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Total bremsstrahlung photon yield and Z-dependence in thick targets produced by beta emitter ^{45}Ca and ^{147}Pm

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Abstract
The total bremsstrahlung photon yield in thick metallic targets (Al, Cu, Sn and Pb) produced by beta emitter ^{45}Ca and ^{147}Pm has been measured by using X-PIPS Si (Li) detector in the photon energy region 5-30 keV. The Z-dependence index ‘n’ and yield constant are determined in the photon energy region 5-30 keV. The Z-dependence index ‘n’ values obtained from experimental bremsstrahlung photon distributions shows better agreement with the index ‘n’ values obtained from the modified Elwert factor (relativistic) Bethe-Heitler theory, which includes the polarization bremsstrahlung into ordinary bremsstrahlung. It was observed, that a yield constant shows exponential decaying dependence on photon energy. Further, it has been found that the Z-dependence index ‘n’ values are not constant and decreases with increasing photon energy. The higher ‘n’ values than unity clearly indicates the inadequacy of theoretical models to represent the dependence of spectral shape of total bremsstrahlung on atomic number. It was observed that total bremsstrahlung photon yield increases with the increase in atomic number and with the decrease in photon energy.

Keywords: Total bremsstrahlung photon yield, Z-dependence, Yield constant

1. Introduction
The bremsstrahlung spectral photon energy distribution depends upon the atomic number of the target atom. Bremsstrahlung cross-section is proportional to the square of the atomic number of the target atom. The Z-dependence of spectral shape of bremsstrahlung spectral photon energy distributions can be studied as a function of photon energy and atomic number of the target element. For monoenergetic electron, several measurements [1-3] pointed out that the dependence of bremsstrahlung on photon energy and atomic number of the target is of complex nature, particularly at lower photon energies. The various factors like screening of electron, interferences between ordinary bremsstrahlung (OB) and polarization bremsstrahlung (PB), absorption of photons and electron backscattering in a target plays the major role particularly at lower photon energy region. Recently [4], the dependence of thick target bremsstrahlung by low incident electron energy of monoenergetic electrons on atomic number has been investigated experimentally.
For the beta emitters, several authors [5-8] reported that the spectral shape of bremsstrahlung spectra is dependent on atomic number Z of the target material. For ^{147}Pm, Dhaliwal [7] has reported the dependence of spectral shape of OB on atomic number (Z) of the target material, at photon energy above 30 keV. However, no study has been reported in the literature for total bremsstrahlung photon yield and Z-dependence of spectral shape of OB and BS spectra of ^{147}Pm and ^{45}Ca, in the energy region 5-30 keV.
The available theoretical models [9-13] for OB and total bremsstrahlung (BS) effectively explain the bremsstrahlung spectral photon distributions as a function of photon energy. But, these theoretical models are not adequate to describe the dependence of spectral shape of bremsstrahlung spectra as a function of atomic number of the target material. For continuous beta particles, Dhaliwal [7] reported the inadequacy of the theoretical models to describe the shape of OB in detail. In order to study the Z-dependence of spectral shape of BS, the number of photons of energy k per unit $m_o c^2$ per beta disintegration at the photon energy k can be expressed as a function of Z.

$$S(k,Z) = R \times K(k) \times Z^n \times \exp(+\mu x) \quad (1)$$

Where 'n' is the index of the Z-dependence of a photon energy k per unit $m_o c^2$ per beta disintegration and K(k) is the proportionality constant considered as yield constant, which is independent of Z at particular photon energy k. Knowledge of the index 'n' is essential for evaluating the Z-dependence of the spectral shape of OB and BS spectra. The corrections due to electron backscattering factor 'R' and absorption factor exp (+µx) are important, particularly at lower photon energy region. The absorption factor plays an important role at lower photon energy region to represent the shape of BS spectral photon distributions. 'µ' is the mass attenuation coefficient taken from Chantler *et al.* [14]. Here, '*x*' is the optimum thickness of the target material. 'R' is the electron backscattering factor given by Semaan and Quarles [15]. The details about the calculation of optimum thickness, range and electron backscattering factor has been already given in [16]. Theoretical and experimental bremsstrahlung spectral distributions were required for the determination of the Z-dependence index 'n' and the yield constant K(k).

The BS photon yield T for the target, with k_{min} and k_{max} as the lower and upper limit of photon energy of the bremsstrahlung spectrum respectively is given by

$$T = \int_{k_{min}}^{k_{max}} S(k,Z)\,dk \quad (2)$$

Where S (k,Z) is given by the relation

$$S(k,Z) = \int_{1+k}^{W_{max}} n(W_e^{'},k,Z)P(W_e^{'})dW_e^{'} \quad (3)$$

Here $P(W_e^{'})dW_e^{'}$ is the beta spectrum of the beta emitter under study. In the present measurement, the beta spectrum of ^{45}Ca and ^{147}Pm were taken from Macklin *et al.* [17]

The bremsstrahlung spectral distribution $[n(W_e^{'},k,Z)]$ in thick target to absorb an electron of energy $W_e^{'}$ with N atoms per unit volume is given by

$$n(W_e^{'},k,Z) = N \int_{1+k}^{W_e^{'}} \frac{d\sigma(W_e,k,Z)/dk}{(-dW_e/dx)} dW_e \quad (4)$$

Here $d\sigma(W_e,k,Z)/dk$ is the bremsstrahlung cross section [12, 13], '$-dW_e/dx$' is the total energy loss per unit path length of an electron in a target given by Berger and Seltzer [18].

Computer programs are written to calculate the bremsstrahlung spectral photon distribution in terms of the number of photons of energy k per unit $m_o c^2$ per beta disintegration, i.e. *S(k,Z)*. The total photon yields T were obtained for different targets from graphical integration of the bremsstrahlung spectra from the plots of *S(k,Z)* versus photon energy k between k_{min} and k_{max}. In the present study, the Z-dependence index 'n', obtained from theoretical bremsstrahlung spectral photon distributions from Elwert corrected (non-relativistic) Bethe-Heitler (EBH) and modified Elwert factor (relativistic) Bethe-Heitler (F_{mod}BH) theories for OB and the modified Elwert factor (relativistic) Bethe-Heitler theory (F_{mod}BH+PB) theory for BS were compared with the Z-dependence index 'n' values obtained from the experimental BS spectra in thick targets of Al, Cu, Sn and Pb, produced by beta particles of ^{147}Pm and ^{45}Ca.

2. Experimental detail

A soft beta emitters of ^{147}Pm (end point energy 225 keV) having activity 0.1 mCi and ^{45}Ca (end point energy 256 keV) having activity 0.5 mCi, were used for the measurements. The experimental arrangement shown in the Fig 1 was used for the measurements of BS spectral photon distributions for a particular beta source under study. In case of ^{147}Pm, the thick targets of Al (67 mgcm^{-2}), Cu (71 mg cm^{-2}), Sn (70 mgcm^{-2}) and Pb (58 mgcm^{-2}) more than the range of beta particles, were used in the present measurement. For ^{45}Ca, the targets of Al (91mgcm^{-2}), Cu (91mg cm^{-2}), Sn (94mgcm^{-2}) and Pb (93mgcm^{-2}) more than the range of beta particles were used.

A Perspex beta stopper technique was used for eliminating the contribution of internal bremsstrahlung (IB), BS generated in the source material and room background. In case of ^{147}Pm and ^{45}Ca, the Perspex beta stopper of thickness 75 mg/cm^2 and 100 mg/cm^2 respectively, used in the present measurements. These thicknesses of Perspex beta stopper are more than the range of the beta particles of the beta emitters. Two sets of measurements were taken for a time interval of 300000 seconds by placing the targets at position A and B respectively. The difference of the above two measurements gave the BS produced in target elements only. The BS photon yield measured experimentally and calculated from different theoretical model is given in Table 1 and 2. The experimental values are different from theories due to the source strength of beta emitters ^{45}Ca and ^{147}Pm.

The correction due to self-absorption of BS in air, target thickness and the Perspex beta stopper was incorporated by using the mass attenuation coefficients tabulated by Chantler *et al.* [14]. The electron backscattering factor R was also incorporated in the measured BS spectral photon distributions. The geometrical full-energy peak detector efficiency for the detector is determined by using the values of the intrinsic efficiency I(k) of the X-PIPS detector and photo-fraction f(k) values at different photon energies.

In the present measurement, the overall uncertainties were estimated to be less than 10 % in the entire studied photon energy region of 5-30 keV. The uncertainties are mainly due to the counting statistics, full energy detection efficiency of the detector, electron backscattering and attenuation of BS photons in the target materials.

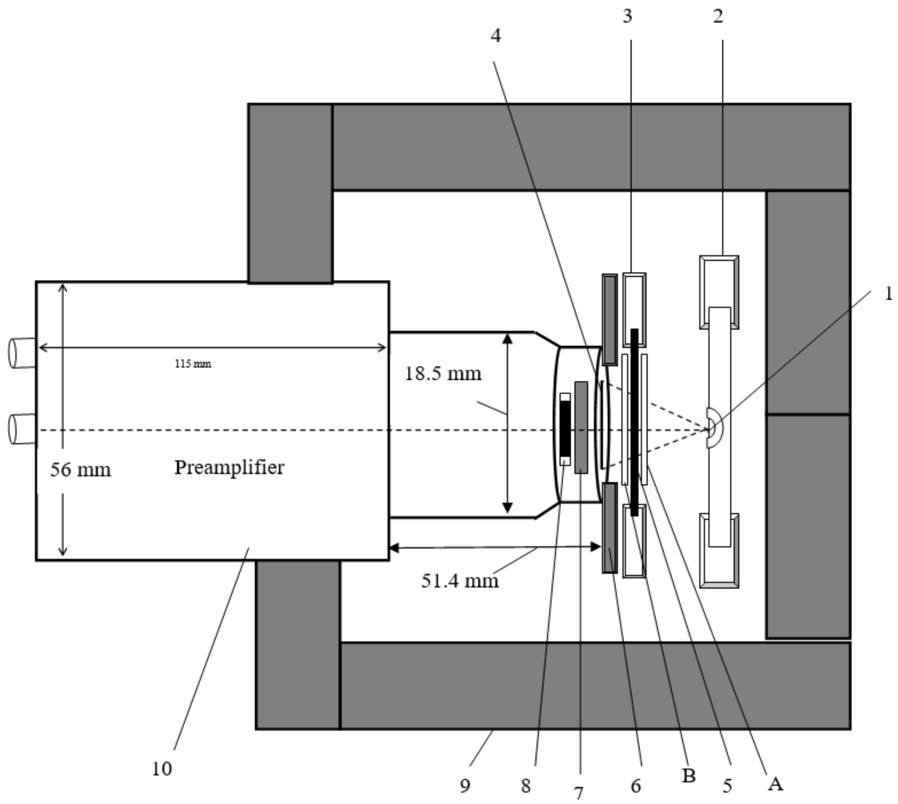


Fig 1: Experimental arrangement

1. Source position; 2.Source holder; 3. Target holder 4. Be window; 5. Perspex beta stopper; 6. Lead Collimator; 7. Detector Collimator; 8. Si (Li) chip; 9. Shielding Lead bricks; 10. X-PIPS Si (Li) Detector

A: position of the target above the Perspex beta stopper; B: position of the target below the Perspex beta stopper;

3. Results and discussions

The Z-dependence index 'n' values are obtained from the spectral shape of bremsstrahlung produced by ^{147}Pm and ^{45}Ca beta particles in thick metallic targets of Al, Cu, Sn and Pb as a function of photon energy are given in Table 3 and 4. The Z-dependence index 'n' values obtained from experimental BS photon distributions shows better agreement with the index values 'n' obtained from theoretical BS photon distribution from the F_{mod} BH+PB theory. It has been found, that the Z-dependence index 'n' values are not constant and decreases with increasing photon energy. A typical plot for determination of index 'n' of Z, at photon energy 15 keV, for experimental BS spectra, in case of ^{147}Pm is given in Fig. 2.

The plots of yield constant K(k) as a function of photon energy are shown in the Fig 3 [a, b] for ^{147}Pm beta emitter and in the Fig 4 [a, b] for ^{45}Ca beta emitter. It is clear from these plots, that the proportionality factor shows exponential decaying dependence on photon energy 'k'. For a given beta emitters the exponential decay dependency found to be same for the theoretical and experimental BS spectral photon distributions. For ^{147}Pm, the exponential function *exp (-2.60×k)* fits the exponential curves showing the variations of K(k) with k. In case of ^{45}Ca, the exponential function *exp (-2.78×k)* fits the exponential curves showing the variations of K(k) with k. This results show that the yield constant K(k) is directly proportional to the end point energy of the beta particles i.e. the exponent is indeed depending on the end point energy of the beta particles. The uncertainties in yield constant values are estimated to be within 10 %. The errors in determination of index 'n' values obtained from experimental data mentioned in Tables 3 and 4 are mainly due to the statistics of data and the uncertainty in the least squares fit.

It has been found that the Z-dependence index values 'n' are continuously deviated from unity in the studied photon energy region of 5-30 keV. It is clear from the Table [3, 4], that the experimental index 'n' values are varying in the range of 3.43-1.52 and 3.31- 1.53 in case of ^{147}Pm and ^{45}Ca beta emitters respectively. The values of index 'n' obtained from F_{mod}BH+PB theory, which includes PB, are varying in the range of 3.35-1.45 and 3.29-1.45, in case of ^{147}Pm and ^{45}Ca beta emitters respectively. The index 'n' values are varying in the range of 2.84-1.35 and 2.79-1.36 obtained from F_{mod}BH theory which describes OB in case of ^{147}Pm and ^{45}Ca beta emitters respectively. At lower energies, the index values 'n' are higher than unity may be due to the larger contribution of PB into OB. However, Dhaliwal [6] has reported that the index 'n' values for OB spectra are only 15-34 % higher than unity in the photon energy region of 30-170 keV. The index 'n' values obtained from F_{mod}BH+PB theory are higher than the 'n' values obtained from F_{mod}BH theory in the range of 6-15 % for ^{147}Pm and ^{45}Ca beta emitters respectively.

Table 1: Values of total photon yield 'T' for beta emitters (^{147}Pm, and ^{45}Ca) in the photon energy region of 5-10 keV, for different thick metallic targets

Beta emitters	Total photon yield/beta disintegration			
(i) ^{147}Pm				
Target	**EBH Theory**	**F_{mod}BH Theory**	**F_{mod}BH+PB Theory**	**Experiment**
Aluminum	2.09E+02	2.24E+02	2.90E+02	1.58E+08
Copper	2.15E+02	2.29E+02	3.02E+02	7.49E+17
Tin	2.81E+19	2.96E+19	4.05E+19	3.23E+21
Lead	9.72E+19	1.04E+20	1.45E+20	3.51E+24
(ii) ^{45}Ca				
Aluminum	1.94E+04	2.07E+04	2.55E+04	8.24E+09
Copper	1.96E+04	2.09E+04	2.85E+04	2.87E+25
Tin	1.35E+26	1.45E+26	1.94E+26	9.93E+30
Lead	4.04E+27	4.35E+27	6.05E+27	7.82E+32

Table 2: Values of total photon yield 'T' for beta emitters (^{147}Pm, ^{45}Ca, ^{90}Sr and ^{204}Tl) in the photon energy region of 10-30 keV, for

Beta emitters	Total photon yield/beta disintegration			
(i) ^{147}Pm				
Target	**EBH Theory**	**F_{mod}BH Theory**	**F_{mod}BH+PB Theory**	**Experiment**
Aluminum	5.52E-03	5.75E-03	6.77E-03	1.26E+05
Copper	1.42E+00	1.48E+00	1.85E+00	5.15E+06
Tin	1.46E+01	1.53E+01	1.91E+01	7.36E+06
Lead	1.57E+02	1.65E+02	2.14E+02	9.08E+07
(ii) ^{45}Ca				
Aluminum	4.51E-02	4.71E-02	5.48E-02	5.83E+04
Copper	7.23E+01	7.53E+01	9.18E+01	1.56E+08
Tin	2.85E+02	2.93E+02	3.62E+02	5.00E+08
Lead	1.96E+03	2.06E+03	2.64E+03	5.40E+09

Table 3: The Z-dependence index 'n' values of the bremsstrahlung as a function of photon energy k for ^{147}Pm beta emitter

Photon Energy (keV)	Index Values (n)			
	EBH Theory	**F_{mod}BH Theory**	**F_{mod}BH+PB Theory**	**Experiment**
5.0	2.73	2.84	3.35	3.43±0.17
7.5	2.52	2.64	3.09	3.08±0.15
10.0	2.46	2.55	2.73	2.76±0.13
12.5	2.35	2.41	2.57	2.58±0.11
15.0	2.18	2.24	2.39	2.67±0.10
17.5	1.97	2.02	2.16	2.18±0.09
20.0	1.72	1.80	1.96	1.92±0.09
22.5	1.59	1.67	1.80	1.89±0.08
25.0	1.47	1.52	1.65	1.70±0.07
27.5	1.38	1.41	1.51	1.58±0.07
30.0	1.34	1.35	1.45	1.52±0.07

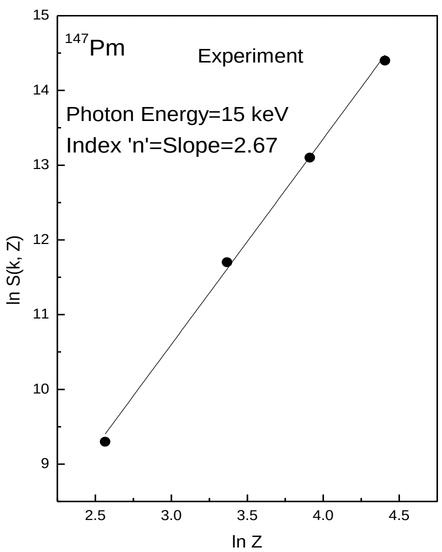
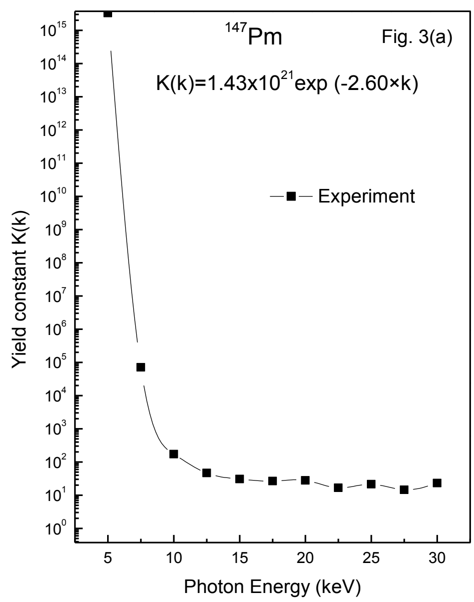


Fig 2: Plot of ln S (k, Z) versus ln Z at 15 keV photon energy for ^{147}Pm beta emitter. (Symbols are the data points and the line is a fit to the points).



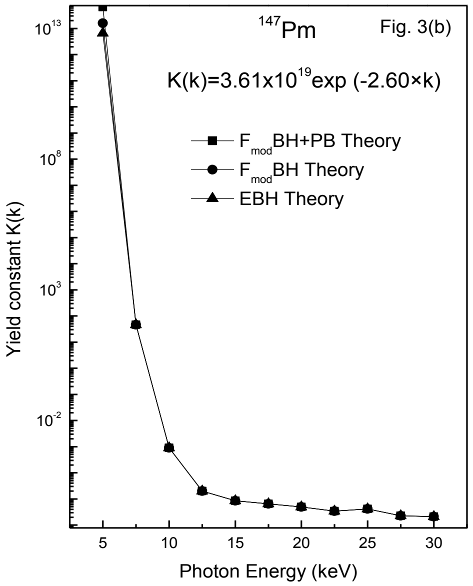
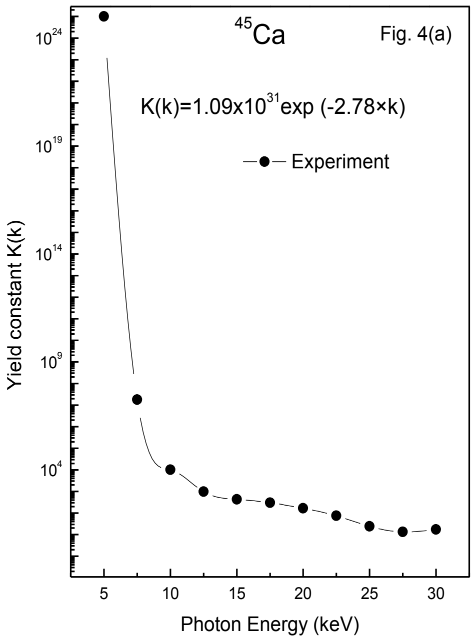


Fig 3: [a, b] Plots of yield constant K(k) versus photon energy k for ^{147}Pm beta emitter (errors are lying within the points).



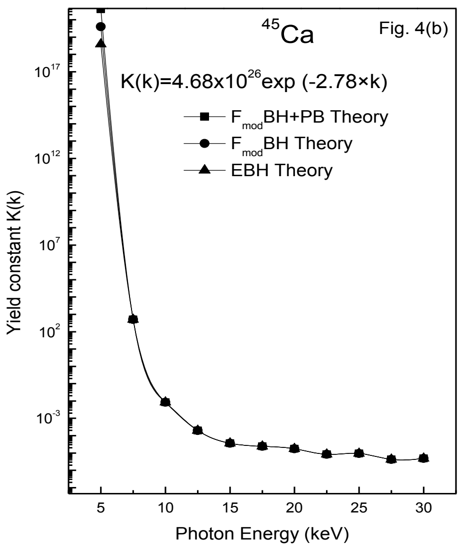


Fig 4: [a, b] Plots of yield constant K(k) versus photon energy k for ^{147}Pm beta emitter (errors are lying within the points).

4. Conclusions

These results are in agreement with our previous results reported [8] with different beta emitters ^{90}Sr and ^{204}Tl, having different end point energies. However, these results are not in agreement with results reported by [4] with monoenergetic electrons. This indicates that the shape of BS and OB spectra is not linearly dependent on the atomic number Z of the target atom as reported by Evans [5]. The higher index 'n' values than unity clearly indicates that the theoretical models are inadequate to represent the dependence of spectral shape of total bremsstrahlung on atomic number of the target material, particularly at lower photon energy region.

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