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On the external bremsstrahlung produced by beta particles in thin foils

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Abstract. The integrated external bremsstrahlung (EB) produced by beta particles from ^{90}Sr–^{90}Y, ^{90}Y, ^{32}P and ^{89}Sr sources in different thicknesses of Cu, Ag, Cd, Sn and Pb targets, is measured with a NaI(Tl) scintillation spectrometer. The external bremsstrahlung intensity increases rapidly with target thickness, but the increase of the intensity is not linear. This nonlinear increase of EB intensity is shown to follow an empirical relation of the type $t \exp(-\Sigma_B t)$, where t is the thickness of the target in mg cm^{-2} and Σ_B is a constant. Σ_B(cm^2 mg^{-1}) is found to be a constant and independent of the atomic number of the target. Σ_B is determined for ^{90}Sr–^{90}Y, ^{90}Y, ^{32}P and ^{89}Sr beta sources. The values of Σ_B are found to be constant and agree with each other within 15–20% for these beta sources, showing that Σ_B is constant, independent of the atomic number of the target and also independent of the end-point energy of the beta spectrum.

1. Introduction

External bremsstrahlung (EB) has been studied by several investigators using electrons of monochromatic energy as well as electrons having the continuous distribution of energy from pure beta sources. Experiments with monochromatic electrons from particle accelerators normally use extremely thin targets (~ 1 µg cm^{-2}) to determine the EB production cross section that is differential in photon energy and angle. If the electrons from a pure beta source are used, an extremely thin target is not suitable because the beta particles have a continuous spectrum of energy from 0 to some maximum value E_{max} typical of the beta source. Even if one uses a target extremely thin compared with the range of beta particles, it has the disadvantage that the EB produced would be negligible in comparison with the internal bremsstrahlung (IB) from the source itself. Therefore, it is necessary to use target thicknesses that are comparable with the range of the beta particles to obtain appreciable EB intensity in the presence of the IB from the source. Many investigators (Sizoo *et al* 1939, Wu 1941, Wyard 1952, Goodrich *et al* 1953, Liden and Starfelt 1955, Starfelt and Svantesson 1955, Bussolati 1959, Voljin and Ciangiru 1965) have determined the differential cross section for EB production in terms of photon energy, using electrons from pure beta sources and thick targets to stop all beta particles within the target.

Theories of external bremsstrahlung have been developed by Bethe and Heitler (1934), Sauter (1934) and Racah (1934) for relativistic electrons and by Sommerfeld (1931) for nonrelativistic incident electrons. A comprehensive summary of EB theories and experiments can be found in review articles of Koch and Motz (1959) and Roy and Reed (1968).

When a thick target is used to stop all the beta particles within the target, the EB is produced in the first few layers of the target and the emitted photons have to pass through the rest of the target thickness. Thus, the observed EB intensity is affected by the slowing down of beta particles and also by the attenuation of the EB photons in the thickness of the target.

From integrated as well as differential EB intensity measurements it has been shown (Mudhole 1969, Mudhole and Umakantha 1972, Mudhole 1972) that for target thicknesses less than approximately 0·4 times the range R of beta particles, the increase of EB intensity with target thickness follows an empirical relation of the type

$$I = KZ^2(t/A)\exp(-\Sigma_B t) \tag{1}$$

where K and Σ_B are constants, Z and A are atomic number and atomic weight of the target and t is the thickness of the target in mg cm^{-2}. Using a ^{90}Sr–^{90}Y beta source and targets of Cu, Ag, Sn and Pb it has been shown that the EB production cross section is proportional to the square of the atomic number of the target and that Σ_B is constant and independent of the atomic number of the target. Using the same source the differential EB intensity was measured as a function of the target thickness from 100 to 1800 keV. From this the EB spectrum in terms of photon energy was determined by linear extrapolation to zero thickness and compared with the Bethe–Heitler theory.

The object of the present investigation was to study the dependence of Σ_B on the end-point energy of different beta spectra by measuring the integrated EB intensity as a function of the target thickness.

2. Experimental details

The experimental arrangement used in the present investigation is as shown in figure 1. The pure beta sources ^{90}Sr–^{90}Y (0·54 and 2·26 MeV), ^{90}Y (2·26 MeV), ^{32}P (1·71 MeV) and ^{89}Sr (1·46 MeV) of strength 100 μCi were obtained from Bhabha Atomic Research Centre, Bombay. Each source was kept in a perspex source holder (2) and all sides of the beta source were covered by perspex to stop beta particles in all except the forward direction and thereby minimize extraneous EB production from the surrounding material. A 1·2 cm thick perspex sheet (3) was kept between the source and the detector so as to prevent beta particles from producing EB in the detector and the shielding material. All integrated and differential EB measurements were made using a NaI(Tl) scintillation spectrometer having a single channel pulse height analyser. The NaI(Tl) crystal was 1″ in diameter and 1″ thick and was coupled optically to a RCA 6199 photomultiplier tube.

A difference method was adopted to eliminate the natural background and the internal bremsstrahlung from the source and thereby determine the true EB intensity produced by the beta particles in the target. Firstly, the integrated EB intensity was measured by keeping the target in position A; this intensity includes the IB from the source plus the EB produced in the target by beta particles. Next, the intensity was measured by keeping the target in position B; this intensity is only due to IB from the source. Since the root mean square atomic number of the perspex is 4·6 (comparable to 4 of Be normally used), the EB produced in perspex is negligible compared to that produced in the high atomic number targets that are used in the experiment. Thus, the difference of these two intensities gives the true EB intensity produced in the target by

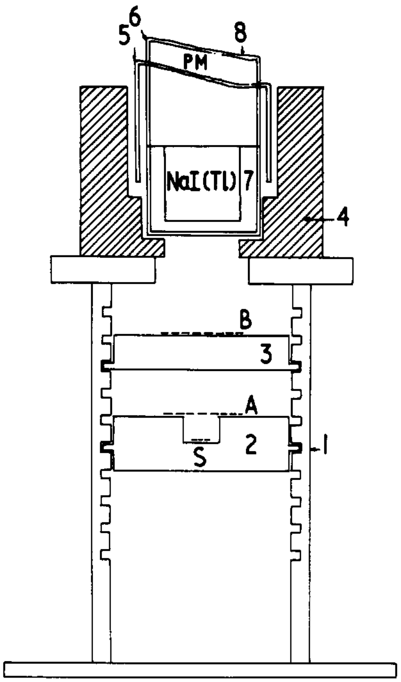

Figure 1. Experimental arrangement. S beta source, A and B target positions, 1 stand, 2 perspex source holder, 3 perspex beta stopper, 4 lead shield, 5 mu-metal shield, 6 black tape, 7 NaI(Tl) crystal, 8 RCA 6199 photomultiplier (PM).

the incident beta particles. In order to eliminate the contribution due to K x rays etc, all integrated EB intensities were recorded above 100 keV.

3. Results and discussion

3.1. Integrated EB intensity

The integrated EB intensity was measured by the difference method as a function of thickness for ^{90}Sr–^{90}Y, ^{90}Y, ^{32}P and ^{89}Sr beta sources using Cu, Ag, Cd, Sn and Pb targets. In figures 2 and 3 we have plotted the values of $\ln(IA/t)$ as a function of target thickness for Cu, Ag, Cd, Sn and Pb targets due to the beta particles from ^{90}Sr–^{90}Y, ^{90}Y, ^{32}P and ^{89}Sr sources. In these figures the full lines are the least squares fit straight lines. We see that the integrated EB intensity follows the empirical relation given in equation (1) for all the four beta sources. In the ^{90}Sr–^{90}Y source ^{90}Sr and ^{90}Y are in secular equilibrium with end-point energies 0·54 MeV and 2·26 MeV respectively. The integrated EB intensity was measured above 100 keV, and both ^{90}Sr and ^{90}Y beta particles contribute to the EB.

In table 1 the least squares fit values of Σ_B are listed for ^{90}Sr–^{90}Y, ^{90}Y, ^{32}P and ^{89}Sr beta sources and for Cu, Ag, Cd, Sn and Pb targets. From column 3 it is seen that Σ_B is constant and independent of the atomic number of the target; also Σ_B is insensitive to the fine structure of the beta spectra. Columns 4, 5 and 6 correspond to ^{90}Y, ^{32}P and ^{89}Sr beta sources. From these data it is clear that for a given source, the values of Σ_B

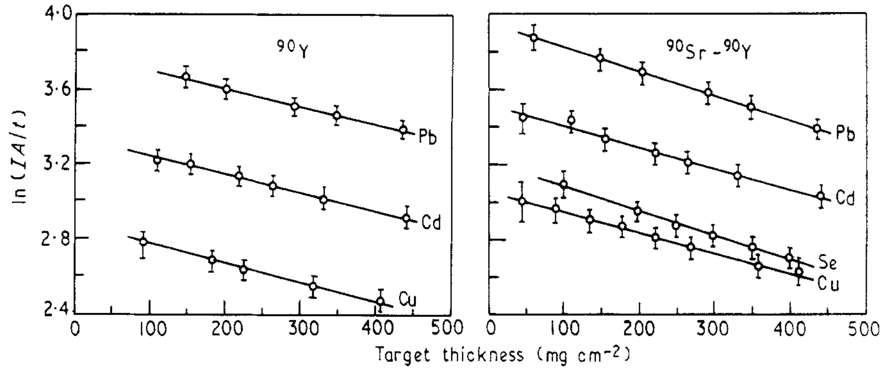

Figure 2. Logarithm of the external bremsstrahlung intensity per atom of the target (in arbitrary units) as a function of the target thickness for Cu, Se, Cd and Pb targets due to ^{90}Sr–^{90}Y and ^{90}Y beta particles.

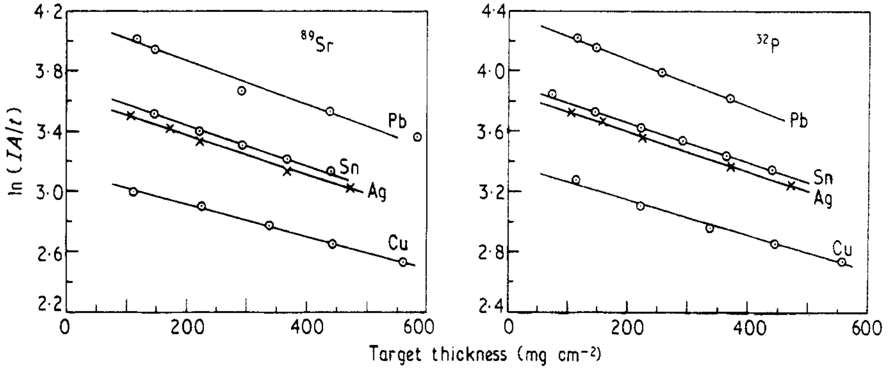

Figure 3. Logarithm of the external bremsstrahlung intensity per atom of the target (in arbitrary units) as a function of the target thickness for Cu, Ag, Sn and Pb targets due to ^{32}P and ^{89}Sr beta particles. (Errors are smaller than the size of the circles.)

Table 1. The least squares fit values of Σ_B (cm^2 mg^{-1}) determined from figures 2 and 3 for ^{90}Sr–^{90}Y, ^{90}Y, ^{32}P and ^{89}Sr beta sources and for Cu, Ag, Cd, Sn and Pb targets

Z	Target element	^{90}Sr–^{90}Y (E_0 = 0·54, 2·26 MeV)	^{90}Y (E_0 = 2·26 MeV)	^{32}P (E_0 = 1·71 MeV)	^{89}Sr (E_0 = 1·46 MeV)
29	Cu	0·0026	0·0025	0·00265	0·0028
47	Ag	—	—	0·0030	0·0031
48	Cd	0·00265	0·0025	—	—
50	Sn	—	—	0·00275	0·0031
82	Pb	0·00265	0·0024	0·0030	0·00306

are constant and independent of the atomic number of the target. Further, from table 1 it is also obvious that the values of Σ_B for ^{90}Sr–^{90}Y, ^{90}Y, ^{32}P and ^{89}Sr beta sources agree with each other within 15–20 % showing that Σ_B is constant and independent of the atomic number of the target material and also independent of the end-point energy of the beta spectra. This is rather a strange result.

3.2. *Differential* EB *intensity*

The differential EB intensity was measured as a function of the target thickness using ^{90}Sr–^{90}Y beta source with a channel width of 40 keV. The values of $\ln(I(E_\gamma)A/t)$ are plotted in figure 4 as a function of t for each band of photon energy about E_γ covering the range from 100 keV to 1800 keV for Pb target. That $\ln(I(E_\gamma)A/t)$ plotted against t is a straight line shows that the EB intensity at each photon energy band also follows equation (1). From figure 4 it is seen that the slope Σ_B is constant and independent of the photon energy. Similar curves have also been obtained for Cu and Cd targets. In figure 5 we have plotted the values of Σ_B as a function of the photon energy for Cd and Pb targets and it is seen that the values of Σ_B agree with each other within 15–20%. The values of Σ_B plotted in figure 5 and those listed in table 1 agree well with each other.

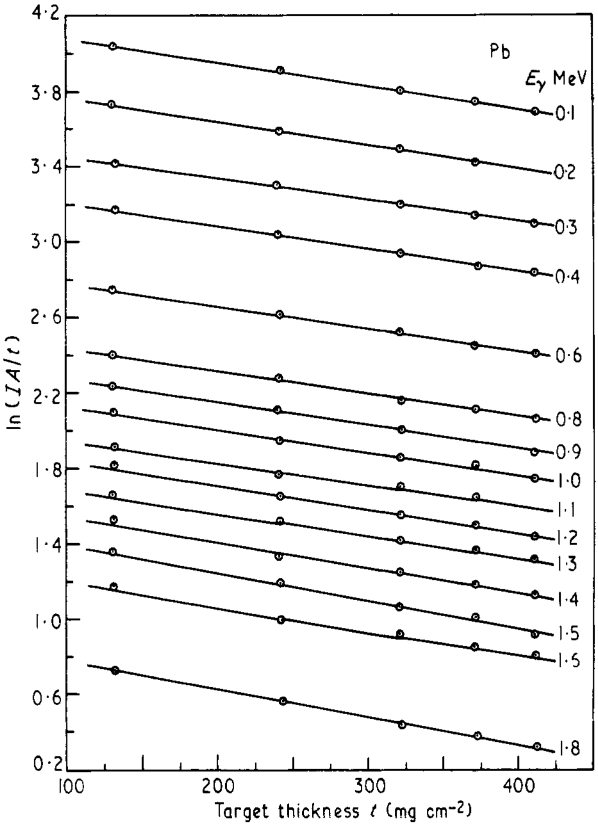

Figure 4. Logarithm of the external bremsstrahlung intensity per atom of the Pb target (in arbitrary units) as a function of the target thickness for various photon energies. (Errors are smaller than the size of the circles.)

4. Conclusions

The mass attenuation coefficient for low energy photons is mainly due to photoelectric and Compton effects and these processes are highly dependent on the atomic number of the absorber. However, Σ_B is found to be independent of the atomic number of the

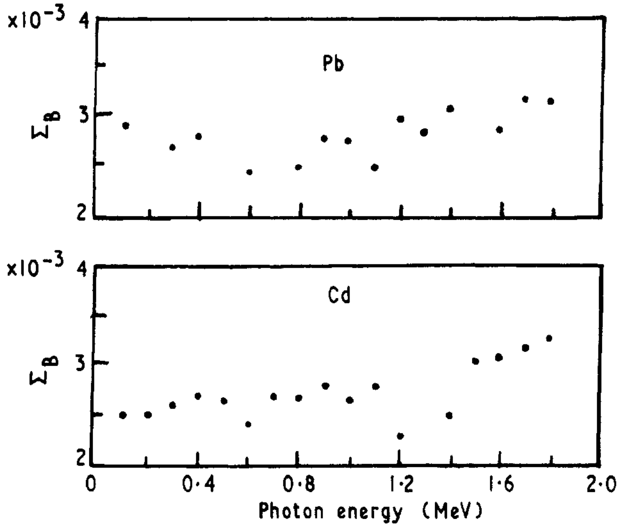

Figure 5. The least squares fit values of Σ_B as a function of photon energy for Cd and Pb targets.

target; thus Σ_B does not correspond to the mass attenuation coefficient. Thus, the nonlinearity in the increase of EB intensity with target thickness is not due to the attenuation of low energy EB photons in the target.

The mass absorption coefficient of beta particles is nearly independent of the atomic weight of the absorber rising slightly with increasing Z and is uniquely determined by the end-point energy of the beta spectrum (Evans 1955). However, Σ_B is found to be independent of the atomic number of the target and also the end-point energy of the beta spectra. Therefore, the nonlinearity in the increase of EB intensity may be due to the slowing down of beta particles within the target. In the process of diffusion and slowing down, beta particles lose a small fraction of their energy and undergo small deflections in each collision. Most of the incident electrons lose their energy through excitation of the atoms. Using nuclear emulsion techniques, Dudley (1951) has shown that in the slowing down of beta particles the shape of the energy spectrum remains nearly constant as the characteristic of the input spectrum and that the angular distribution pattern of beta rays remains substantially constant throughout the process of slowing down. Therefore, the exact interpretation of Σ_B is possible only if one determines the spectrum of beta particles at each point in the target by using Monte Carlo calculations. Such calculations are in progress.

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