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Studies of total bremsstrahlung in thick targets of Al, Ti, Sn and Pb for ^{90}Sr beta particles in the photon energy region of 1–100 keV

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HIGHLIGHTS

- Thick targets BS for ^{90}Sr beta particles are measured with Si(Li) detector.
- PB contribution in low energy region, its variation with Z of target is established.
- BS spectrum at high energy regions in SA approximation needs further considerations.
- Screening and secondary effects in a target are important in the BS process.

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ABSTRACT

Total bremsstrahlung (BS) spectra in thick targets of Al, Ti, Sn and Pb produced by beta emitter ^{90}Sr (End point energy=546 keV) are studied in the photon energy range of 1–100 keV. The experimentally measured BS spectra are compared with the theoretical spectral distributions calculated from Elwert corrected (non relativistic) Bethe–Heitler [EBH] theory, modified Elwert factor (relativistic) Bethe–Heitler [F_{mod} BH] theory for ordinary bremsstrahlung (OB) and the Avdonina and Pratt [F_{mod} BH+PB] theory, which include the contribution of polarization bremsstrahlung (PB) into OB. The present results are indicating the correctness of F_{mod} BH+PB theory in the low energy region, where PB dominates into the BS, but at the middle and higher photon energy region of the bremsstrahlung spectrum, the F_{mod} BH theory is more close to the experimental results. The description of the bremsstrahlung process in stripped atom (SA) approximation, which indicates the suppression of the bremsstrahlung at higher energy ends due to the production of PB in the low energy region, needs further considerations. Hence, the present measurements for BS for different target materials indicates that the considerations of the screening effects along with other secondary effects during the interaction of incident electrons with the target nuclei are important while describing the production of bremsstrahlung, particularly for the higher energy regions.

1. Introduction

The thick target bremsstrahlung studies have been undertaken by the number of authors for mono-energetic electrons (Goel and Shanker, 1997; Semaan and Quarles., 2001; Berger and Motz, 2004; Agnihotri et al., 2008; Lixia et al., 2009) and for continuous beta particles (Rudraswamy et al., 1984; Gopala et al., 1988; Dhaliwal et al., 1991, 1993; Dhaliwal, 2002) for various targets and for different electron energies. In the present communication, the investigation of thick target bremsstrahlung energy spectra of Al, Ti, Sn and Pb are made for ^{90}Sr ($\Delta J=2$, yes); a unique first forbidden beta emitter. This beta emitter finds an extensive application in medicine as a radioactive source for superficial radiotherapy of some cancers and as radiotracers in the field of medicine (Iftimia et al., 2004; Cohen et al., 2013).

The consideration of the bremsstrahlung in the domain of a deacceleration of electron in the static screened coulomb field of the target nuclei is termed as ordinary bremsstrahlung (OB). The polarization bremsstrahlung (PB) is produced due to the change in dipole-moment of the system from the polarization of the target atom by the incident electron. PB is more complex than the OB process, as in addition to the electron–photon interaction, one has to consider the dynamic response of the target atom created by the action of the two fields produced by the incident electron and the emitted photon.

Amusia et al. (1985, 1986) have initially derived the clear physical picture of stripped atom (SA) approximation for describing the PB in a target, and later Avdonina et al. (1986) confirmed it

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with their numerical calculations within the framework of non-relativistic Born approximation. It has been described that in SA approximation, the decrease of OB due to screening of outer shell electrons is completely compensated by additional PB produced by the same outer shell electrons. Later, Korol et al. (1992) extended the SA approximation beyond the Born approximation and applied it to the case of intermediate energy projectile electrons. With the use of distorted partial wave approximation (DPWA), the stripping effect was established for the high photon energy region (photon energy greater than the ionization potential of 1 s shell). Nuclear field contributes effectively to the total bremsstrahlung in this limit. Korol et al. (1999) gave a general approach to describe the case of all possible photon energies in the non-relativistic region of the incident electron energies. Avdonina and Pratt (1999) simplified the complex problem of the exact assessment of the total bremsstrahlung from atoms and ions at non-Born incident electron energies. In this approach direct application of the results of SA approximation was made to the region of low relativistic energies where the Born approximation was not valid. The advantage of this approach is that it decreases the direct calculations of the bremsstrahlung amplitude to the analysis of the free-free dipole photon matrix elements of OB in a point Coulomb field and in the screened Coulomb potentials. Korol et al. (2002) and Avdonina and Pratt (1999) have given the equivalent method for the BS spectra in SA approximation. SA approximation approach neglects the specific structure of the bremsstrahlung cross-section near each sub shell threshold, where polarization bremsstrahlung often becomes large in comparison with OB.

In the literature Singh et al. (2010, 2012) investigated the OB and BS spectral distributions in thick targets of Al, Ti, Sn and Pb in the photon energy region of 5–10 keV and 10–30 keV with X-PIPS Si(Li) detector by ^{90}Sr beta emitter. They indicated the importance of PB in building the BS spectra in target materials and reported an agreement between their measurements with the modified theoretical approach of Avdonina and Pratt (1999) for BS, which includes contribution of PB. Further, they also observed that the contribution of PB into OB decreases with increase in end-point energy of beta emitter and the energy of the emitted photon. However, for ^{90}Sr beta emitter, these measurements are inadequate to describe the accuracy of various theories for OB and BS in the photon energy region of 1–100 keV. The present measurements are carried out with a high resolution and good efficiency Si(Li) detector in the photon energy region of 1–100 keV. The uncertainties due to escape peaks and the Compton continuum are very small in these measurements and hence may ascertain the accuracy and reliability of the present experimental measurement, especially for low photon energies. In the present paper, OB and BS studies in Al, Ti, Sn and Pb targets with ^{90}Sr beta emitter in the photon energy region of 1–100 keV are carried out. These studies shall be useful to check the correctness of various theories for OB and BS processes, and may further define the energy range up to which the PB contributes into the bremsstrahlung spectrum formation for different target materials.

2. Theory

For OB, Avdonina and Pratt (1999) incorporated the modified Elwert correction factor to the (non relativistic) Bethe and Heitler theory. Further, they described the formation of BS energy spectra having the contributions of both, i.e., OB and PB over a wide range of the photon energy region by using SA approximation. In their modified approach the Avdonina and Pratt (1999) described that in the soft photon energy region of the bremsstrahlung energy spectrum the contribution of PB is larger than in the hard photon energy region of the spectrum. PB effect will decrease to zero with increasing photon energy and will also vary with the change in the atomic number of the target material. Further, it has also been described that the production of PB in the low energy region due to the dynamic response of the target atom suppresses the production of bremsstrahlung at higher energy ends.

Avdonina and Pratt (1999) gave an analytical expression for soft and hard photon energy region of the BS energy spectrum in terms of Gaunt factor, $G_{BS}(W_e, k, Z)$,

$$G_{BS}(W_e, k, Z) = G_B(W_e, k, Z) - \frac{\sqrt{3}}{\pi}\ln\left(\frac{q_+}{q_-}\right) + G_{OB}(W_e, k, Z) \tag{1}$$

Here, the first term $G_B(W_e, k, Z)$ is the bremsstrahlung energy spectrum for neutral atom in the Born approximation with screening parameter $\lambda_o^2 = 0.798Z$, $q_\pm = p_i \pm p_f$ is the maximum and minimum momentum transfer, Z is the atomic number of the target material and $G_{OB}(W_e, k, Z)$ is the modified corrected OB energy spectrum, given as,

$$G_{OB}(W_e, k, Z) = C(T_i, Z)F_{\text{mod}}G_{BH}(W_e, k, Z) \tag{2}$$

where, F_{mod} is the modified Elwert factor, $C(T_i, Z)$ is the higher order Born approximation factor which includes the multiple scattering effect to some extent and $G_{BH}(W_e, k, Z)$ is the Gaunt factor for the Bethe–Heitler cross-section.

Thick target bremsstrahlung depends upon both the thin target bremsstrahlung cross-section and the electron energy loss and scattering in the target and the effect of secondary electron in the target. In order to calculate the bremsstrahlung energy spectrum in thick targets an expression $n(W_e^{\prime}, k, Z)$ for a target with N number of atoms per unit volume to absorb a mono-energetic electron of energy $W_e^{\prime}$ has been modified in accordance with the expression given by Semaan and Quarles (2001) for incorporating the affects of electron backscattering factor (R) into the theoretical considerations.

$$n(W_e^{\prime}, k, Z) = NR\int_{1+k}^{w_e^{\prime}} \frac{d\sigma(W_e, k, Z)/dk}{(-dW_e/dx)}dW_e \tag{3}$$

Here the values of $d\sigma(W_e, k, Z)/dk$, i.e., the singly differential bremsstrahlung cross-sections are taken from Elwert corrected (non relativistic) Bethe–Heitler [EBH] and modified Elwert factor (relativistic) Bethe–Heitler [F_{mod} BH] theories for OB and, Avdonina and Pratt [F_{mod} BH+PB] theory, which include the PB into OB in SA approximation, separately. The singly differential bremsstrahlung cross-section is considered due to the experimental measurements are taken for a target at an angle of 180° to incident electrons only. $-dW_e/dx$ is the total energy loss per unit path length (collision stopping power and the radiation stopping power of the electrons), i.e., the average energy loss per unit path length, due to inelastic Coulomb collisions resulting in the emission of bremsstrahlung of an electron in a target material. Values of total energy loss per unit path length of an electron are taken from the tabulations by Berger and Seltzer (2000). In addition, the electron backscattering factor is incorporated while calculating the thick target bremsstrahlung energy spectrum.

Here the self absorption correction for a thick target for obtaining theoretical and experimental results, separately for comparison of bremsstrahlung spectral photon energy distributions does not affect the shape of the bremsstrahlung energy spectrum at different photon energies, as incorporated in a semi-empirical relation for $n(W_e^{\prime}, k, Z)$ by Semaan and Quarles (2001). This has been verified after applying the self absorption corrections for different materials by using the tabulated values for mass attenuation coefficients, given by Chantler et al. (2005) (version 2.1).

Further, for continuous beta particles, the bremsstrahlung spectral photon distributions in an optimum thick target for OB and BS are given by $S(k, Z)$, i.e., the number of photons of energy k