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Thick-target external-bremsstrahlung spectra of ^{147}Pm and ^{35}S β rays

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External-bremsstrahlung spectra excited by soft β particles of ^{147}Pm ($E_\beta^{\max}=225$ keV) and ^{35}S ($E_\beta^{\max}=167$ keV) in targets of Al, Cu, Sn, and Pb have been studied. The experimental and theoretical results are compared in terms of the number of photons of energy k per m_0c^2 per unit photon yield to exclude the uncertainty in the source strength measurement and overcome the inherent inadequacy of the normalization procedure used by earlier workers. The results of present measurements for medium- and high-Z elements show better agreement with the theory of Tseng and Pratt [Phys. Rev. A **3**, 1714 (1976)] than with Elwert's corrections [Ann. Phys. (N.Y.) **34**, 78 (1939)] to the Bethe-Heitler theory [Proc. R. Soc. London Ser. A **14**, 83 (1934)], particularly at the higher-energy ends. However, for low-Z elements, both theories are found to be adequate.

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I. INTRODUCTION

^{147}Pm ($\Delta J=0$, yes) is a nonunique first-forbidden soft-β-particle emitter with an end-point energy of 225 keV. Its half-life is 2.62 yr. An early study of external bremsstrahlung (EB) excited by ^{147}Pm β-particles in thick targets of C and Al was conducted by Langevin-Joliet [1] and the experimental results were compared with the Bethe-Heitler theory. Later Gopala *et al.* [2] measured the EB spectra of various metallic targets excited by ^{147}Pm β-particles. Their experimental results showed better agreement with Elwert's corrections to the Bethe-Heitler theory than with the Tseng and Pratt theory up to 120 keV and deviated positively from both of the theories at higher energies.

^{35}S ($\Delta J=0$, no) is an allowed β-particle emitter with an end-point energy of 167 keV. External-bremsstrahlung spectra excited by β-particles of ^{35}S have been reported by Starfelt and Svantesson [3], Langevin-Joliet [1], and Prasad Babu, Murty, and Murty [4] in a number of thick targets. A general agreement between the experimental EB distributions and the Sommerfeld (Elwert) theory has been reported for low-Z elements such as carbon and aluminum. However, for intermediate- and high-Z elements, the experimental results deviated positively from the theoretical distributions and these deviations increased with increases in EB photon energy and atomic number of the target material. In all these studies the experimental and theoretical distributions were expressed in terms of the number of photons of energy k per m_0c^2 per β-particle disintegration and were normalized at a particular photon energy. These measurements contained a number of uncertainties (including an estimated error of 8% in the source strength measurement) which affect the values of EB photon yields. Moreover, a comparison of thick-target EB spectra excited by ^{35}S β particles with the exact calculations of Pratt *et al.* [5] is not available in the literature. Again there are no studies which compare results with the more accurate compilations of Seltzer and Berger [6]. These compilations incorporate the contribution of electron-electron bremsstrahlung to electron-nucleus bremsstrahlung.

The object of the present studies is to compare the experimental EB spectra from thick targets of Al, Cu, Sn, and Pb, excited by soft β particles of ^{147}Pm and ^{35}S with the theoretical distributions obtained from Elwert's corrections to the Bethe-Heitler (EBH) theory and the Tseng and Pratt theory, with and without the contributions of electron-electron bremsstrahlung to electron-nucleus bremsstrahlung, in terms of the number of photons of energy k per m_0c^2 per unit photon yield. This method makes the results independent of source strength and does away with the normalization procedure. Thus the present measurements are expected to check the results of various theories more rigorously for the EB spectra excited by soft β particles.

II. THEORY

Sommerfeld [7] developed the theory for EB for nonrelativistic electrons without taking into account nuclear screening effects. For relativistic electrons, Bethe and Heitler [8], Sauter [9], and Racah [10] derived independently an expression for the EB cross section $[d\sigma_n(W_e,k,Z)/dk]$ under a first-order Born approximation without incorporating the Coulomb-field effects of the nucleus. Later Elwert [11] and Guth [12] introduced a multiplicative Coulomb correction factor F_E to the Bethe and Heitler cross sections. Tseng and Pratt [13] and Lee, Kissel, and Pratt [14] developed a quantum-mechanical theory for bramsstrahlung of relativistic electrons using relativistic (screened) self-consistent-field wave functions. Later compilations of Seltzer and Berger [6] incorporated the contribution of electron-electron bremsstrahlung to the electron-nucleus bremsstrahlung given by Pratt *et al.* [5]. These EB theories are applicable to thin-target spectra only in which the incident electron has only a single radiative interaction in the target.

In the case of thick targets, processes such as electron scattering, excitation, and ionization that compete with bremsstrahlung must be taken into account. This finally leads to an integral that includes the energy loss per unit path length. Bethe and Heitler gave an expression for the number $[n(W_e',k)]$ of EB photons of energy k when all of the incident electron energy W_e' is absorbed in the target, as

$$n(W_e',k)=N\int_{1+k}^{W_e'}\frac{[d\sigma_n/dk]}{-(dW_e/dx)}dW_e \ . \tag{1}$$

Here N is the number of atoms per cm^3 and (dW_e/dx) is the total energy loss per unit path length of an electron in a target of atomic number Z.

The EB spectral distribution obtained on complete absorption of β particles of a β-particle emitter with end-point energy $W_{\max}$ is expressed as the number of photons of energy k per m_0c^2 per β-particle disintegration and is denoted by $S(k)$:

$$S(k)=\int_{1+k}^{W_{\max}}n(W_e',k)P(W_e')dW_e' \ . \tag{2}$$

Here $P(W_e')dW_e'$ is the β-particle spectrum of the β-particle emitter under study.

The EB photon yield T for the target, with $k_{\min}$ and $k_{\max}$ as the lower and upper limits of photon energy of the EB spectrum, is given by

$$T=\int_{k_{\min}}^{k_{\max}}S(k)dk \ . \tag{3}$$

In the present measurements $n(W_e',k)$ and $S(k)$ were calculated for Elwert's corrections to the Bethe-Heitler theory by using $d\sigma_n/dk$ and f_E obtained from the formulas given by Bethe and Heitler and Elwert, while for the Tseng and Pratt theory the tabulated values of cross sections given by Pratt *et al.* [5] and Seltzer and Berger [6] were used. Values of photon yield T were obtained by graphical integration of EB spectra. Final results were expressed as the number of photons of energy k per m_0c^2 per unit photon yield $S(k)/T$.

III. EXPERIMENTAL DETAILS

The experimental setup for studying the external-bremsstrahlung spectra is shown in Fig. 1. It consisted of a (4.5-cm-diam and 5.1-cm-thick) NaI(Tl) detector coupled to a photomultiplier tube. A NaI(Tl) detector is more suited for the study of continuous EB spectra due to its high efficiency and moderate resolution than the solid-state detector with lower efficiency and high resolution. The photomultiplier tube was placed in a cylindrical magnetic shield of Mumetal. The detector assembly was enclosed in an iron cylinder with an opening of 5 cm diameter. Further, the detector was shielded by a 4-cm-thick lead castle with aluminum lining its inner surface to minimize the background. A lead collimator, with its conical surface lined with aluminum, placed coaxially above the detector on an annular brass plate, shielded the detector from scattered photons and reduced the background count rate to a low level. The lead collimator was covered with a 4-mm-thick Perspex disk with a 2.8-cm central hole to absorb the incoming β particles.

Carrier-free ^{147}Pm and ^{35}S β-particle emitters were procured from the Bhabha Atomic Research Center (BARC), Bombay, as promethium chloride and sulfuric acid in dilute HCl. Thin β-particle sources were prepared by evaporating a few drops of a liquid on a circular disk with a cavity at the center. The source size was limited to less than 5 mm in diameter and the source material was uniformly distributed with the aid of a plain Insulin solution. The sources were dried carefully under an infrared lamp and were protected by the thin polythene films of thickness 1 mg/cm^2. The bremsstrahlung spectra were recorded by using an ND-62 series multichannel analyzer. Targets of research-grade purity of the order of 99% were used to record the different EB spectra. For ^{147}Pm, the targets of Al (62 mg/cm^2), Cu (55 mg/cm^2), Sn (54 mg/cm^2), and Pb (56 mg/cm^2) were used whereas in the case of ^{35}S, target thicknesses were 37 mg/cm^2, 40 mg/cm^2, 37 mg/cm^2, and 38 mg/cm^2, respectively.

The magnetic-field-deflection technique coupled with

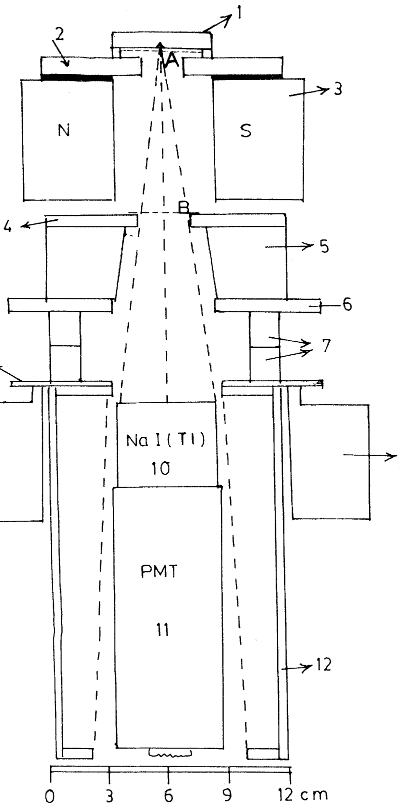

FIG. 1. Experimental setup: 1, source holder; 2, Perspex sheet; 3, poles of electromagnetic; 4, Perspex sheet; 5, collimator; 6, ebonite plate; 7, two lead annular rings; 8, copper plate; 9, lead castle; 10, NaI (Tl) crystal; 11, photomultiplier tube shielded with Mumetal; 12, iron cylinder.

the difference method was employed to exclude the contributions of internal bremsstrahlung (IB), EB originating in the source material, source γ rays (121 keV) in the case of ^{147}Pm, and room background. In this technique the source was placed at a distance of 20 cm on the axial line of the detector (Fig. 1). Between the source and the detector a magnetic field was applied using an electromagnet having pole pieces of 7 cm diameter and the yoke at right angles to the detector assembly. The pole pieces were covered with a 4-mm-thick Perspex sheet to minimize the production of EB by β particles striking them. The separation between the pole pieces was 5 cm and they were kept at a distance of 12 cm from the face of the detector. The strength of the magnetic field was adjusted so as to deflect all the β particles coming from the source. It was checked by a separate measurement with a Geiger-Müller (G.M.) tube that no β particles reached the surface of the collimator. In order to ensure that the magnetic field had no appreciable effect on the photomultiplier tube covered with a Mumetal shield, the positions of the photopeak of the ^{137}Cs γ-ray emitter was checked with and without the magnetic field. It was observed that the peak shift was less than 0.5%.

After calibrating the spectrometer with standard γ-ray emitters two sets of measurements were taken by placing the target at positions A and B shown in Fig. 1. In a typical experiment, first the target was placed at position A above the electromagnet but in contact with the β-particle source. The detector recorded IB, EB originating in the source material, γ rays, if any, EB (target), and the room background. Next the target was placed at position B on the collimator. In this case the detector recorded only IB, EB originating in the source material, γ rays, if any, and the room background, since no β particles reached the target. The difference between these two measurements gave the contributions of EB produced in a target. Before recording the spectra in positions A and B, it was important to check the absence of scattering of radiation from the source into the detector because the metallic target was displaced by 8.0 cm from one position (A) to another position (B). This was done with discrete γ-ray sources of ^{137}Cs and ^{60}Co. The total number of counts above 30 keV at target positions A and B were identical within 0.2%. Finally, a number of data runs for different targets were taken at positions A and B to improve the statistical accuracy of measurements particularly at the high-energy and of the EB spectrum. Intermediate runs were taken to check the peak shift due to electronic shift and ensure the reproducibility of the data. Next, the difference of the weighted averages of several runs taken at positions A and B gave the contribution of external bremsstrahlung produced in a target. These observations were taken with targets of aluminum, copper, tin, and lead for the two β-particle emitters. The statistical accuracy of data was better than 3% at 150 keV for ^{147}Pm and at 120 keV for ^{35}S. It improved with decreasing photon energy.

IV. CORRECTIONS TO EXPERIMENTAL EB SPECTRA

In order to transform an experimentally measured EB spectrum into the one emitted by a target a number of corrections were applied after reducing it to a common channel width of 10 keV. First of all, the experimental EB pulse-height distribution was corrected for energy resolution of the detector. This correction varied from 6.2% at 50 keV to 12% at 150 keV for ^{147}Pm, while in the case of ^{35}S it was 5.2% at 50 keV and decreased with an increase in photon energy due to better resolution of the detector at higher energies. The correction due to escape of iodine K x rays was also calculated. It was significant only for low-energy photons in the EB spectrum due to their low penetration and high photoelectric cross sections. The correction for the loss of iodine K x rays for ^{147}Pm was 16% at 50 keV and 1.3% at 150 keV, whereas in the case of ^{35}S it was 14% at 50 keV and 1.5% at 120 keV. It was further observed from the experimental spectra of monoenergetic γ rays in the energy region below 300 keV that there was no appreciable backscattering. Therefore, no correction was applied to the experimental EB spectra for this effect. Due to the large value of photofraction $f(k)$ coupled with a high value of photoelectric absorption cross sections for soft photons, the correction due to the Compton continuum was found to be negligible. It was found to vary from 0.3% at 30 keV

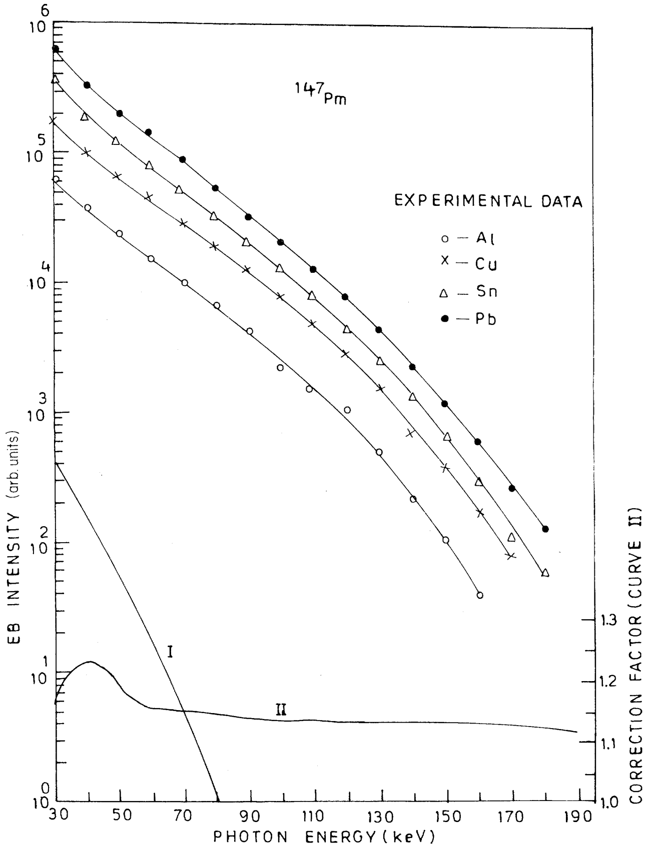

FIG. 2. Experimental EB pulse-height distributions for ^{147}Pm β particles and various corrections for the Pb target. Curve I: Compton continuum. Curve II: Correction due to the iodine K x-ray escape peak and detector resolution.

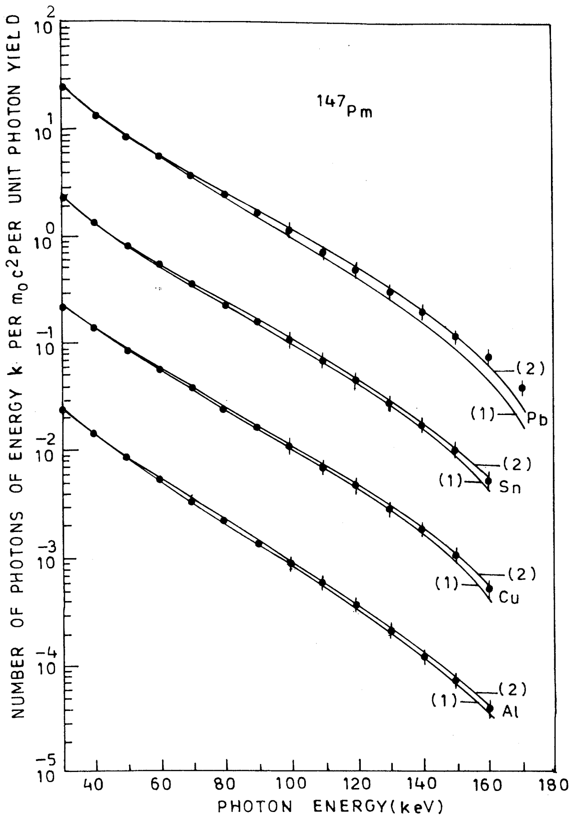

FIG. 3. Plots of the number of EB photons of energy k per m_0c^2 per unit photon yield $[S(k)/T]$ vs photon energy k (keV) for the ^{147}Pm β-particle emitter. Curve (1): Elwert's corrections to the Bethe-Heitler theory. Curve (2): Tseng and Pratt distributions, with and without the contribution of electron-electron bremsstrahlung. Solid circles are measured values, given with experimental errors.

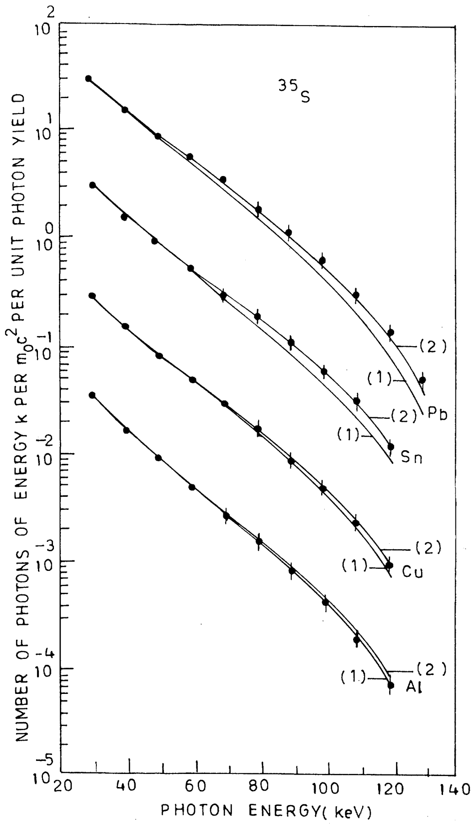

FIG. 4. Plots of the number of EB photons of energy k per m_0c^2 per unit photon yield $[S(k)/T]$ vs photon energy k (keV) for the ^{35}S β-particle emitter. Curve (1): Elwert's corrections to the Bethe-Heitler theory. Curve (2): Tseng and Pratt distributions, with and without the contribution of electron-electron bremsstrahlung. Solid circles are measured values given with experimental errors.

to 0.04% at 150 keV for ^{147}Pm. The experimental spectra were also corrected for absorption of EB photons in the aluminum container of the detector. The correction due to self-absorption of EB photons in a target was applied by using tabulated values of attenuation coefficients.

In order to convert a measured pulse-height distribution into the one actually emitted by the target, the corrected EB spectrum was divided by the geometrical full-energy-peak detection efficiency. It was then reduced to the number of photons of energy k per m_0c^2 by dividing the data by the channel width (in m_0c^2 units). The EB spectra of Al, Cu, Sn, and Pb targets corrected for self-absorption, along with various other corrections for the ^{147}Pm β-particle emitter, are shown in Fig. 2. Next, the areas under the spectral distributions were measured graphically to obtain the values of photon yields (T). Finally, the experimental spectra were converted into the number of photons of energy k per m_0c^2 per unit photon yield by dividing them by the values of photon yields. They were then compared with the different theoretical distributions obtained from the EBH and the Tseng and Pratt theories. These results are given in Figs. 3 and 4.

V. ERRORS

The major errors in the present measurements of EB spectra were due to counting statistics and uncertainties in intrinsic and geometrical detection efficiencies, photofraction, and energy resolution of the detector. The statistical accuracy of the recorded data was better than 3% for ^{147}Pm and ^{35}S at 150 and 120 keV, respectively, for all the targets. It was better than 1% in low-energy regions due to better counting statistics. Uncertainty in the full-energy-peak detection efficiency was 2–3 % while the experimentally measured photofractions were uncertain by 4%. The errors involved in corrections due to energy resolution, iodine K x-ray escape, and the Compton continuum were less than 2% as these corrections by themselves were small. The errors due to attenuation coefficients used in the correction for self-absorption of EB photons in a target were less than 2% in the entire energy region. The overall uncertainty in the results of the present measurements excluding systematic errors, if any, is estimated to be 10% at 150 and 120 keV for ^{147}Pm and ^{35}S, respectively, for all the targets. The accuracy is better at lower energies due to improved statistics.

VI. RESULTS AND DISCUSSION

The results of experimentally measured EB spectra from targets, of Al, Cu, Sn, and Pb for ^{147}Pm and ^{35}S soft-β-particle emitters were compared with the spectral distributions obtained from Elwert's corrections to the Bethe-Heitler theory and the Tseng and Pratt theory. Figures 3 and 4 show these experimental and theoretical results in terms of plots of $S(k)/T$, i.e., the number of photons of energy k per m_0c^2 per unit photon yield versus photon energy k.

In the case of the ^{147}Pm β-particle emitter the experimental EB spectra of Al, Cu, and Sn are in agreement with both the theoretical distributions within 10% in the entire energy region from 30 to 160 keV. However, for the Pb target both the theories are in agreement with the experimental results up to 80 keV only. The Tseng and Pratt distribution gives better agreement up to 150 keV. The experimental results are higher at 160 and 170 keV. It is observed that the experimental results show much better agreement with the Tseng and Pratt theory than with the EBH theory. A comparison of present measurements with those of Gopala *et al.* [2] shows that the present studies give a much better agreement with the Tseng and Pratt theory than that reported by these workers. Their results are higher than the EBH and other theories above 120 keV for all targets. The reason for this discrepancy most probably lies in the measurement of source strength which affects the accuracy with which the EB photon yield can be measured.

In the case of ^{35}S, the comparison of experimental and theoretical EB spectral distributions is shown in Fig. 4. It is observed that for the Al target the experimental results are in agreement with both the theoretical distributions within 10% in the entire energy range from 30 to 120 keV. However, for Cu, Sn, and Pb targets, the Tseng and Pratt distributions explained the experimental results more accurately. But in the case of the Pb target the experimental results above 80 keV are somewhat higher than the Tseng and Pratt theory. The deviations are found to be 50% of 130-keV photon energy. A similar behavior for lead targets has been observed in earlier studies [15,16] with other β-particle emitters. This may be due to the inadequacy of the theory for high-Z elements.

It is observed that the spectral distributions given by the Tseng and Pratt theory, with and without the contributions of electron-electron bremsstrahlung to electron-nucleus bremsstrahlung, are close to each other within 2%. The present results overcome the uncertainty in the source strength measurements and thus give a more accurate procedure for comparison of experimental and theoretical distributions.

It is concluded that for the EB spectra excited by soft β particles in various targets, the Tseng and Pratt theory gives better agreement than the Elwert's corrections to the Bethe-Heitler theory, particularly for medium- and high-Z elements. In view of the discrepancies between the experiment and theory at the high-energy end of the EB spectra for lead targets it is desirable to undertake a more comprehensive study of EB spectra from high-Z elements with various β-particle emitters. This will help to check the correctness of predictions of the Tseng and Pratt theory more rigorously.

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