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External bremsstrahlung of ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in detector compounds

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HIGHLIGHTS

- Bremsstrahlung spectra of ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in compounds CsI and NaI has been measured.
- This paper also describes a new procedure for the calculation of attenuation coefficient Bremsstrahlung.
- The measured yields may be useful to apply corrections for CsI and NaI detectors.

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ABSTRACT

External Bremsstrahlung spectra produced by the complete absorption of beta particles from ^{90}Sr to ^{90}Y, ^{147}Pm and ^{204}Tl in nuclear radiation detection compounds like Cesium iodide (CsI) and Sodium Iodide (NaI) has been measured using 0.038 m × 0.038 m NaI(Tl) crystal and is compared with Tseng–Pratt theory. The Bremsstrahlung yields are calculated using the unfolded spectra. This paper also describes a new procedure for the calculation of effective absorption coefficient of Bremsstrahlung from the Bremsstrahlung spectra. The measured spectra show fairly good agreement at low energy end of spectrum and some deviation at higher energy end of spectrum with the theory. The measured Bremsstrahlung yields may be useful to apply corrections, whenever beta particle passes through CsI and NaI detectors.

1. Introduction

When a beta particle passes through the Coulomb field of the target nucleus, it accelerates and emits out external Bremsstrahlung (EB). Accurate theory for EB is developed by Tseng and Pratt (1971) using the self-consistent coulomb field wave function. A similar approach of Tseng et al. is followed by Seltzer and Berger (1986) to extend it to the field of an atomic electron. Bethe and Heitler (1934) gave an expression for EB produced in thick target elements. Most of the EB works of beta have been carried out using only metal/element as a thick target but using compound as a thick target is lacking (Quarles 2000; Tajinder et al., 2009; Lixia Tian et al., 2009). Manjunatha and Rudraswamy (2007a, 2007b) formulated the new method for estimating EB cross sections in compounds. In continuation with this work, Manjunatha and Rudraswamy (2007c); Manjunatha et al. (2010) measured the EB spectra for a set of compounds and compared with the Tseng–Pratt theory. In our recent report (Manjunatha and Rudraswamy, 2011), Bremsstrahlung yield of ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in some lead compounds has been measured and the Bremsstrahlung photon yield and energy yield constants (K' and K) are evaluated. Markowicz, VanGriken (1984) proposed an 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

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

Here,

$$Z_{\text{mod}} = \frac{\sum_i^l \frac{W_i Z_i^2}{A_i}}{\sum_i^l \frac{W_i Z_i}{A_i}} \tag{2}$$

E_γ and E_0 are emitted photon energy and incident electron energy, respectively. I_k represents the number of continuum photons with energy E_γ with 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. Shivaramu (1990) evaluated the atomic number (Z) for set of compounds for Bremsstrahlung process from the measured yields.

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He reported that Z agrees fairly well with Z_{mod} than the mean atomic number.

Production and attenuation of EB take place simultaneously up to the range (R) of the beta/electron beyond this range only attenuation of EB takes place. Literature survey of the experimental and theoretical work on EB indicated that precise information regarding the attenuation of EB is not available in the literature. Singh and Powar (1984) gave an empirical relation for attenuation of Bremsstrahlung from hard beta emitters and no general conclusions could be drawn from it. Dhaliwal et al. (1991) adopted a procedure for the calculation of the attenuation of EB from ^{204}T1 to ^{32}P emitters in metallic targets and compared their results with the experimentally measured values. Abdel-Hady et al. (1996) studied the attenuation of EB from ^{204}T1 to ^{99}Tc in metallic targets and the correctness of the procedure of Dhaliwal et al. (1991) has also been tested for the low energy β-emitter ^{99}Tc (E_{max}=0.293 MeV). There is need for the study of EB attenuation which is important in the field of radiation transport, medical therapy and controlled photonuclear research.

Cesium iodide (CsI) and Sodium Iodide (NaI) are mainly used in detectors to detect radiation. There is a possibility of production of secondary EB in the detector itself whenever beta passes through these detectors. This component is normally neglected while carrying out the regular experiment on measurement of primary EB of same or other compound which are normally kept between beta source and the detector. This traditionally neglected Bremsstrahlung component within the detector itself decreases the efficiency of the detector. To include the Bremsstrahlung component produced within the detector itself, it is necessary to measure the accurate Bremsstrahlung yields in CsI and NaI. So far, to our knowledge, no study has been done for the measurement of Bremsstrahlung yields of ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in nuclear radiation detection compounds like CsI and NaI. This prompted us to undertake a rigorous and exhaustive measurement of Bremsstrahlung spectra and yields of ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in CsI and NaI using 3.8 cm × 3.8 cm NaI(Tl) crystal and is compared with Tseng and Pratt theory. This paper also describes a procedure for the calculation of attenuation coefficient of EB from the Bremsstrahlung spectra and attenuation coefficients for mono energetic gamma rays in compounds.

2. Present work

Present study consist of three parts namely

(1) Estimation of EB cross section using Lagrange's interpolation technique.
(2) Evaluation of theoretical EB spectrum in a given compounds.
(3) Measurement of EB spectra in given compounds and comparison with theoretical results.
(4) Estimation of EB attenuation coefficient from measured and theoretical spectra.

2.1. Estimation of EB cross section

In the present work, it has been evaluated Z_{mod} using Markowicz's Eq. (2). The estimated Z_{mod} for CsI and NaI are 54.08 and 45.78, respectively. The six elements whose atomic numbers adjacent to that of CsI are Te, I, Xe, Cs, Ba and La, and their Z values are 52, 53, 54, 55, 56 and 57, respectively. Similarly, six adjacent elements are considered for NaI to evaluate EB cross section. The EB cross section for these compounds is evaluated using Lagrange's interpolation technique, Seltzer and Berger (1986) theoretical EB cross section data given for elements and the evaluated results of Z_{mod} using the following expression

$$\sigma_{Z_{mod}} = \sum \left(\frac{\prod_{Z' \neq Z} (Z_{mod} - Z)}{\prod_{z \neq Z} (z - Z)} \right) \sigma_z \quad (3)$$

where lower case z is the atomic number of the element of known EB cross section σ_z adjacent to the modified atomic number (Z_{mod}) of the compound whose EB cross section $\sigma_{Z_{mod}}$ is desired and upper case Z are atomic numbers of other elements of known EB cross section adjacent to Z_{mod}.

2.2. Evaluation of theoretical EB spectrum

The number $n(T, k)$ of EB photons of energy k when all of the incident electron energy T completely absorbed in thick target is given by Bethe and Heitler (1934) is

$$n(T, k) = N \int_{1+k}^{T} \left(\frac{\sigma(E, k)}{(-dE/dx)} \right) dE \quad (4)$$

where $\sigma(E, k)$ is EB cross section at photon energy k and electron energy E, N is the number of atoms per unit volume of target and E is the energy of an electron available for an interaction with nucleus of the thick target after it undergoes a loss of energy per unit length $(-dE/dx)$. For a beta emitter with end point energy T_{max}, spectral distribution of EB photons $[S(k)]$ is given by

$$S(k) = \frac{\int_T^{T\max} n(T, k)\, P(T)\, dT}{\int_T^{T\max} P(T)\, dT} \quad (5)$$

where $P(T)$ is the beta spectrum. Evaluated results of $\sigma(E, k)$ of Eq. (3) and tabulated values of $(-dE/dx)$ of Seltzer and Berger (1986) data are used to get $S(k)$ for CsI and NaI.

2.3. Experiment

The spectral distributions of external Bremsstrahlung (EB) excited by the beta particles in the given thick target compounds were measured using 0.038 m × 0.038 m 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 (Manjunatha and Rudraswamy 2007c; Manjunatha et al., 2010) and it is also shown in Fig. 1. In the present experiment, beta particles from ^{147}Pm (E_{max}=225 keV), ^{204}Tl (E_{max}=763.47 keV) and ^{90}Sr–^{90}Y (E_{max}=546 keV, 2274 keV) are used to produce EB in thick target detector compounds such as CSI and NaI. ^{204}Tl is a unique first-forbidden beta emitter (ΔJ=2, yes), with a half life of 3.79 years and maximum beta energy of 763.47 keV there is also exists a weak electron-capture branch (2.1%) in it. ^{147}Pm is a non unique first-forbidden soft beta emitter (ΔJ=0, yes) with an end point energy 225 keV and its half life is 2.62 years. The beta isotope of ^{90}Sr/^{90}Y (the end point energies of the beta spectrum are 546 keV and 2274 keV) emits two groups of beta particles both being first forbidden unique transitions. The source strength was determined by absolute beta counting technique (Burtt, 1949) and was found to be 51.800 ± 2.960 MBq, 2.773 ± 0.015 MBq and 1.924 ± 0.010 MBq for ^{90}Sr–^{90}Y, ^{204}Tl and ^{147}Pm, respectively. These sources are in the form of a disc of diameter 5 mm obtained from BRIT (India). A Perspex sheet (with thickness sufficient to stop all beta particles) is placed between source and the target, so that the spectrum measured by the detector is IB+BG. Here IB and BG are internal Bremsstrahlung and background, respectively. Then the Perspex sheet is placed below the target to get the spectrum due to EB+ IB+ BG. The difference in the two spectra gives raw EB spectrum. Here the role of Perspex sheet is to cut the beta component of the source. The measured EB+ IB+ BG and

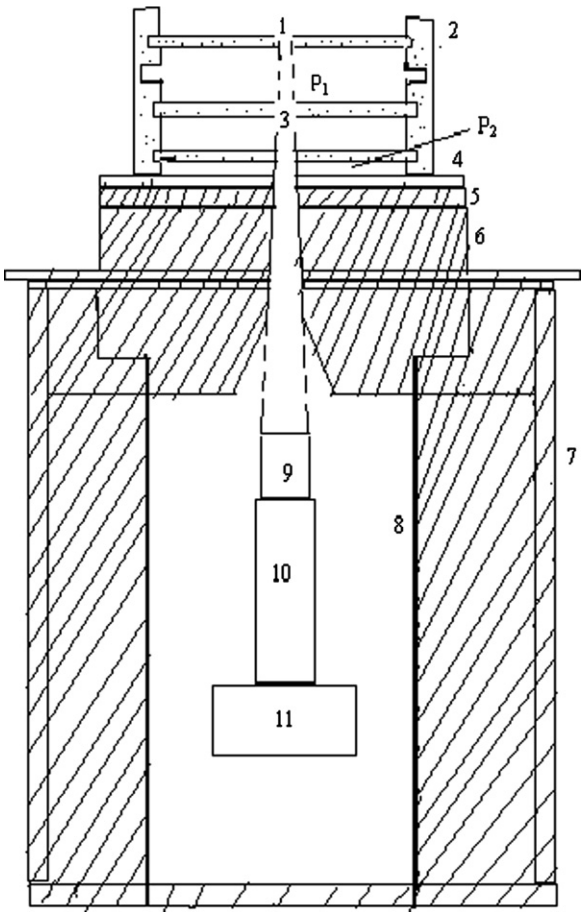

Fig. 1. Experimental setup.

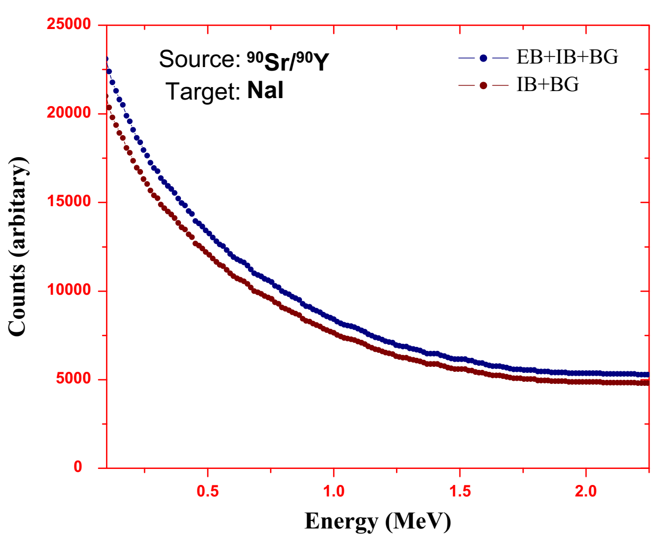

Fig. 2. The measured raw spectrum of ^{90}Sr–^{90}Y in NaI.

IB+BG for ^{90}Sr–^{90}Y in NaI are shown in Fig. 2. Liden-Starfelt (1955) procedure is followed to unfold the measured into true photon spectrum $S(k)$ which gives No. of photons per m_oc^2 per beta. Observed pulse height distribution were corrected for background, Dead time of analyzer, resolving power, Compton distribution, K X-ray escape gamma detection efficiency and absorption in target compound, air, Aluminium can. The major error in the present measurement were statistical error (error in determining intrinsic and geometric efficiencies, Photo fraction, energy resolution of the detector, EB absorption in target compound, air, aluminum can etc.,) and beta source strength. The uncertainities due to statistics in recording the data were less than 6%. The correction for escape of iodine X-rays from the detector is less than 3%. Uncertainty in the full energy peak detection efficiency was about 3%. The total error involved in the correction for energy resolution, iodine escape peak and Compton contribution was 6% at highest energy studied for each target. The absorption of EB photons in Aluminum container of the detector and the correction due to self absorption of EB photons in a target was applied by using the attenuation coefficients from WINXCOM program (Gerward et al., 2004). The total uncertainty in the measurement was less than 12% for all studied beta isotopes.

2.4. *Effective absorption coefficient of bremsstrahlung* (μ_B)

The effective absorption coefficient is a measure of the number of primary photons which have interactions during the absorption in the target. It is the conventional attenuation coefficient of

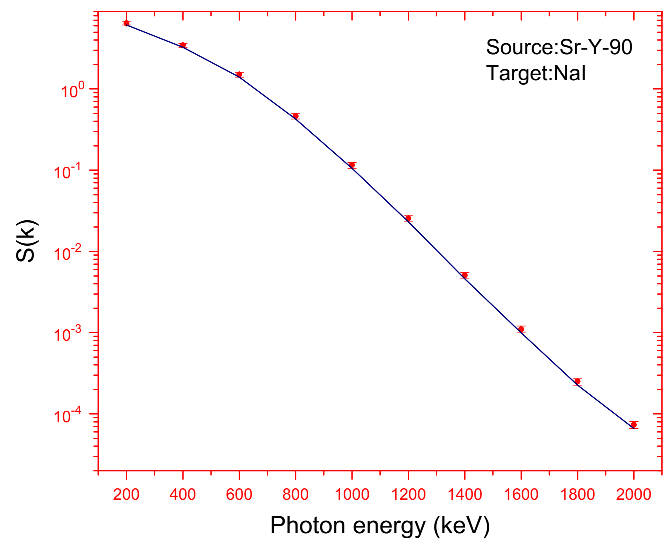

Fig. 3. Unfolded measured EB spectrum (circle) of ^{90}Sr–^{90}Y in NaI with the theoretical distribution (line).

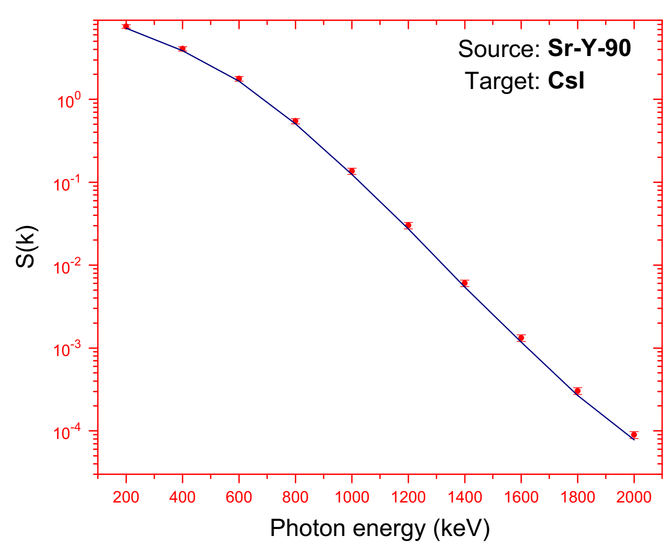

Fig. 4. Unfolded measured EB spectrum (circle) of ^{90}Sr–^{90}Y in CsI with the theoretical distribution(line).

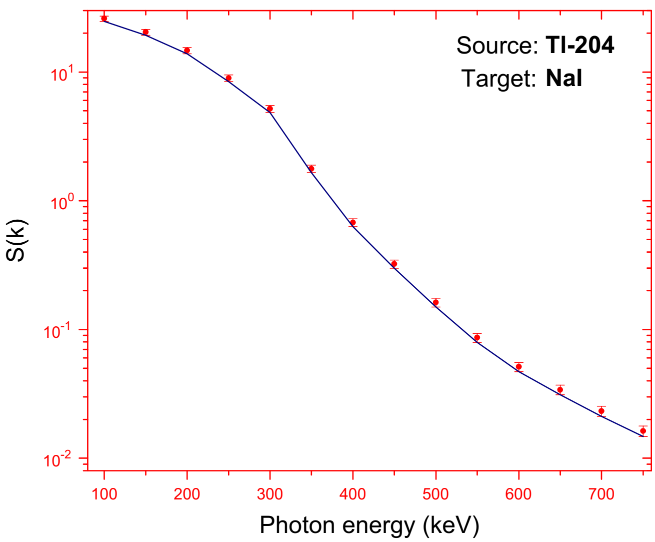

Fig. 5. Unfolded measured EB spectrum (circle) of ^{204}Tl in NaI with the theoretical distribution (line).

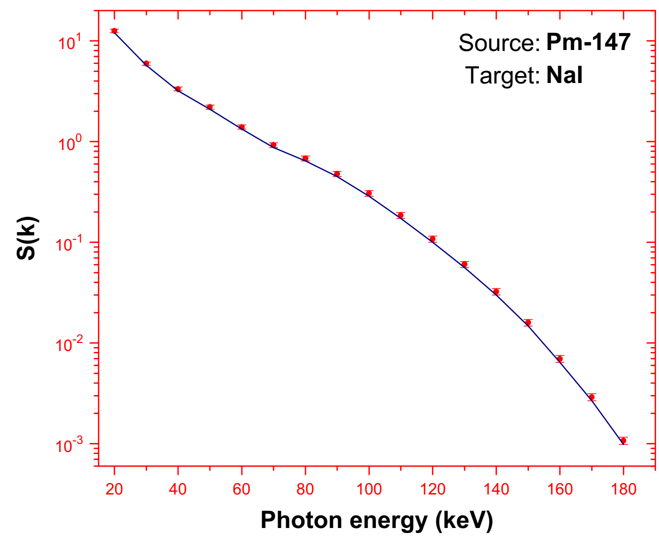

Fig. 7. Unfolded measured EB spectrum (circle) of ^{147}Pm in NaI with the theoretical distribution (line).

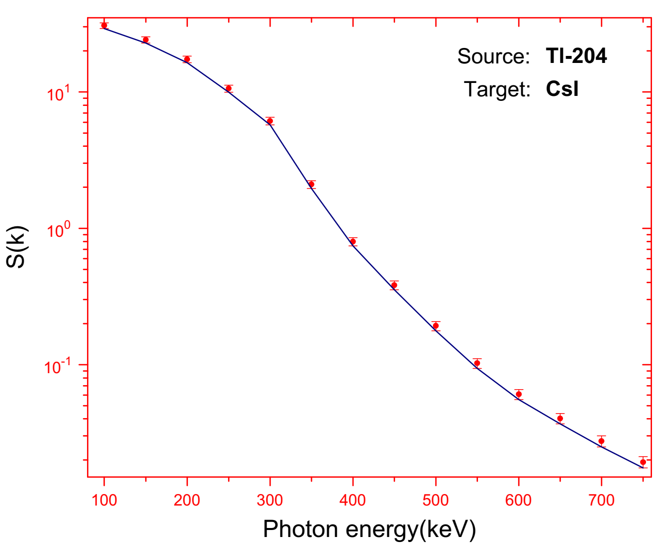

Fig. 6. Unfolded measured EB spectrum (circle) of ^{204}Tl in CsI with the theoretical distribution (line).

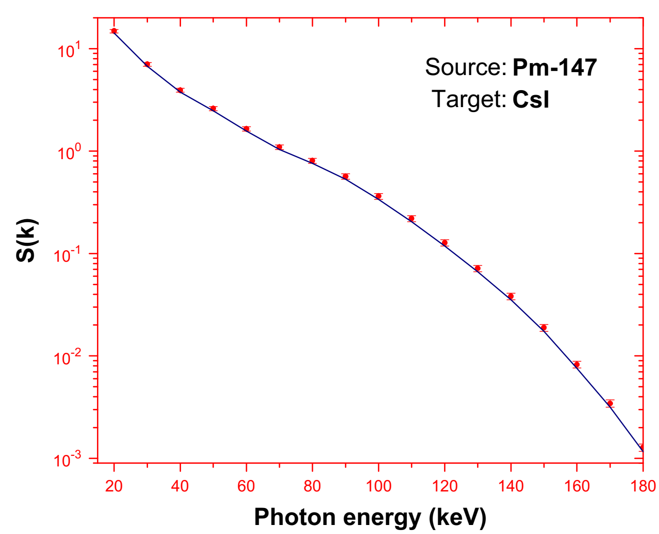

Fig. 8. Unfolded measured EB spectrum (circle) of ^{147}Pm in CsI with the theoretical distribution (line).

Bremsstrahlung which depends on the energy of emitted photon (k). EB spectrum [$S(k)$] gives the number of EB photons produced per disintegration of beta. The attenuation coefficient of Bremsstrahlung radiation [$\mu_B(E)$] can be calculated from the $S(k)$ and is given by

$$\mu_B(E) = \frac{\int_{kmin}^{kmax} S(k)\mu(k)\,dk}{\int_{kmin}^{kmax} S(k)\,dk} \tag{6}$$

here, k_{min} and k_{max} are lower and upper limits of photon energy of the EB spectrum. The nominator in the above equation represents the intensity of the attenuated Bremsstrahlung radiation and denominator represents the intensity of the non attenuated Bremsstrahlung radiation. $\mu_B(E)$ is evaluated from the Bremsstrahlung spectrum $S(k)$ and corresponding photon attenuation coefficients [$\mu(k)$]. In the above equation, the integration is performed from k_{min} (equals 0) to k_{max} (equals E), E is variable which can vary from 0 to E_{max}. For example μ_B at 100 keV for ^{204}Tl is evaluated by integrating above equation from 0 keV to 100 keV. Similarly μ_B at 700 keV for ^{204}Tl is evaluated by integrating formula 6 from 0 to 700 keV. Hence μ_B is a function of photon

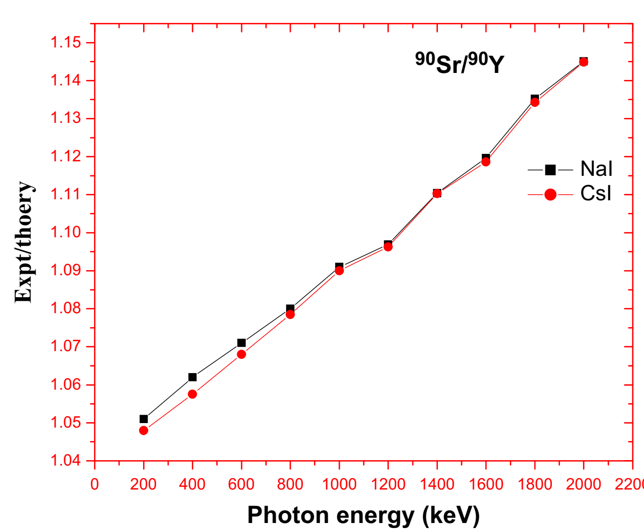

Fig. 9. The ratio between experiment and theory of EB spectra for ^{90}Sr/^{90}Y.

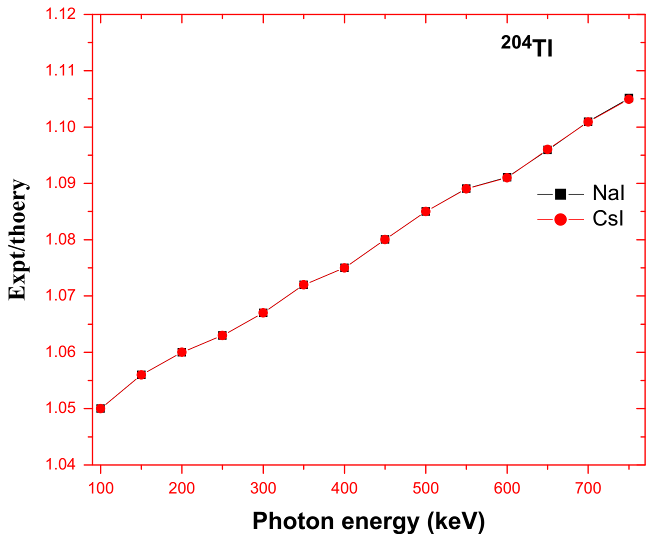

Fig. 10. The ratio between experiment and theory of EB spectra for ^{204}Tl.

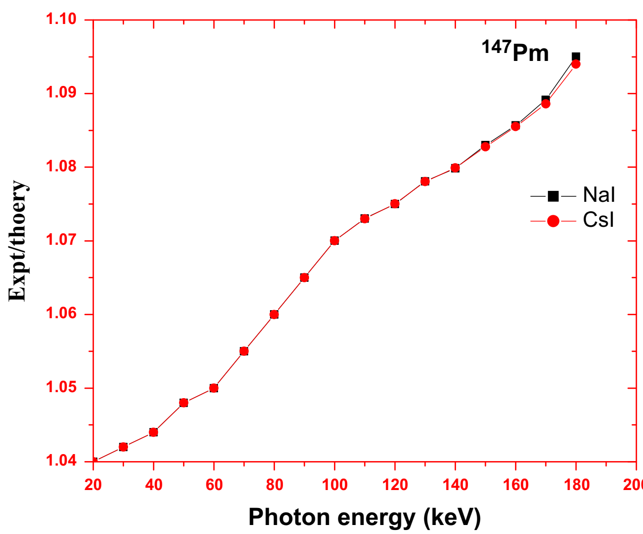

Fig. 11. The ratio between experiment and theory of EB spectra for ^{147}Pm.

energy (k). The beta of maximum energy E_{max} may produces Bremsstrahlung photon of energy from 0 to E_{max}. In the above equation, E in the parenthesis is the upper limit of the Bremsstrahlung energy and that $\mu_B(E)$ is the effective absorption coefficient from 0 to E. $\mu(k)$ values can be obtained from WINXCOM program (Gerward et al., 2004).

3. Results and discussions

The obtained unfolded measured spectra excited by ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in NaI and CsI along with the evaluated theoretical spectra are shown in Figs. 3–8. The experimental results show fairly good agreement with theory at low energy end (less than 5%) of spectrum and some deviation (less than 11%) at higher energy end of beta spectrum for given beta sources (Figs. 9–11). The reason for the deviation between theory and experiment is discussed in the previous report (Manjunatha et al., 2010). The measured Bremsstrahlung photon yields (N) and energy yields (I) of ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in NaI and CsI along with theoretical values are given in Tables 1 and 2. Bremsstrahlung production is high in CsI compared to NaI. The effective absorption coefficient

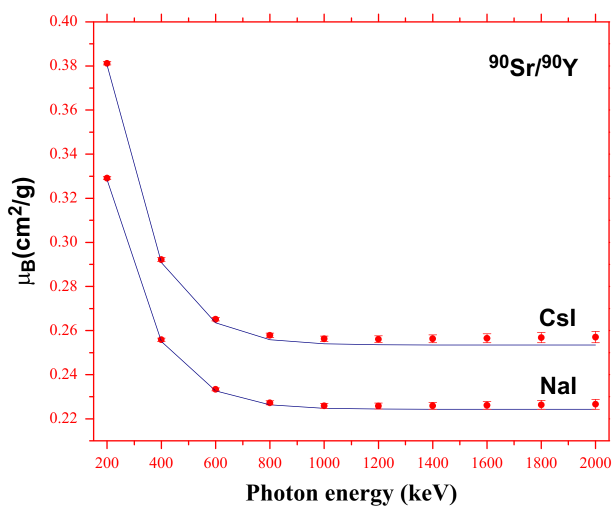

Fig. 12. Theoretically evaluated (continues line) and derived in present work d (solid circles) Bremsstrahlung attenuation coefficient (μ_B) with energy for ^{90}Sr-^{90}Y beta source.

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_{theory}	N_{exp}	N_{theory}	N_{exp}	N_{theory}	N_{exp}
NaI	2.2690	2.3920 ± 0.2081	0.5403	0.5736 ± 0.0459	2.4653	2.6757 ± 0.2128
CsI	2.6808	2.8279 ± 0.2545	0.6393	0.6759 ± 0.0550	2.9171	3.1440 ± 0.2630

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_{theory}	I_{exp}	I_{theory}	I_{exp}	I_{theory}	I_{exp}
NaI	0.7700	0.8165 ± 0.0710	0.0190	0.0204 ± 0.0016	0.5188	0.5646 ± 0.0461
CsI	0.9104	0.9650 ± 0.0869	0.0225	0.0240 ± 0.0020	0.6138	0.6645 ± 0.058

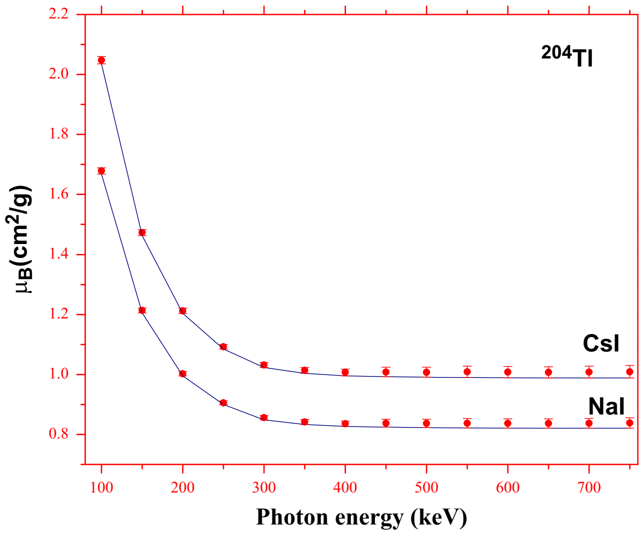

Fig. 13. Theoretically evaluated (continues line) and derived in present work (solid circles) Bremsstrahlung attenuation coefficient (μ_B) with energy for ^{204}Tl beta source.

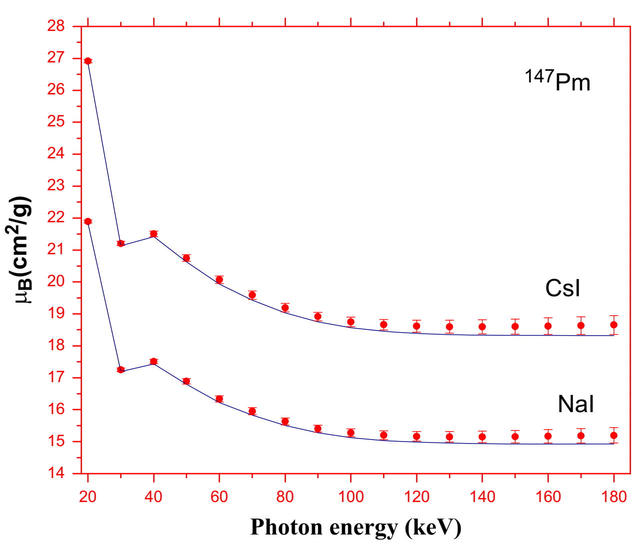

Fig. 14. Theoretically evaluated (continues line) and derived in present work (solid circles) Bremsstrahlung attenuation coefficient (μ_B) with energy for ^{147}Pm beta source.

of Bremsstrahlung [$\mu_B(E)$] evaluated from the measured and theoretical spectrum is shown in Fig. 12–14. We have not directly measured the effective absorption coefficient of Bremsstrahlung but we have evaluated this from the measured spectrum. In the present measurement, measured bremsstrahlung spectrum almost agrees with theoretical spectrum. Hence in the Figs. 12–14, theoretical effective absorption coefficient of Bremsstrahlung agrees with the evaluated values of effective absorption coefficient from measured spectrum. The measured $\mu_B(E)$ is fitted with first order exponential decay and it is given as

$$\mu_B = \mu_{B0} + A_1 \exp\left(-E/t_1\right) \qquad (7)$$

here, μ_{B0}, t_1 and A_1 are Bremsstrahlung attenuation fitting constants. These values are given in Table 3. The errors given in this table is the errors associated with the fitting. This numerical equation is useful to calculate μ_B of ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in NaI and CsI detector compounds for the given energy (10 keV to 2200 keV). The gamma attenuation coefficients of NaI and CsI for the

Table 3
Exponetial decay fitting constants(μ_{B0}, t_1 and A_1) for effective absorption coefficient of Bremsstrahlung.

Source	Target	Parameter	Value	Error	χ^2	R^2
^{90}Sr–^{90}Y	NaI	μ_{B0}	0.22413	±0.00012	9.8074E−8	0.99993
		A_1	0.35685	±0.00388		
		t_1	162.75558	±1.34679		
^{90}Sr–^{90}Y	CsI	μ_{B0}	0.25426	±0.00014	1.307E−7	0.99994
		A_1	0.43566	±0.00456		
		t_1	161.53821	±1.27997		
^{204}Tl	NaI	μ_{B0}	0.82014	±0.00078	5.3014E−6	0.99992
		A_1	4.14854	±0.04422		
		t_1	63.03838	±0.38594		
^{204}Tl	CsI	μ_{B0}	0.98738	±0.00098	8.2713E−6	0.99992
		A_1	5.12754	±0.0553		
		t_1	63.01206	±0.39016		
^{147}Pm	NaI	μ_{B0}	14.97238	±0.03968	0.01238	0.99654
		A_1	16.73171	±0.61219		
		t_1	22.25582	±0.73924		
^{147}Pm	CsI	μ_{B0}	14.97238	±0.03968	0.01238	0.99654
		A_1	16.73171	±0.61219		
		t_1	22.25582	±0.73924		

Table 4
Polynomial fitting constants (m_0, m_1, m_2, m_3 and m_4) for gamma attenuation coefficients.

Parameter	NaI	CsI
m_0	5.9463	6.6677
m_1	−6.7254	−8.2611
m_2	3.9271	5.6694
m_3	−1.3991	−2.1481
m_4	0.1897	0.2935

same energy region were computed. It is possible to fit the following fourth order polynomial relation to the linear attenuation coefficient of gamma for the same energy region (10 keV to 2200 keV).

$$Log\,(\mu) = \sum_{i=0}^{i=4} m_i [Log\,(E)]^i \qquad (8)$$

where m_i is the polynomial fitting coefficient and it can takes the values m_0, m_1, m_2, m_3 and m_4 for fourth order. i represents the order of the polynomial fit and it takes the values from 0 to 4. These evaluated polynomial fitting coefficients (m_0, m_1, m_2, m_3 and m_4) are shown in Table 4. From Eqs. (7) and (8), it is clear that the Effective absorption coefficient of Bremsstrahlung exponentially decay with the energy (not single exponential term) where as gamma attenuation does not follow the exponentially decay with the energy. This is due to the continuous nature of Bremsstrahlung spectrum which undergoes a change in its shape on passing through target. In case of CsI, there is Iodine K absorption edge at 33.169 keV and the cesium K absorption edge at 40.443 keV. In case of NaI, there is Iodine K absorption edge at 33.169 keV and the sodium K absorption edge at 1.0722 keV. Hence In the Fig. 14, the kink at the energy of about 40 keV for CsI is due to the cesium and Iodine K absorption whereas the kink for NaI at same energy is due to Iodine K absorption edge only.

Cesium iodide (CsI) and Sodium Iodide (NaI) are mainly used in detectors to detect radiation. There is a possibility of production of secondary EB in the detector itself whenever beta passes through these detectors. This component is normally neglected while carrying out the regular experiment on measurement of primary EB of same or other compound which are normally kept between beta source and the detector. This traditionally neglected

Bremsstrahlung component within the detector itself decreases the efficiency of the detector.

The evaluated and measured Bremsstrahlung yields may be useful to include the correction for Bremsstrahlung component produced within the detector itself which can improves the efficiency of CsI and NaI detectors.

4. Conclusion

The measured Bremsstrahlung spectra produced by beta particles of ^{90}Sr–^{90}Y, ^{147}Pm and ^{204}Tl in CsI and NaI are compared with Tseng–Pratt theory. The experimental results show fairly good agreement with theory at low energy end (less than 5%) of spectrum and some deviation (less than 11%) at higher energy end of beta spectrum for a given beta sources. The Bremsstrahlung energy (I) and photon (I) yields are also calculated using the spectra. The measured Bremsstrahlung yields may be useful to apply corrections, whenever beta particle passes through CsI and NaI detectors. This paper also describes a new procedure for the calculation of effective absorption coefficient of Bremsstrahlung from their spectra which is useful in the Bremsstrahlung attenuation studies in the compound targets. This procedure may be useful to calculate the Bremsstrahlung attenuation coefficient for other beta sources and targets.

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