Investigation of polarization bremsstrahlung in thick compound targets of lead in the photon energy region 10-100 keV

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ABSTRACT *Total bremsstrahlung spectral photon distribution in thick compound targets of lead chloride ($PbCl_2$), lead acetate tri hydrate ($Pb(CH_3COO)_2.3H_2O$) and lead nitrate ($Pb(NO_3)_2$) produced by ^{204}Tl beta emitter has been investigated theoretically and experimentally in the photon energy region of 10-100 keV. The comparison of theoretical and experimental results reveals that polarization bremsstrahlung plays a vital role in the formation of total bremsstrahlung spectra in the photon energy region 10-30 keV. The experimental results are in agreement with the F_{mod}BH+PB theory that includes polarization bremsstrahlung in the total bremsstrahlung up to 30 keV and beyond this energy region the results are closer to the F_{mod}BH theory. The polarization bremsstrahlung contribution in the total bremsstrahlung in compounds has been observed to decrease with the increase in photon energy and with the decrease in modified atomic number of compounds.*

Keywords: *Modified atomic number, thick compound targets, polarization bremsstrahlung.*

I. Introduction

Bremsstrahlung is a fundamental process of emission of radiations due to scattering of charged particles with the target atoms. Bremsstrahlung can be generated in materials by the interaction of target atoms with mono energetic charged particles or by continuous beta particles emitted by beta sources. In both the cases characteristic X rays are emitted along with the continuous bremsstrahlung, but in case of continuous beta particles internal bremsstrahlung (IB) is also emitted from the beta source which is a characteristic of beta source. Ordinary bremsstrahlung (OB) is generated due to static behavior of electric field of target atoms towards the projectile electrons. Polarization bremsstrahlung (PB) is generated in the target material due to the polarization of the atoms of target by the charged particles. The intensity of total bremsstrahlung (BS) is the sum of OB and PB intensities.

There are many theoretical studies to investigate the OB spectra in thick targets. In the first order Born approximation, Bethe and Heitler (1934) gave an expression for OB cross section by neglecting the Coulomb field effects on the wave functions of incident and scattered electrons. Elwert (1939) provided a Coulomb correction factor to the Bethe and Heitler cross section. Tseng and Pratt (1971) developed the quantum mechanical theory of bremsstrahlung for relativistic electrons. Pratt et al. (1977) gave the tabulated values of OB cross sections for pure elements with atomic number range of 2-92 for electron energy range 1 keV- 2MeV. Bumistrove and Trakhtenberg (1975) gave the concept of polarization bremsstrahlung by the polarization of target atoms by projectile electrons. Amusia et al. (1985) described that in the stripped atom approximation (SAA), PB can be added to OB in the BS. Further, Avdonina and Pratt (1999) derived an equivalent method to study BS spectra by using SAA.

In the experimental studies in pure element targets, Portillo and Quarles (2003) investigated bremsstrahlung cross sections in gaseous targets of noble gases and proved the contribution of PB in the total bremsstrahlung spectra. Quarles and Portillo (2006) reviewed the experimental studies of rare gas atoms and thin film targets in the OB and BS in the stripped atom approximation. Singh et al. (2010) reported the contribution of PB in the total bremsstrahlung in the thick metallic targets in the low photon energy region up to 30 keV produced by different beta emitters. Singh and Dhaliwal (2015) investigated the total bremsstrahlung spectra in thick metallic targets of Al, Ti, Sn and Pb produced by continuous beta particles in the photon energy range 1-100 keV. The experimental results were in agreement with Avdonina and Pratt (1999) theory that includes PB in the total bremsstrahlung spectra for low photon energy range, for medium and higher photon energy region the modified Bethe Heitler theory was found to be more accurate. These studies strengthened the evidence of presence of PB in the total bremsstrahlung in thick pure metallic targets in the low photon energy region of the spectrum.

Only few studies of bremsstrahlung in compound targets, have been reported so far by using beta particles as compared to the pure elemental targets. Manjunatha and Rudraswamy (2010) investigated the spectral photon distribution in thick compound targets of $PbCl_2$ and CdO by beta particles with the help of NaI(Tl) detector and reported that at low photon energy the results were in good agreement with Tseng and Pratt (1971) theory and deviation from theory was observed at high photon energy. Singh et al. (2017) investigated the bremsstrahlung generated in thick targets of oxides of Lanthanides (Pr_6O_{11}, Gd_2O_3, Tb_4O_7 and Er_2O_3) by continuous beta particles emitted from 89Sr beta source in the photon energy range 1-100 keV. The experimental results were in agreement with the Avdonina and Pratt (1999) theory that includes PB in the total BS up to limited photon energy and varies with the Zeff of the compounds.

The present study describes the BS in thick targets of lead compounds $PbCl_2$ (Z_{mod} = 62.95), $Pb(CH_3COO)_2.3H_2O$ (Z_{mod} = 42.11) and $Pb(NO_3)_2$ (Z_{mod} = 50.04) produced by beta particles of ^{204}Tl beta source (end point energy 765 keV) in the photon energy region 10-100 keV. The experimental results are compared with the theoretical results from Elwert corrected (non-relativistic) Bethe Heitler theory (EBH), modified Elwert factor (relativistic) Bethe Heitler theory (Fmod BH) for OB and modified Elwert factor (relativistic) Bethe Heitler theory (F_{mod} BH+PB) which includes PB into OB by using SAA. The study will reveal the importance of PB in the formation of total bremsstrahlung spectra in thick compound targets by using ^{204}Tl beta source and will determine the accuracy of theoretical models in determination of total BS spectra of thick targets of lead compounds in the energy range 10-100 keV.

The modified atomic number (Z_{mod}) of compounds has been evaluated from the Markowicz and Grieken (1984) formula and is given as

$$Z_{mod} = \frac{\sum_i^l \frac{w_i z_i^2}{A_i}}{\sum_i^l \frac{w_i z_i}{A_i}} \qquad (1)$$

Here, W_i, - weight fraction,
Z_i - atomic weight and
A_i - atomic number of ith element in the compound.

Bethe and Heitler (1934) derived an expression for the bremsstrahlung spectral distribution $n(k, W_e'. Z_{mod})$ in a thick target to absorb an electron of energy W_e' with N atoms per unit volume. The expression for bremsstrahlung spectral photon distribution in thick target of compounds after applying absorption correction is given as

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

Here, $d\boldsymbol{\sigma}(W_e, k, Z_{mod})/dk$ is the singly differential bremsstrahlung cross section and can be obtained from different theoretical models i.e. Elwert corrected (non-relativistic) Bethe Heitler theory (EBH), modified Elwert factor (relativistic) Bethe Heitler theory (F_{mod} BH) for OB and modified Elwert factor (relativistic) Bethe Heitler theory (F_{mod} BH+PB) which includes PB in SAA.
'$(-dW_e/dx)$' - total energy loss per unit path length of electrons in the target material.
'R' is electron backscattering factor.
The BS spectral photon distribution is represented in terms of number of photons of energy k per unit m_0c^2 per beta disintegration and is given by

$$S(k, Z_{mod}) = \int_{1+k}^{W_{max}} n_{cor}(W_e', k, Z_{mod}) P(W_e') dW_e' \qquad (3)$$

Here, $P(W_e')\, dW_e'$ is the beta spectrum of the ^{204}Tl beta emitter and is obtained from Laslett et al. (1950).
At lower photon energy in thick targets, photon absorption correction due to detector elements, air and beryllium window become significant and can't be neglected in the low photon energy region. The expression for spectral photon distribution after applying these corrections is given as

$$S_{cor}(k, Z_{mod}) = RS(k, Z_{mod}) \boldsymbol{\xi}(k) \exp(+\boldsymbol{\mu} x_0) \qquad (4)$$

'μ' - mass attenuation coefficient
'x_0' - optimum thickness of the target which is given by

$$x_0 = (x - R_0) \qquad (5)$$

'x' - target thickness in terms of mg/cm^2
'R_0' - mean range of beta particles in target.
'ξ(k)' - detector efficiency.

Computer programmes are written in Fortran to calculate $S_{cor}(k,Z_{mod})$ by using the bremsstrahlung differential cross section from the above mentioned theoretical models. The total photon yields T was obtained by graphical integration of the BS spectra from the plots of $S_{cor}(k,Z_{mod})$ versus photon energy k between k_{min} (10 keV) and k_{max} (100 keV).

2. EXPERIMENT DETAILS

^{204}Tl (ΔJ=2, yes) is a unique first order forbidden beta source with end point energy 765 keV. The role of polarization bremsstrahlung in the formation of BS by using ^{204}Tl source has never been studied in thick compound targets in the photon energy range 10-100 keV. In the present study, ^{204}Tl beta emitter with activity 200 μCi has been used to study the BS spectral photon distribution in thick targets of compounds $PbCl_2$ (285.2 mg/cm^2), $Pb(NO_3)_2$ (291.9 mg/cm^2), $Pb(CH_3COO)_2.3H_2O$ (295.3 mg/cm^2), with the help of Si(Li) detector. The thickness of targets is chosen according to the range of ^{204}Tl beta emitter (291.6 mg/cm^2) to stop all the beta particles in the target. The experimental set up is shown in figure 1, the lead bricks were used to cover the detector to shield the detector from background and multiple scattering effects. Perspex beta stopper technique has been used to eliminate the contribution from IB, background and bremsstrahlung generated in source material and to record the bremsstrahlung produced in target material only. After the calibration of spectrometer two sets of measurements are taken for a time period of 1,50,000 second each by placing the target at position A and position B (figure 1). The experimentally measured BS spectra in thick compound targets by using ^{204}Tl beta emitter are converted into a true spectrum by applying the corrections due to self absorption of BS photons in the target material and Perspex beta stopper, electron backscattering and geometrical efficiency.

The bremsstrahlung spectra are converted into a common channel width of 1 keV. The electron backscattering factor R and the geometrical full-energy peak detector efficiency was incorporated in the measured bremsstrahlung spectral photon distribution. Further, the experimental bremsstrahlung spectra are converted in the form of number of photons of energy k per unit energy in m_0c^2 units. The final experimental results are expressed in the form of number of photons of energy k per unit m_0c^2 per unit total photon yield $S_{cor}(k,Z_{mod})/T$ to make the experimental results independent of source strength.

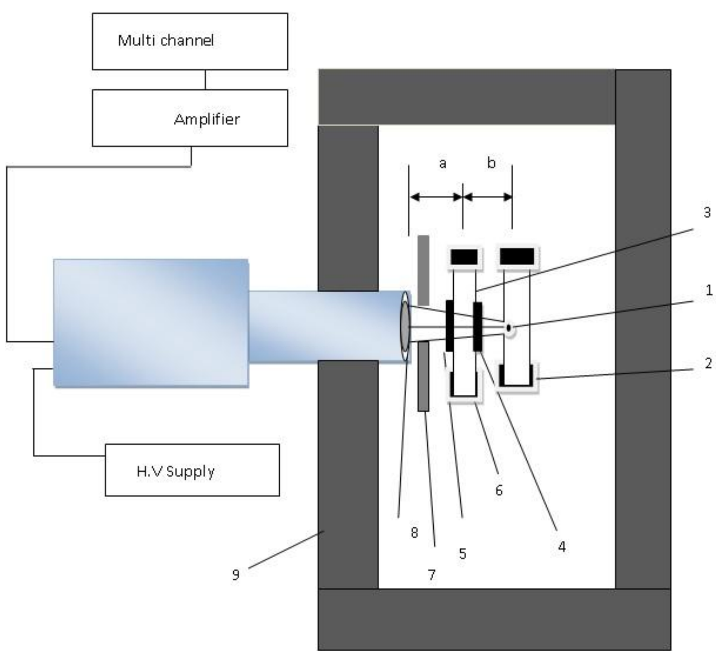

Fig. 1. Experimental set up 1. Beta source 2. Source stand 3. Perspex beta stopper 4. Position A of target 5. Position B of target 6. Perspex stand 7. Lead Collimator (diameter10 mm, length 10 mm) 8. Beryllium window (25 μm, diameter 10 mm) 9. Lead shielding.

'a' – distance of detector from position A of target =5 mm

'b'- distance of source and detector is 16 mm.

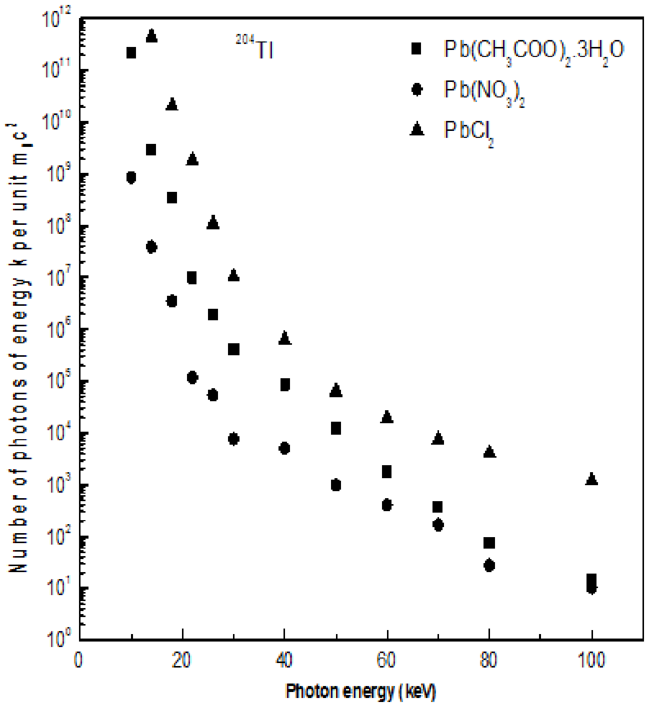

Fig. 2. Plot of number of photons of energy k per unit m_0c^2 versus photon energy (keV).

3 ERRORS

The errors in the experimental measurements are primarily due to the full energy detection efficiency of the detector, counting statistics, electron backscattering and attenuation of bremsstrahlung photons in the target materials. The overall error in the experimental measurements in thick target compounds generated by ^{204}Tl beta particles are less than 12 %. The errors due to statistics of data was better than 2% due to long detection time, uncertainty in the calculation of photo fraction were less than 3% which results an overall error of less than 5% in the geometrical full-energy peak detector efficiency of the detector. The errors in the mass attenuation coefficients of target, beta stopper and air thickness are less than 1%, except near the edge regions. The error in the calculation of modified atomic number (Z_{mod}) from Markowicz and VanGrieken (1984) formula was less than 1%.

4. RESULTS AND DISCUSSIONS

Figure 2 shows the spectral photon distribution in these compound targets obtained experimentally with Si(Li) detector in terms of number of photons of energy k per unit m_0c^2 with the photon energy. Tables 1 and 2 show the theoretically and experimentally obtained values of total bremsstrahlung spectra in terms of total number of photons of energy k per unit m_0c^2 per unit total photon yield i.e. $S_{cor}(k,Z)/T$ in order to remove any uncertainty due to source strength. In case of $Pb(CH_3COO)_2.3H_2O$ (fig. 3) target the experimental data is in agreement with F_{mod}BH+PB theory within 11% up to 30 keV photon energy. The PB contribution is found to decrease from 11% to 1% at 10 keV to 26 keV, photon energy. The experimental results get close to F_{mod}BH theory beyond the photon energy region 30 keV but a significant deviation in results from EBH theory has been observed.

In case of lead nitrate $Pb(NO_3)_2$ (fig. 4) the experiment is in agreement with the F_{mod}BH +PB theory within 8% to 12% from 10 keV to 18 keV, respectively. The deviations of experimental results from F_{mod}BH theory is 21%, 27% and 50% at 22 keV, 50keV and 100keV respectively. The PB contribution is found to decrease with increase in photon energy from 25% to 5% at 10 keV to 26keV photon energy, respectively. The deviations of experimental results from F_{mod}BH theory is 21%, 27% and 50% at 22 keV, 50keV and 100keV respectively. In $PbCl_2$ compound target (fig. 5) the experimental data is in agreement with F_{mod}BH +PB theory within 15% at 10 keV- 27 keV photon energy. The experimental results deviates from F_{mod}BH theory by 41% and 52% at 30 keV and 100 keV, respectively. The PB contribution in this compound varies from 32% to 1% at 10 keV to 26 keV photon energies, respectively.

Table 1. Total bremsstrahlung spectra of lead acetate tri hydrate and lead nitrate thick compound targets in the photon energy region of 10-100 keV by using ^{204}Tl beta source

Photon energy	Number of photons of energy k per unit m_0c^2 per unit total photon yield			
	EBH Theory	F_{mod}BH Theory	F_{mod}BH+PB Theory	Experiment
Target: Lead acetate tri hydrate (Z_{mod}= 42.11)				
10	4.72E-01	7.40E-01	8.31E-01	0.91
14	6.31E-03	9.80E-03	1.08E-02	0.12E-1
18	6.43E-04	1.45E-03	1.56E-03	0.18E-2
22	3.08E-05	2.45E-05	2.53E-05	3.03E-05
30	1.83E-06	3.58E-06	2.82E-06	4.01E-06
40	2.40E-07	5.28E-07	4.09E-07	6.07E-07
60	4.07E-09	8.35E-09	6.19E-09	1.14E-08
80	1.13E-10	2.45E-10	1.55E-10	3.79E-10
100	1.57E-11	5.29E-11	2.97E-11	8.46E-11
Target: Lead nitrate (Z_{mod}= 50.04)				
10	6.40E-01	5.28E-01	7.04E-01	7.65E-01
14	1.88E-02	2.52E-02	3.15E-02	3.50E-02
18	1.35E-03	2.45E-03	2.75E-03	3.13E-03
22	1.39E-04	8.24E-05	8.96E-05	1.05E-04
30	5.38E-06	5.36E-06	4.47E-06	6.87E-06
40	2.29E-06	3.25E-06	2.46E-06	4.48E-06
60	1.76E-07	2.25E-07	1.48E-07	3.61E-07
80	1.06E-08	1.25E-08	7.44E-09	2.48E-08
100	3.36E-09	4.57E-09	2.57E-09	9.17E-09

Table 2. Total bremsstrahlung spectra of lead chloride thick compound target in the photon energy region of 10-100 keV by using ^{204}Tl beta emitter.

Photon energy	Number of photons of energy k per unit m_0c^2 per unit total photon yield			
	EBH Theory	F_{mod}BH Theory	F_{mod}BH+PB Theory	Experiment
Target: Lead chloride (Z_{mod} = 62.95)				
10	2.01E-01	5.11E-01	7.52E-01	8.57E-01
14	2.20E-02	4.08E-02	5.23E-02	8.15E-02
18	1.42E-04	2.98E-04	3.43E-04	2.70E-03
22	4.70E-08	2.15E-07	2.22E-07	9.87E-05
30	9.30E-10	2.70E-09	2.16E-09	3.81E-07
40	3.03E-11	1.59E-10	1.24E-10	1.44E-08
60	3.97E-13	5.52E-12	3.68E-12	2.12E-09
80	1.26E-14	9.16E-13	5.72E-13	9.71E-10
100	3.03E-15	5.76E-13	3.39E-13	6.32E-10

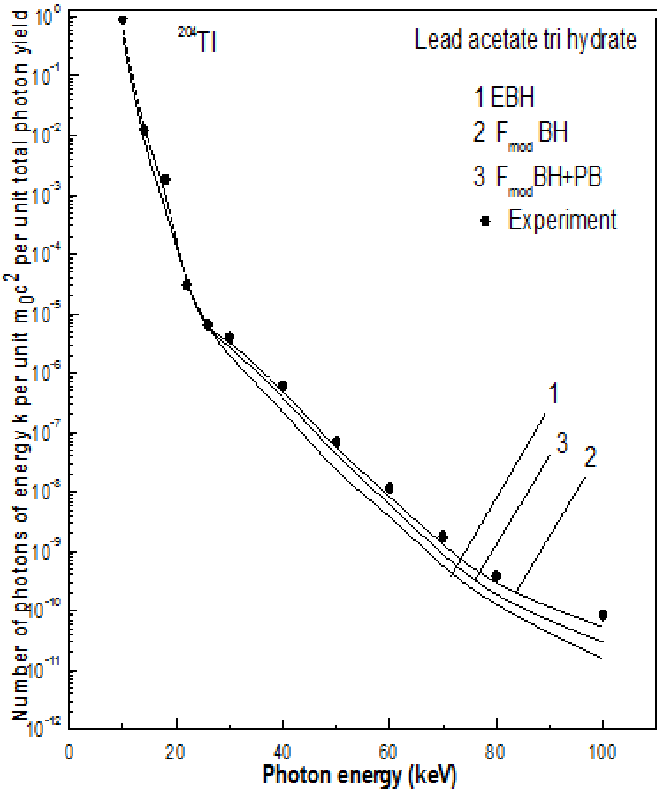

Fig. 3 Plot of number of BS photons of energy k per unit m_0c^2 per unit photon yield for lead acetate tri hydrate target in the photon energy region of 10-100 keV.

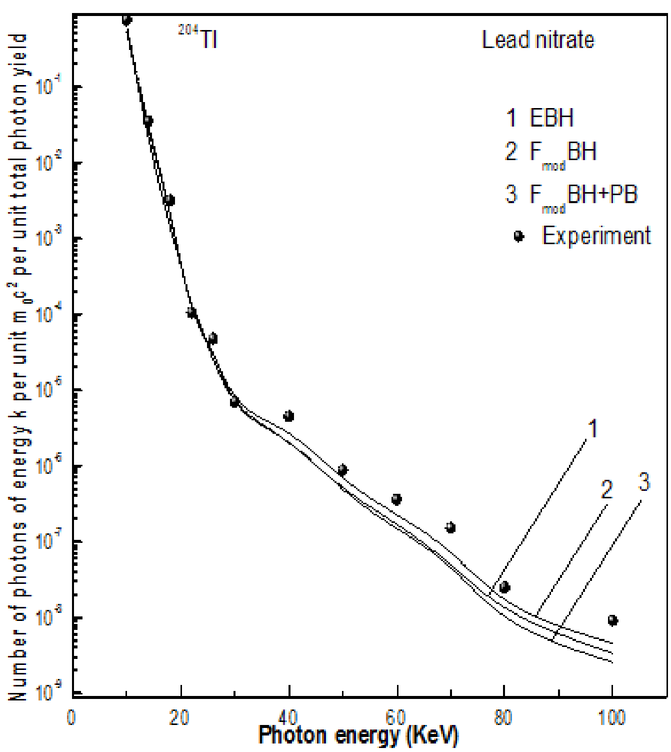

Fig. 4 Plot of number of BS photons of energy k per unit m_0c^2 per unit photon yield for lead nitrate target in the photon energy region of 10-100 keV

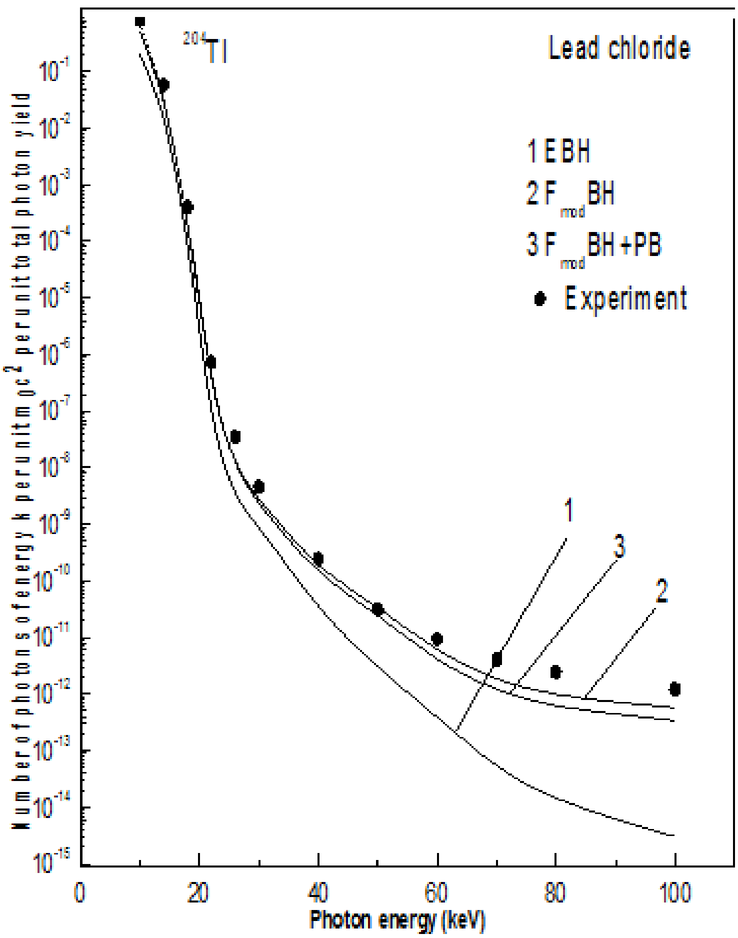

Fig. 5 Plot of number of BS photons of energy k per unit m_0c^2 per unit photon yield for lead chloride target in the photon energy region of 10-100 keV.

5. CONCLUSIONS

F_{mod}BH+PB is an accurate theory to study the total BS in thick compound targets of lead of higher modified atomic number (Z_{mod}) in the photon energy region 10-30 keV. It concludes that PB plays a significant role in the formation of total BS in compounds up to photon energy 30 keV. In the photon energy region 30-100 keV, the experimental results are close to F_{mod}BH than F_{mod}BH+PB theory showing that PB varies with the photon energy and vanishes beyond the photon energy 30 keV. The significant positive deviation of experimental results from F_{mod}BH + PB theory is expected due to interference of PB and OB, multiple photon scattering and anisotropic absorbance properties of compounds in this photon energy region. The PB contribution is higher in compound targets of higher modified atomic number (Z_{mod}).

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References

[1] Amusia, M., Kuchiev, M., Korol, A. and Solov'ev, A. 1985. Bremsstrahlung of Relativistic Particles and Dynamic Polarizability of Target Atom. Sov. Phys. JETP, 61: 224-227.

[2] Avdonina, N. B. and Pratt, R. H. 1999. Bremsstrahlung Spectra from Atoms and Ions at Low Relativistic Energies, J. Phys. B: At. Mol. Opt. Phys., 32: 4261-4276.

[3] Bethe, H. and Heitler,W. 1934. On the Stopping of Fast Particles and On the Creation of Positive Electrons, Proc. Roy. Soc. Lond. A, 146: 83–112.

[4] Buimistrov, V. and Trakhtenberg, L. 1975. Bremsstrahlung Cross Section in Scattering of Electrons by a Hydrogen Atom, Sovt. Phys. JETP, 42: 54-57.

[5] Elwert,G. 1939. Verschärfte Berechnung Von Intensität und Polarization Im Kontinuierlichen Röntgenspektrum, Ann. Phys., 34: 178–208.

[6] Laslett, J., Jensen, E., Paskin, A. 1950. First-Forbidden Spectra and the Beta Spectrum of ^{90}Sr-^{90}Y, Phys. Rev., 79: 412-412.

[7] Manjunatha, H.C., Suresh, K.C., and Rudraswamy, B., 2010. External Bremsstrahlung of ^{147}Pm in $PbCl_2$ and CdO, Nuclear Instruments and Methods in Physics Research A, 619: 326–329.

[8] Markowicz, A.A. and VanGrieken R.E. 1984. Composition Dependence of Bremsstrahlung Background in Electron-Probe X-ray Microanalysis, Anal. Chem., 56: 2049-2051.

[9] Portillo, S. and Quarles, C.A. 2003. Absolute Doubly Differential Electron Bremsstrahlung Cross Sections from Free Atoms, AIP Conf. Proc., 680: 115-120.

[10] Pratt, R., Tseng, H., Lee, C., Kissel, L., MacCallum, C., and Riley, M. 1977. Bremsstrahlung Energy Spectra from Electrons of Kinetic Energy 1 keV to 2000 keV Incident on Neutral Atoms $2\leq Z \leq 92$, At. Data Nucl. Data Tables, 20: 175-209.

[11] Quarles, C. and Portillo, S. 2006. Review of Absolute Doubly Differential Cross Section Experiments and Cross-Section Ratios for Electron Bremsstrahlung from Rare Gas Atom and Thin-Film Targets, Rad. Phys. Chem., 75: 1187–1200.

[12] Singh, A., Dhaliwal, A.S. 2015. Studies of Polarization Bremsstrahlung and Ordinary Bremsstrahlung from ^{89}Sr Beta Particles in Metallic Targets in the Photon Energy Region of 1–100 keV, Phys. Lett. A, 379: 1127–1132.

[13] Singh, A., Singh, T., Dhaliwal, A.S. 2017. Studies of Total Bremsstrahlung Spectra in the Oxides of Lanthanides, Radiation Physics and Chemistry, 141: 207-212.

[14] Singh, T., Kahlon, K. S. and Dhaliwal, A. S. 2010. Total Bremsstrahlung Spectra in Targets of Al, Ti, Sn and Pb Produced by Complete Absorption of ^{90}Sr β Particles, X Ray Spectrom, 39: 291-295.

[15] Tseng, H. and Pratt, R. 1971. Exact Screened Calculations of Atomic-Field Bremsstrahlung, Phys. Rev. A., 3: 100–115.