminating the raw data at 0.3% confidence level and with BLS, very closely follows LF distribution (up to about 170 keV), barring the distortion produced by the resolution correction at the low energy end. This curve is normalized at the middle of the energy range to the LF spectrum (i.e. at 110 keV). Beyond 170 keV, the statistical insufficiency of the data makes it difficult to arrive at any conclusion. In this study, the authors intended to study the shape of the IB spectrum only rather than the absolute intensities. It may be concluded that most of the discrepancies found in the experimental study of IB intensities can be attributed to counting statistics. Our conclusion is based on the study of six other isotopes which gave meaningful results without unrealistic high intensities near the end point energies by the use of counts with good statistical strength and base line shifting.

Acknowledgement

Thanks are due to Prof L Paramesh and Prof M S Madhava, of the Department of Studies in Physics, Manasagangotri, Mysore 570 006, for laboratory facilities and Kidwai Memorial Institute of Oncology, Bangalore 560 029, for computer facilities.

References

1 Knipp J K & Uhlenbeck G E. Physica, 3 (1936) 125.
8 Starfeht N & Cederlund J. Phys Rev. 105 (1957) 241


