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Modified atomic number dependence of total bremsstrahlung spectra in compounds

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Abstract: The total bremsstrahlung (BS) generated in compounds of $BaCl_2.2H_2O$, $CuCl_2.2H_2O$, $Pb(CH_3COO)_2.3H_2O$, $PbCl_2$, $Pb(NO_3)_2$, and $CuSO_4.5H_2O$ by ^{90}Sr was investigated using a Si(Li) detector to determine the dependence of the BS spectra on the modified atomic number (Z_{mod}) of compounds in the photon energy range of 1–100 keV. A continuous decrease in the Z_{mod} dependence of the bremsstrahlung spectra in the energy range of 1–30 keV was observed, followed by a slow increase thereafter, i.e. in the range of 30–100 keV. The stronger Z_{mod} dependence of the spectra at low photon energy was expected to be the result of the high intensity of polarization bremsstrahlung (PB) at low photon energy, increased interference of ordinary bremsstrahlung and PB, and interference by bremsstrahlung from different atoms of the compounds in these compounds.

Key words: Z_{mod} dependence, compounds, polarization bremsstrahlung

1. Introduction

Bremsstrahlung is a phenomenon caused by the production of photons resulting from the interaction of charged particles with the atoms of a target material. It is a useful tool for research in many areas like atomic physics, nuclear physics, and plasma and medical physics. The total bremsstrahlung (BS) is generated in a material due to ordinary bremsstrahlung (OB) and polarization bremsstrahlung (PB) in the target material. OB is produced due to the scattering of incident-charged particles in the Coulomb field of the static target nuclei, whereas the production of PB is due to the dynamic response of an atom in an external field of the incident-charged particle. It is necessary to study the formation of the BS spectrum in compound targets by the OB and PB for monoenergetic and continuous beta particles. Furthermore, the dominance of either OB or the PB when building the BS spectra in thick targets can be described at different photon energies to check the accuracy of various theoretical models for the bremsstrahlung energy spectrum.

Bethe and Heitler [1] and Tseng and Pratt [2] presented prominent theories to study OB in different materials. Various experimental studies of OB in pure elements and compound targets are available in literature. Furthermore, some theoreticians believed that PB radiation was also emitted along with OB to produce BS in

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targets. Avdonina and Pratt [3] and Korol et al. [4] gave theoretical models that described the PB contribution in the formation of BS, which was further reviewed in detail by Korol et al. [5] and Amusia [6]. Portilo and Quarles [7] and Singh et al. [8] experimentally verified the presence of PB in pure element targets and Sharma et al. [9] reported the contribution of PB in the BS spectra of lead compounds at a photon energy range of 1–30 keV.

Moreover, experimental investigations in bremsstrahlung were made to explore the relationship of bremsstrahlung spectra with the atomic number (Z) of target atoms at different photon energies using monoenergetic electrons and continuous beta particles. Hippler et al. [10] and Semaan and Quarles [11] studied the bremsstrahlung spectra of different metallic targets at various electron energies and reported a linear relation between OB spectra and the Z of atoms of the target material. Evans [12], and Edwards and Pool [13] performed investigations using beta particles and reported that the bremsstrahlung spectra were independent of the target atom's Z. Dhaliwal [14] reported an increase in the Z dependence of OB spectra of the target atoms, with an increase in photon energy at an energy range above 30 keV and 170 keV for ^{147}Pm and ^{32}P beta emitters, respectively. Singh et al. [15] experimentally checked the Z dependence relationship of bremsstrahlung spectra in metallic targets by beta particles at an energy range of 5–30 keV and reported a strong dependence of BS spectra on the Z of atoms of the target at a low photon energy range. This study verified the presence of PB in metallic targets at a soft energy range. Recently, Czarnecki et al. [16] investigated the bremsstrahlung spectra produced in metallic thick targets by monoenergetic electrons of energy at 4.25 keV and 5 keV and found that the intensity of bremsstrahlung was more strongly dependent on the Z for photons with energy approximately equal to the incident electron energy, and a stronger dependence of bremsstrahlung in thick metallic targets on the Z was observed in cases of high-energy incident electrons. Furthermore, they concluded that the experimentally determined Z dependence was greater than the theoretical results from the penetration and energy loss of positrons and electrons (PENELOPE) code [17] at a low energy range, possibly because of the high intensity of PB in the bremsstrahlung spectrum, as PENELOPE did not simulate the PB contribution in the theoretical results.

In compound targets, Manjunatha and Rudraswamy [18] determined the Z dependence of OB in cadmium and lead compounds using continuous beta particles of ^{90}Sr–^{90}Y, and ^{147}Pm and ^{204}Tl, and a NaI(Tl) scintillation detector at photon energy ranges of 546–2274 keV, 20–180 keV, and 100–700 keV, respectively. A modified atomic number (Z_{mod}) dependence on the photon yield (N) and energy yield (I) was reported to have varied linearly in these thick compound targets. The experimentally determined Z dependence relation was higher than the theoretical values obtained in the theory of Tseng and Pratt [2].

A survey of the literature revealed that there are many studies available that describe the relationship of OB and BS spectra with the Z of target atoms of pure element targets at different energies, but there is a lack of studies about the relationship between BS spectra and Z_{mod} in compounds. The present study will be effective for investigating the relation of BS spectra with the Z_{mod} of compounds and checking the applicability of theoretical models for studying the bremsstrahlung in compound targets. Furthermore, the study will also provide a comparison of the Z dependence of BS spectra in pure elements and in thick compound targets to understand the bremsstrahlung phenomenon more precisely in compounds. This study dealt with the interactions of beta particles of a ^{90}Sr source (end point energy 546 keV) with the compound targets. The bremsstrahlung spectrum of energy studied was 1–100 keV. The experimental results were compared with 2 theoretical models: one model that represented OB and another that represented the BS, which included OB as well as PB. The present study was performed within a low photon energy range (1–100 keV) when compared to that by Goethem et al. [19], where the interactions of the nucleus with protons took place at higher energy (190 MeV); at such high energy, hard multiple scattering takes place, which may suppress the bremsstrahlung. Similarly, the incoherent bremsstrahlung was previously evaluated by Maydanyuk and Zhang [20], which was significant, at high photon energy of a few hundred MeV.

Thick targets of compounds $BaCl_2.2H_2O$, $CuCl_2.2H_2O$, $Pb(CH_3COO)_2.3H_2O$, $PbCl_2$, $Pb(NO_3)_2$, and $CuSO_4.5H_2O$ were used along with a ^{90}Sr beta source and high resolution Si(Li) detector to determine the Z_{mod} dependence of BS spectra in compounds. The compound targets were chosen to cover a low to medium range of Z_{mod} (Table 1). Theoretical results were obtained from the OB theory of Bethe Heitler [1] and Elwert [21], and the OB + PB theory of Avdonina and Pratt [3].

Table 1. Modified atomic number (Z_{mod}) of the thick compound targets.

Thick compound target	Z_{mod}
$CuSO_4.5H_2O$	13.25
$CuCl_2.2H_2O$	18.69
$BaCl_2.2H_2O$	34.96
$Pb(CH_3COO)_2.3H_2O$	42.11
$Pb(NO_3)_2$	50.04
$PbCl_2$	62.95

To make the comparison between the theoretical and experimental results, it was necessary to express the results in S (k, Z_{mod}), i.e. the number of photons of energy k per unit m_oc^2 per beta disintegration in the compounds, which can be evaluated using the relation in Eq. (1):

$$S(k, Z_{\text{mod}}) = \int_{1+k}^{W_{\max}} n_{cor}(W_e^{'}, k, Z_{\text{mod}}) P(W_e^{'}) dW_e^{'}, \tag{1}$$

where n_{cor} (W'_e, k, Z_{mod}) is the bremsstrahlung spectral distribution in the compounds, which can be obtained as follows:

$$n_{cor}\left(W_e^{'}, k, Z_{mod}\right) = RN \int_{1+k}^{W_e^{'}} \frac{d\sigma(W_e, k, Z_{mod})/dk}{(-dW_e/dx)} dW_e, \tag{2}$$

where R is the backscattering factor, N is the total number of atoms per unit volume in the compound target, $P(W_e^{'})$ dW_e is the beta spectrum of the beta emitter obtained from Laslett et al. [22], and Z_{mod} is the modified atomic number of the compounds obtained from Markowicz and VanGriken [23].

The bremsstrahlung photon spectral distribution $n_{cor}\left(W_e^{'}, k, Z_{mod}\right)$ was obtained theoretically using the bremsstrahlung cross-section formula from the Elwert-corrected Bethe Heitler [21] OB theory and Avdonina and Pratt [3] OB + PB theory.

The relation of the bremsstrahlung spectral distribution with Z_{mod} can be expressed through the relation in Eq. (3), by replacing the Z of the atoms by the Z_{mod} of the thick target compounds, as given by Dhaliwal [14].

$$S(k, Z_{mod}) = K(k)(Z_{mod})^n, \tag{3}$$

where n shows the Z_{mod} dependence of the bremsstrahlung spectra and K(k) is the proportionality constant.

Taking the natural log on both sides of Eq. (3), we get:

$$\ln S(k, Z_{mod}) = \ln K(k) + n \ln(Z_{mod}). \quad (4)$$

The above calculations of $S(k, Z_{mod})$ by the OB and OB + PB theories were made with the Fortran computer program for each compound target separately. The plots were drawn between $\ln S(k, Z_{mod})$ and ln (Z_{mod}). The slope of the plot at different photon energies was determined by the least square fitting computer program using the bremsstrahlung spectral distribution from the OB and OB + PB theories. The slope at different energies of the plot was determined, which theoretically described the Z_{mod} dependence of the BS spectra, i.e. a higher slope showed greater Z_{mod} dependence.

2. Experimental details

The experimental BS spectrum of the compound targets generated by the ^{90}Sr beta source was recorded using a Si(Li) detector. The targets of the $BaCl_2.2H_2O$ (185 mg/cm^2), $CuCl_2.2H_2O$ (192 mg/cm^2), $Pb(CH_3COO)_2.3H_2O$ (190 mg/cm^2), $PbCl_2$ (187 mg/cm^2), $Pb(NO_3)_2$ (188 mg/cm^2), and $CuSO_4.5H_2O$ (192.5 mg/cm^2) compounds were prepared to study the bremsstrahlung spectra. The target thickness was selected so that all of the beta particles emitted by beta emitter were stopped by the target.

The experimental set up and method of measurement were almost similar to those in our previous study [9]. Figure 1 shows the experimentally obtained bremsstrahlung spectral distribution in different thick target compounds, which showed the decrease in intensity of BS with the decrease in the Z_{mod} of the compound targets. The relation between the BS spectra and Z_{mod} of the compounds was determined by the slopes of the plots between $\ln S(k, Z_{mod})$ and $\ln(Z_{mod})$ at different photon energies. Figure 2 shows the typical plot to determine the experimental Z_{mod} dependence at a photon energy of 60 keV for the compound thick targets using a ^{90}Sr beta emitter. Table 2 shows the obtained theoretical and experimental values of the slopes to determine the Z_{mod} dependence relationship with bremsstrahlung spectra in the given compounds. The uncertainties in the observed measurements were due to the detector parameters, i.e. the detection efficiency of the detector, electron backscattering, and absorption of the photons in the target. The intrinsic efficiency of the detector used in the study varied from 5% to 7% at 1 keV to 100 keV. Figure 3 depicts the plot of detection efficiency of the detector and photon energy at a range of 1–100 keV.

The errors in the determination of the Z_{mod} index values were mainly due to uncertainty in the least square of the data. The statistical error was less than 2%, as the measurements were recorded over a longer time interval, i.e. 150,000 s for each measurement. Accuracy in the evaluation of the peak detection efficiency of the detector was greater than 3% for the given energy range. The error due to the attenuation coefficient was less than 1% in the given energy range, except near the edges. The total uncertainty in the evaluation of the final results was estimated as less than 10%.

3. Results and discussion

The experimentally measured Z_{mod} dependence of the BS spectra was compared with the results obtained using the OB and OB + PB theories. The experimental results were in accordance with the OB + PB theory at a photon energy range of 1–30 keV and beyond that, at 30–100 keV, the results were a better match with the OB theory. Table 2 shows that the Z_{mod} dependence of the bremsstrahlung spectra was not constant and varied with an increase in photon energy. There was a stronger Z_{mod} dependence of the BS spectra at low photon

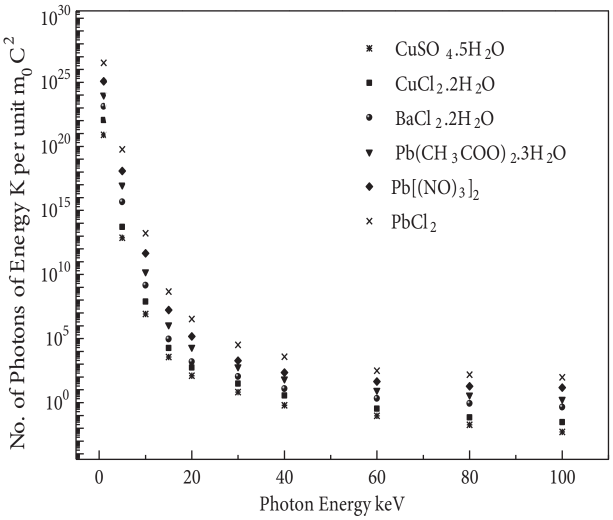

Figure 1. Plot of the number of photons of energy k per unit m_0c^2 vs. the photon energy (keV) for the given compounds for the ^{90}Sr beta particles.

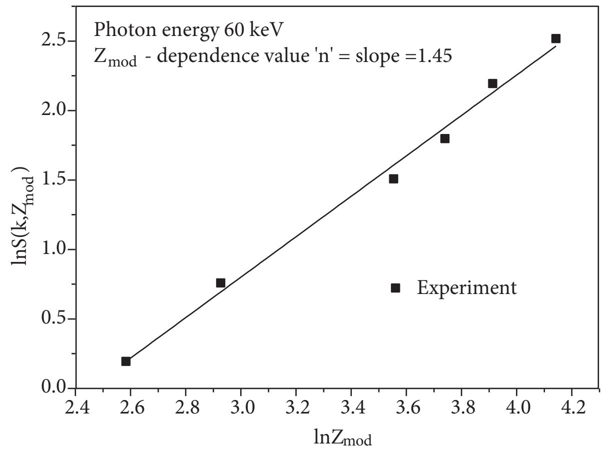

Figure 2. Plot of the ln S(k, Z_{mod}) vs. ln Z_{mod} at a photon energy of 60 keV for the ^{90}Sr beta emitter (symbols are the data points and the line is fit to the points).

Table 2. Z_{mod} dependence index values of the BS spectral photon distribution in thick target compounds (with Z_{mod} values from 13.25 to 62.94) using the Sr^{90} beta source (the shown errors are the errors in the fitting of data).

Photon energy	Z_{mod} dependence values (n)		
	OB theory	OB + PB theory	Experiment
1	2.45	2.54	2.60 ± 0.13
5	2.31	2.45	2.50 ± 0.10
10	2.00	2.26	2.37 ± 0.08
15	1.72	1.88	1.98 ± 0.05
20	1.55	1.70	1.80 ± 0.05
30	1.40	1.37	1.43 ± 0.04
40	1.41	1.23	1.43 ± 0.11
60	1.43	1.25	1.45 ± 0.12
80	1.44	1.28	1.46 ± 0.12
100	1.46	1.32	1.48 ± 0.12

energy and it decreased with an increase at a photon energy range of 1–30 keV, which was due to a decrease in the PB intensity at higher photon energy in the compound targets. A comparison of the present study of compounds with the study of pure element (metallic) targets reported by Singh et al. [15] showed that the intensity of the BS spectra was more strongly dependent on the Z in cases of pure element targets; however, the reported trend was similar. The present results were in agreement with the trend reported by Dhaliwal [14] for Z dependence for pure elements at an energy range of 30–100 keV produced by a ^{147}Pm beta emitter (end point energy 225 keV).

4. Conclusion

PB is an integral part of BS in compounds, which was dominant at a low photon energy of up to 30 keV, and its contribution in the BS spectra cannot be ignored at a soft energy range. The intensity of the BS spectra was a

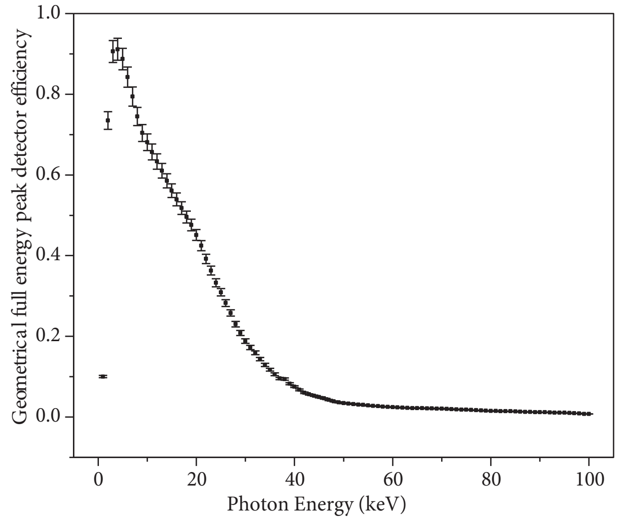

Figure 3. Plot of the geometrical full energy peak detector efficiency of the Si(Li) detector vs. the photon energy in keV.

function of photon energy, Z_{mod} of the compounds, and weight fraction of the atoms in the given compounds. The decrease in Z_{mod} dependence of the BS intensity with an increase in photon energy was due to the low contribution of PB at a high photon energy range, decreased interference between PB and OB at a high photon energy range, and low interference of bremsstrahlung from the constituent atoms of the compounds at high photon energy. Hence, it is necessary for theoretical models to include the OB and PB interference terms in theory to explain more accurately the Z_{mod} dependence of BS spectra in compounds, especially at a soft energy range of 1–30 keV.

Further studies of various other compounds using different beta sources could lead to identifying the deficiencies in theories and reaching more explicit conclusions about Z_{mod} dependence of the BS spectra in thick target compounds.

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