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Yield constants of external Bremsstrahlung excited by ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in CdO and lead compounds

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ABSTRACT

Bremsstrahlung yield of ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in CdO, PbF_2, $Pb(NO_3)_2$ and $PbCl_2$ has been measured using 3.8 cm × 3.8 cm NaI(Tl) crystal and is compared with Tseng and Pratt theory. The Z dependence of external Bremsstrahlung (EB) is also measured and compared with the theory. The Bremsstrahlung photon yield and energy yield constants (K' and K) are evaluated from the measured and theoretical yields. These values decrease with the increase in E_{max} of beta. The evaluated K' and K may be useful to calculate the photon yield and the energy yield, when these beta particles interact with the compounds of modified atomic number ranging from 42 to 73.

1. Introduction

External Bremsstrahlung (EB) is a continuous electromagnetic radiation emitted when an electron or a beta particle is deflected in the Coulomb field of the nucleus. The previous workers developed many theories [1–4] to explain the Bremsstrahlung process. An accurate theory has been developed by Tseng and Pratt [5]. Seltzer and Berger [6] extend the Tseng–Pratt theory to the field of atomic electron. Most of the EB works of beta have been carried out using only metal as a thick target but using compound as a thick target is lacking. Manjunatha and Rudraswamy [8,9] measured the external Bremsstrahlung spectra for a set of compounds and compared with the Tseng–Pratt theory. Markowicz and VanGriken [10] proposed a new expression for the prediction of the continuum intensity (I_k) to take into account the self-absorption of Bremsstrahlung for the accurate description of the Bremsstrahlung process:

$$I_k = \text{const}\frac{\Delta E}{E_\gamma} Z_{mod}(E_0 - E_\gamma)[1-f] \quad (1)$$

Here,

$$Z_{mod} = \frac{\sum_i^l (W_i Z_i^2/A_i)}{\sum_i^l (W_i Z_i/A_i)} \quad (2)$$

E_γ and E_0 are the emitted photon energy and incident electron energy, respectively. I_k represents the number of continuum photons with energy E_γ in a photon energy range ΔE_γ. A_i, W_i and Z_i are atomic weight, weight fraction and atomic number of the ith element in a compound. As seen from Eq. (1) the continuum intensity is a function of a modified atomic number (Z_{mod}). f is a function of E_0, E_γ and composition (for pure elements $f=0$). l denotes the number of elements in the compound. 'Const' in Eq. (1) refers constant. The new Markowicz formula derived in a more rigorous way gives theoretical results for composite samples, which are in better agreement with the experimental values of Vander Wood et al. [7] than those predicted by Kramer's law. Shivaramu [11] evaluated the atomic number (Z) for set of compounds for the Bremsstrahlung process from the measured yields. He reported that Z agrees fairly well with Z_{mod} than the mean atomic number.

The EB produced by beta particles stopping in thick targets has been discussed by Evans [12]. The expectation value of the total Bremsstrahlung energy that is produced by absorption of the entire β-ray spectrum in a material of atomic number Z will be proportional to

$$\int_1^{W_0} (W-1)^2 N(W)\,dW$$

where $W=(E/0.51)+1$ and W_0 corresponds to the maximum energy E_0, in MeV, of the continuous β-ray spectrum. $N(W)dW$ represents the probability that a given β-ray source will emit an electron with a total energy between W and $W+dW$. The total number of β-rays emitted by this source is proportional to

$$\int_1^{W_0} N(W)\,dW$$

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Consequently the average total energy yield (I) of the Bremsstrahlung per β-ray disintegration is

$$I = KZ(0.51)^2 \frac{\int_1^{W_0} (W-1)^2 N(W)\mathrm{d}W}{\int_1^{W_0} N(W)\mathrm{d}W} \tag{3}$$

where

$$E_{RMS}^2 = (0.51)^2 \frac{\int_1^{W_0} (W-1)^2 N(W)\mathrm{d}W}{\int_1^{W_0} N(W)\mathrm{d}W}$$

$$I = KZE_{RMS}^2 \tag{4}$$

This expression is derived on assumption that the basic cross-section depends on the square of the nuclear charge of the target material (Z^2). Energy yield (I) is the total Bremsstrahlung energy radiated per incident beta particle. The energy yield (I) of Bremsstrahlung for compounds can be expressed as

$$I = KZ_{mod}E_{RMS}^2(\mathrm{MeV/beta\ particle}) \tag{5}$$

where K is called the energy yield constant (in MeV^{-1}) and E_{RMS} is the root mean square energy of the beta particles (in MeV). Analogously one can write the EB photon number yield (N) as

$$N = K'Z_{mod}E_{RMS}(\mathrm{photons/beta\ particle}) \tag{6}$$

where K' is the photon number yield constant (in MeV^{-1}). The number of EB photons produced by electrons or beta particle while passing through a thick target enough to absorb them can be defined as photon yield (N) of the target. I depends on the cross-section for radiation as well as the average path length of the electron. The cross-section depends on Z^2 whereas the average path length depends on Z^{-1} [12]. So in Eqs. (3) and (4) we have Z instead of Z^2. Experiments suggest that the EB cross-sections are not strictly Z^2 dependent [13]. Hence we write Eqs. (5)

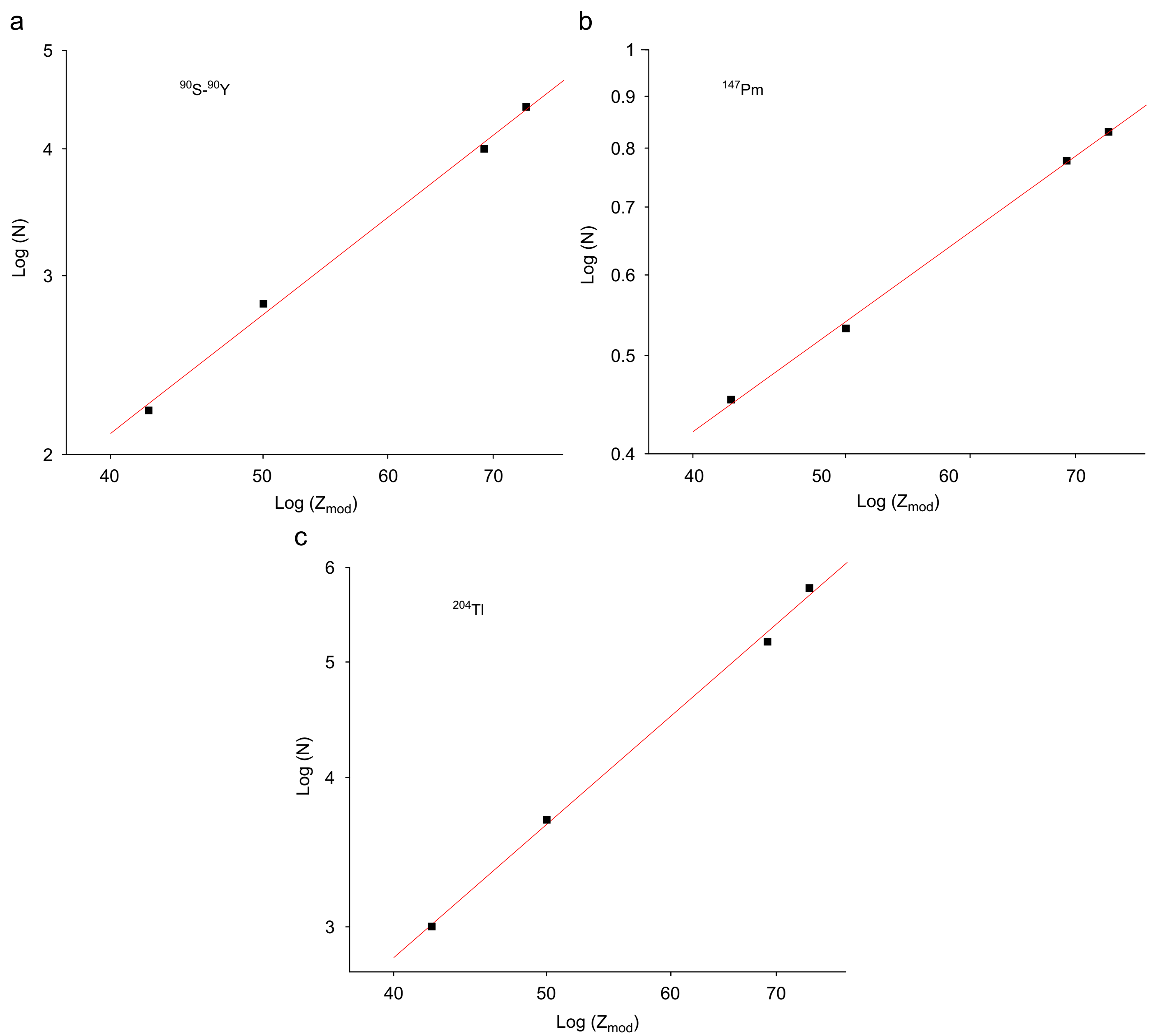

Fig. 1. Measured Bremsstrahlung photon yield (N) plotted against the modified atomic number (Z_{mod}) for beta particles of (a) ^{90}Sr–^{90}Y, (b) ^{147}Pm and (c) ^{204}Tl.

and (6) as

$$N = K'Z_{mod}^{m}E_{RMS} \quad (7)$$

$$I = KZ_{mod}^{m}E_{RMS}^{2} \quad (8)$$

where 'm' is the index of the Z_{mod} dependence of Bremsstrahlung yields. The aim of the present work is to estimate the EB energy and photon yield and their constants K and K' for beta sources like ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in some compounds like CdO, PbF_2, $Pb(NO_3)_2$ and $PbCl_2$. Hence to determine the degree to which the index of Z dependence (m) differs from unity. The evaluated Z_{mod} values for $PbCl_2$, PbF_2, $Pb(NO_3)_2$ and CdO are 73.48, 69.12, 50.039 and 42.29, respectively.

2. Present work

The spectral distributions of external Bremsstrahlung (EB) excited by the beta particles in the given thick target compounds were measured using 3.8 cm × 3.8 cm NaI(Tl) detector mounted on photomultiplier coupled to a PC based sophisticated 16k multi channel analyzer (MCA). The details of experimental arrangement are as explained elsewhere [9]. In our previous work [8,9], we have measured the spectral distributions of (EB) excited by ^{147}Pm and ^{204}Tl beta particles in $PbCl_2$ and CdO. In the present work, we have measured the spectral distributions of EB excited by ^{90}Sr–^{90}Y beta particles in $PbCl_2$, PbF_2, $Pb(NO_3)_2$ and CdO. The present work also measures the spectral distributions of EB excited by the ^{147}Pm and ^{204}Tl beta particles in PbF_2 and $Pb(NO_3)_2$. The present set of measurements covers the compound thick targets of modified atomic numbers ranging from 42 to 73. The beta isotope of ^{90}Sr–^{90}Y (the end-point energies of the beta spectrum are 546 and 2274 keV) emits two groups of beta particles both being first forbidden unique transitions. The given compounds in the fine powder form were filled in Perspex planchet of 1 cm diameter. The thickness of these compounds was so chosen to stop all the beta particles of energy up to 2274 keV, so that, in the present E_{max} of ^{90}Sr–^{90}Y beta is considered to be 2274 keV. A Perspex sheet was placed between the source and the target compound with the thickness sufficient to stop beta particles with energies up to 546 keV. The lower energy

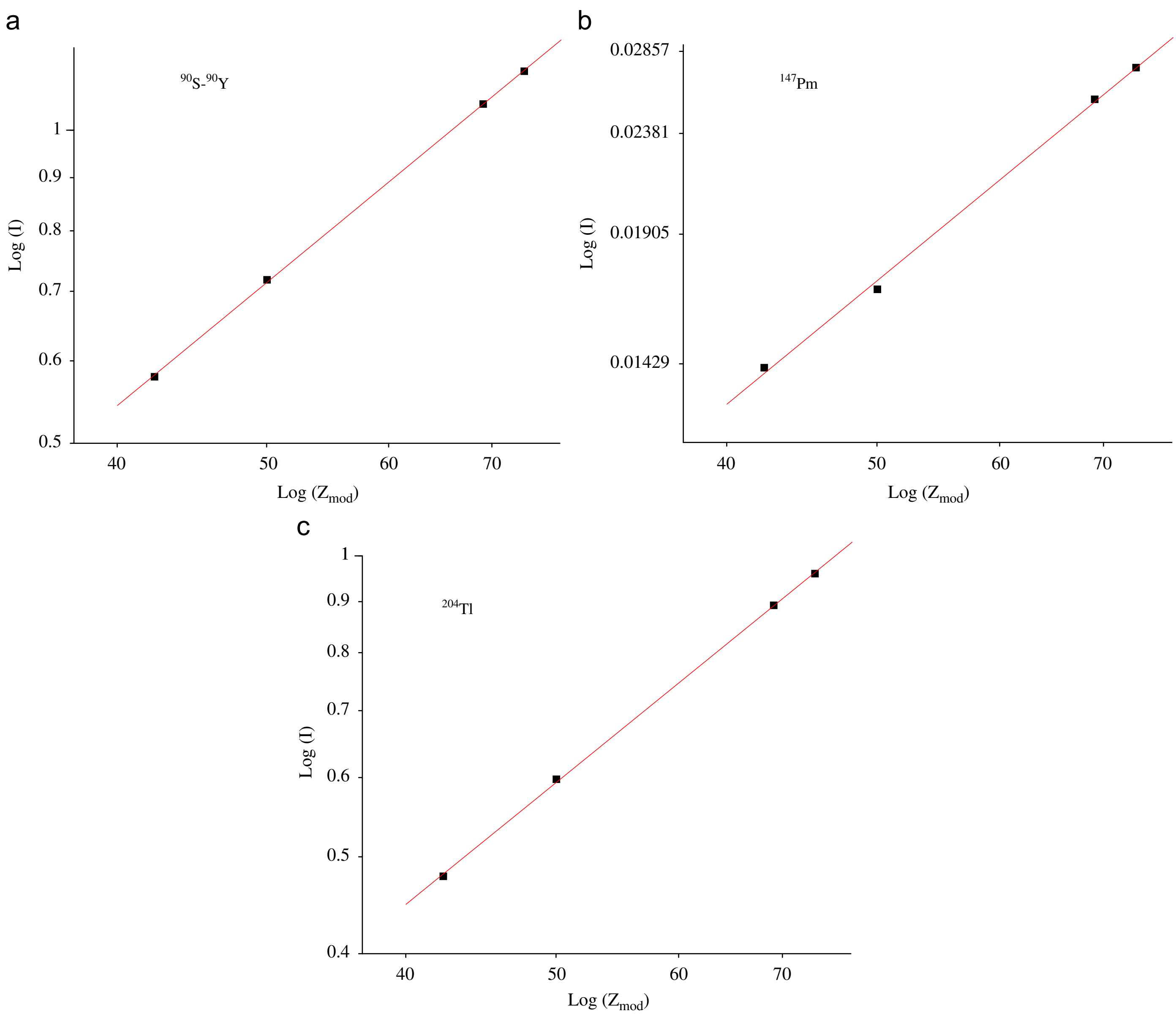

Fig. 2. Measured Bremsstrahlung energy yield (I) plotted against the modified atomic number (Z_{mod}) for beta particles of (a) ^{90}Sr–^{90}Y, (b) ^{147}Pm and (c) ^{204}Tl.

beta component was filtered out, leaving only the higher energy beta, so that they attribute the results from the $^{90}Sr–^{90}Y$ source to a 2274 keV beta spectrum. Liden–Starfelt procedure [14] is followed to unfold the measured into true photon spectrum $S(k)$, which gives the number of photons of energy k per unit energy interval per beta disintegration [11]. To evaluate the theoretical EB spectral distribution it is necessary to evaluate the EB cross-section. The Lagrange's interpolation technique [15,16] is used to evaluate the EB cross-section for these compounds corresponding to their Z_{mod} from the Seltzer–Berger's [6] theoretical EB cross-section data given for elements. The EB spectral distribution $S(k)$ is evaluated from cross-section using Bethe–Heitler [2] analytical expression. The details of this evaluation are explained elsewhere [9,10]. EB photon yield (N) and energy yield (I) are evaluated from $S(k)$ from the following expressions:

$$N = \int_{k_{min}}^{k_{max}} S(k)\mathrm{d}k \quad (9)$$

$$I = \int_{k_{min}}^{k_{max}} kS(k)\mathrm{d}k \quad (10)$$

where k is the photon energy and k_{min} and k_{max} are the minimum and maximum energy of the measured photon spectrum, respectively. The evaluated theoretical yield is compared with the measured yield. Log I and log N were plotted separately versus log Z_{mod} for the given beta isotopes (Figs. 1 and 2). The plots turn out to be linear showing that I and N in Eqs. (7) and (8) do not linearly depend on Z_{mod}, but depend on $(Z_{mod})^m$ where m is the index of Z dependence. The EB photon yield constant K' and energy yield constant K are obtained from the intercepts of the linear graphs.

3. Results and discussions

The external Bremsstrahlung photon yields (N) and energy yields (I) of $^{90}Sr–^{90}Y$, ^{147}Pm and ^{204}Tl in CdO, PbF_2, $Pb(NO_3)_2$ and $PbCl_2$ are given in Tables 1 and 2. The measured yields are compared with theory. The experimental yields show closer agreement with theory and the positive deviation of experimental yields with theory is found to be less than 9% for all compound targets and given beta sources. This positive deviation could be understood qualitatively as follows. The thick target calculation of EB yields assumes isotropic production of Bremsstrahlung, because thick target multiple collisions may be expected to smear out the angular dependence. However single radiative collisions of electrons in which all the energies are lost still retain angular dependence, especially at high energy regions of β-spectrum. The emission in the forward direction increases as the energy of the electrons increases, i.e. as we go toward the end-point energy of the β-spectrum. Theory can be improved for thick target compounds by including various 'solid-state effects', namely, multiple scattering, absorption of photons, energy loss of incident electrons and their secondaries and backscattering processes that are inherently present while the Bremsstrahlung photons are emitted from thick targets under bombardment of electrons.

The evaluated values of K and K' with their uncertainties for measured and theoretical yields are given in Tables 3 and 4, respectively. The errors given in Tables 3 and 4 are the result of the fitting process by which K, K' and m were determined from the plots. The true experimental errors from the measurements are given in Tables 1 and 2. The calculated values of K and K' decrease with the increase in E_{max} of the beta spectrum. The calculated indices of Z_{mod} dependence (m) on photon yields and energy yields are also given in Tables 3 and 4. I and N depend on the cross-section for radiation as well as the average path length of the beta.

Table 1
Bremsstrahlung photon yields (photons/beta particle). The given errors are the true experimental errors from the measurements.

Target	$^{90}Sr–^{90}Y$		^{147}Pm		^{204}Tl	
	N_{exp}	N_{theory}	N_{exp}	N_{theory}	N_{exp}	N_{theory}
CdO	2.2100 ± 0.1540	2.1000	0.4520 ± 0.0311	0.4401	3.0011 ± 0.2101	2.8740
PbF_2	2.8160 ± 0.2110	2.6060	0.5320 ± 0.0391	0.5120	3.6881 ± 0.2761	3.3822
$Pb(NO_3)_2$	4.0000 ± 0.3120	3.8000	0.7770 ± 0.0600	0.7570	5.2001 ± 0.4051	4.8470
$PbCl_2$	4.4000 ± 0.3520	4.2000	0.8300 ± 0.0660	0.8091	5.7670 ± 0.4611	5.2903

Table 2
Bremsstrahlung energy yields (MeV/beta particle). The given errors are the true experimental errors from the measurements.

Target	$^{90}Sr–^{90}Y$		^{147}Pm		^{204}Tl	
	I_{exp}	I_{theory}	I_{exp}	I_{theory}	I_{exp}	I_{theory}
CdO	0.5793 ± 0.0405	0.5369	0.0142 ± 0.0010	0.0136	0.4780 ± 0.0334	0.4394
PbF_2	0.7179 ± 0.0520	0.6964	0.0168 ± 0.0012	0.0168	0.5977 ± 0.0448	0.5483
$Pb(NO_3)_2$	1.0593 ± 0.0805	0.9886	0.0257 ± 0.0020	0.0248	0.8923 ± 0.0695	0.8265
$PbCl_2$	1.1391 ± 0.0911	1.0620	0.0276 ± 0.0022	0.0266	0.9596 ± 0.0767	0.8977

Table 3
Photon yield constants (K') and index of Z dependence (m). The given errors are the result of the fitting process by which K' and m were determined from the plots.

Source	E_{max} (MeV)	K' ($\times 10^{-3}$ MeV^{-1})		m	
		Experimental	Theory	Experimental	Theory
$^{90}Sr–^{90}Y$	0.546, 2.274	0.1239 ± 0.0111	0.1020 ± 0.0091	1.2204 ± 0.0106	1.1840 ± 0.0651
^{147}Pm	0.225	0.7221 ± 0.0383	0.7006 ± 0.0371	1.1159 ± 0.0446	1.1257 ± 0.0450
^{204}Tl	0.766	0.4597 ± 0.0322	0.4019 ± 0.0281	1.1495 ± 0.0230	1.2012 ± 0.0240

Table 4
Energy yield constants (K) and index of Z dependence (m). The given errors are the result of the fitting process by which K and m were determined from the plots.

Source	E_{max} (MeV)	K ($\times 10^{-3}$ MeV^{-1})		m	
		Experimental	Theory	Experimental	Theory
^{90}Sr–^{90}Y	0.546, 2.274	0.0483 ± 0.0039	0.0380 ± 0.0030	1.1362 ± 0.0568	1.20415 ± 0.0652
^{147}Pm	0.225	0.8409 ± 0.0505	0.8558 ± 0.0513	1.2269 ± 0.0491	1.2102 ± 0.0484
^{204}Tl	0.766	0.3204 ± 0.0077	0.2926 ± 0.0070	1.2582 ± 0.0252	1.2914 ± 0.0258

The cross-section depends on $(Z_{mod})^2$ whereas the average path length depends on $(Z_{mod})^{-1}$, so that the photon yields (N) and energy yields (I) depend on Z_{mod}. However the present studies (Tables 3–4) show that the photon yields (N) and energy yields (I) do not strictly depend on Z_{mod}. The index of Z_{mod} dependence (m) on I and N varies from 1.1 to 1.3. This may be due to the fact that the EB cross-sections are not strictly $(Z_{mod})^2$ dependent as suggested by the previous worker [13]. Motz [13] proved through the experiments that the EB cross-sections of elements are not strictly Z^2 dependent. In the similar way, EB cross-section of thick target compounds are also not strictly $(Z_{mod})^2$ dependent. The evaluated values of K and K' are useful to calculate the Bremsstrahlung photon yield and energy yield when these beta particles (^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl) interact with compounds of modified atomic number ranging from 42 to 73. The radiation dosimetry and diagnosis (Bremsstrahlung imaging) calculations assume that I and N are proportional to Z_{mod} but not to $(Z_{mod})^m$. This will cause some errors and these errors can be reduced by considering the variation in the Z_{mod} dependence (m). It is expected that the presented new data on K, K' and index of Z_{mod} dependence (m) may be useful, in view of their importance in medical dosimetry. Also, to the best knowledge of the authors, these data are the first of their kind.

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