Nuclear Instruments and Methods in Physics Research B 318 (2014) 23–26

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research B

journal homepage: www.elsevier.com/locate/nimb

Bremsstrahlung in carbon thick targets by proton incidence

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ARTICLE INFO

Article history:
Received 14 March 2013
Received in revised form 7 May 2013
Accepted 13 June 2013
Available online 20 July 2013

Keywords:
X-ray bremsstrahlung
Proton impact
PIXE
Atomic bremsstrahlung

ABSTRACT

The subtraction of the continuum from an X-ray spectrum emitted by proton bombardment is usually carried out by means of a mathematical fitting. The purpose of the present work is to develop an analytical function to model the continuous spectrum generated in a PIXE experiment for different incident beam energies in carbon thick targets. With this purpose, PIXE spectra of a carbon bulk sample were measured in an ion accelerator. The proton beam energies were varied between 0.7 MeV and 2 MeV and the X-rays generated were collected by an energy dispersive spectrometer. The spectra analysis was performed taking into account the main effects underlying the production of the continuous spectrum. Nevertheless, for the cases considered here, it was found that the atomic bremsstrahlung is the most important and other contributions were neglected. The experimental spectra from carbon thick targets were corrected by self-absorption and detector efficiency. The results show that the spectral shape corresponding to thick targets corrected by these effects is similar to the functional behavior presented by thin targets.

1. Introduction

The subtraction of the continuum from an X-ray spectrum emitted by proton bombardment is usually carried out by means of a mathematical fitting [1]. Sometimes, this procedure leads to good fittings, although it does not allow to distinguish which counts belong to a peak and to the continuum. A fitting model that includes more physical features could solve this problem. The purpose of this work is to develop an analytical function to model the continuous spectrum generated in a PIXE experiment for carbon thick targets.

The choice of low Z targets is useful because they are often selected as substrates for the analysis of thin targets. The continuous background generated in these configurations is mainly given by the substrate bremsstrahlung.

Some theoretical expressions for the continuous spectra were developed by other authors [2]. Usually, four continuous X-ray production mechanisms are taken into account. These mechanisms are: Secondary Electron Bremsstrahlung (SEB), Quasi Free Electron Bremsstrahlung (QFEB), Nuclear Bremsstrahlung (NB) and Atomic Bremsstrahlung (AB) [3–5]. Even assuming thin flat targets, the resulting expressions are very complex and some approximated versions were also given [6]. In this work, a semi-empirical approach is presented for thick carbon targets.

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http://dx.doi.org/10.1016/j.nimb.2013.06.048

2. Materials and methods

PIXE spectra were measured using the High Voltage Engineering Tandetron 3 MV ion accelerator of the “Laboratório de Implantação Iônica” in the “Universidade do Rio Grande do Sul” (Porto Alegre – Brazil).

The spectra were measured using a carbon thick target at proton energies (E_0) of 0.7, 0.8, 0.9, 1, 1.2, 1.5, 1.8 and 2 MeV. The X-rays generated were collected by an energy dispersive spectrometer (EDS) with a Si(Li) detector. No filter was used in order not to add uncertainties to the prediction of the generated bremsstrahlung. On the other hand, the detection dead time was kept always lower than 5% to avoid pile up and any other kind of detection artifact, which could hamper the spectra analysis. For these reasons, very low beam currents were used. The total charge Q collected varied between 0.02 and 0.25 μC (beam current values between 0.03 and 0.42 nA).

The carbon target was a pure planchet for analytical purpose, thus, its spectra were almost clean of X-ray lines due to impurities.

The solid angle $\Delta\Omega$ subtended by the detector was determined with the help of a photography of the sample chamber (see Fig. 1). It can be expressed as:

$$\Delta\Omega = \frac{A}{R^2}$$

where the available Si crystal area A is 63.6 mm^2, according to the manufacturer, and the sample-detector distance $R = (44.4 \pm 1.0)$ mm was

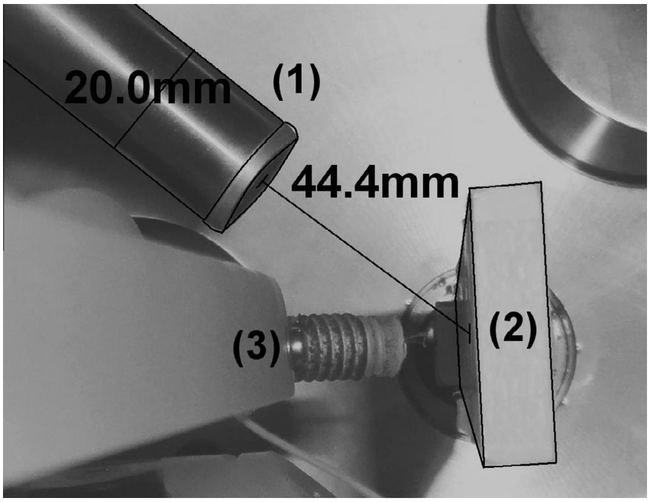

Fig. 1. Photography of the experiment set up. (1) EDS detector, (2) sample holder and (3) proton beam.

obtained by normalizing the corresponding length in the picture with ratio between the depth of the sample holder measured with a caliper and the one determined in the picture. Assuming an uncertainty of 0.1 mm^2 in A, the value obtained for the solid angle was $\Delta\Omega = (0.032 \pm 0.001)$ str.

The detector front window is made of Be (12.5 μm nominal width) in order to protect the inner components from backscattered particles. The contact is made of a Ni thin layer and there is no dead layer in the crystal, but only a charge reflection layer whose attenuation effects are taken into account by assuming a Ni layer thickness of 12 nm, according to the manufacturer.

3. Spectral processing

The measured spectra were processed considering the collected charge, detector efficiency and X-ray absorption within the sample. The collected charge was used to obtain the number of incident protons to normalize the spectra. The detector efficiency involves two aspects: the solid angle subtended by the crystal and the intrinsic efficiency. The different components of the detector and their thicknesses were obtained from manufacturer data.

Each mechanism contributing to the continuous spectrum presents a threshold energy which is the maximum energy that can be transferred to an electron in a direct collision with an incident proton:

$$T_{\mathrm{SEB}} = 4\frac{m_e}{m_p}E_p = 4T_{\mathrm{QFEB}}, T_{\mathrm{QFEB}} = \frac{1}{2}m_e V_{p^2}$$

where m_e and m_p are the electron and proton mass and E_p and V_p are the incident proton energy and velocity [7]. In the range of incident energies studied in this work, T_{QFEB} is below 1 keV or around. Therefore QFEB effect was neglected because the Be window inhibits X-ray detection in the low energy region. On the other hand, T_{SEB} for 2 MeV incident protons is 4.36 keV. It should be noted that the probability that a proton transfers the maximum energy T_{SEB} to an electron and also that this electron emits all its kinetic energy as a bremsstrahlung photon is very low. These reasons allowed to disregard SEB respect to AB. Then, it was considered that AB is the most important contribution to the continuous spectrum.

Bearing in mind that the AB mechanism involves an electron decay to an atom vacancy, it was assumed that the number of AB photons generated in the sample is proportional to the number of ionized atoms. This rough approximation allowed to link the depth distribution ionization function with the regions of bremsstrahlung generation. According to Ishii et al. [8] the main contribution to AB above the energy of a K peak is due to K-shell electrons. Therefore, the number N of ionized atoms as a function of the penetration depth z can be considered proportional to the K-shell ionization cross section $\sigma(E)$:

$$N(z) \propto \sigma(E(z)) \tag{1}$$

The proton energy E can be related to z by means of the stopping power $S = -(1/\rho)dE/dz$:

$$E(z) = \int_0^z -\frac{1}{\rho}\frac{dE}{dz'}dz'$$

where ρ is the material density.

The function given in Eq. (1) was calculated for carbon using data of σ and S given by Lapicki [9] and Berger [10], respectively; the results are shown in Fig. 2. As it can be seen from the figure, the dependence of the number of ionized atoms with depth can be reasonably approximated by a step function whose threshold matches with the proton range.

If X-ray fluorescence in the sample is neglected, the background intensity B_e emitted from the sample surface (by AB mechanism) can be described by:

$$B_e = \int B_g(z)A(z)dz \tag{2}$$

where $B_g(z)$ is the continuous spectrum generated by a thin layer at depth z and $A(z) = \exp(-(\mu/\rho)(\rho z)\mathrm{cosec}(\psi))$ is the corresponding attenuation factor when the detector is placed forming an angle ψ with the surface normal and μ is the carbon X-ray attenuation coefficient. Assuming the step model for $B_g(z)$ and solving the integral of Eq. (2), the generated bremsstrahlung can be obtained from the experimental data:

$$B_g = \frac{\mu\mathrm{cosec}(\psi)}{1 - \exp[-(\mu/\rho)(\rho z_{\max})\mathrm{cosec}(\psi)]}B_e$$

where $z_{\max}$ is the depth obtained with the method explained before. It is worth remembering that B_e can be obtained from the

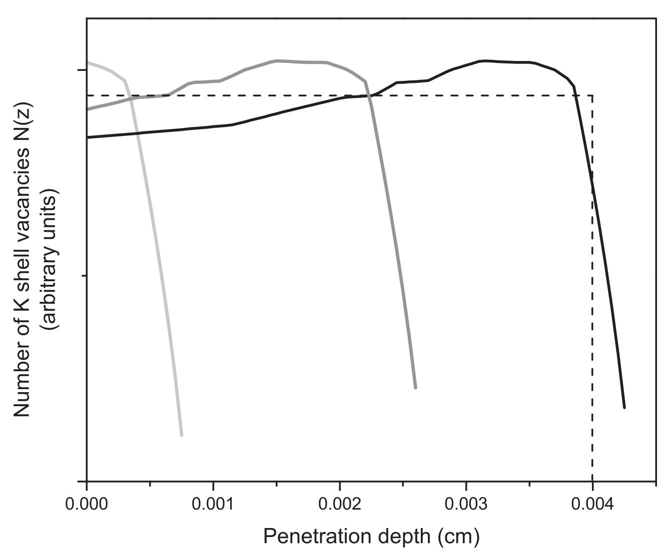

Fig. 2. Number of K-shell vacancies as function of depth for several incident energies: 2 MeV (black solid line), 1.5 MeV (gray solid line) and 0.7 MeV (light gray solid line). The dashed line is the step function that approximates the 2 MeV situation.

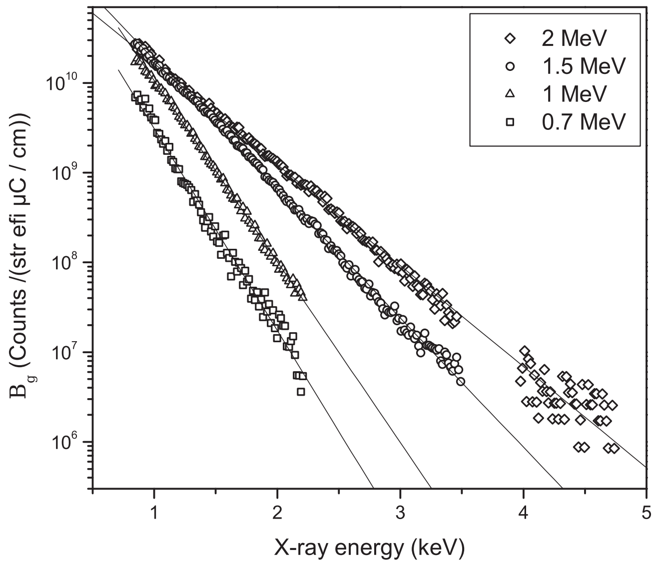

Fig. 3. Bremsstrahlung spectra of carbon generated within the sample for several incidence proton energies. Only four curves are plotted for clarity.

background intensity B_m measured by the detector, normalizing by the incident charge and detector efficiency:

$$B_e = \frac{B_m}{Q\varepsilon\Delta\Omega/4\pi}$$

where the detector intrinsic efficiency ε can be expressed as:

$$\varepsilon = \exp[-(\mu_{Be}x_{Be} + \mu_{Ni}x_{Ni})] \tag{3}$$

The attenuation coefficients μ_{Be} and μ_{Ni} refer to the Be window and the Ni contact, respectively. Layer thicknesses x, corresponding also to the mentioned components, are given in Section 2. The active crystal is thick enough that there is no need to consider photon transmission through the detector.

The modified spectra B_g are shown in Fig. 3.

4. Results

According to Murozono et al. [6] the differential cross section of AB X-ray production σ_{AB} can be expressed as:

$$\sigma_{AB} = \exp(P_{1AB} + P_{2AB}\hbar\omega) + \exp(P_{3AB} + P_{4AB}\hbar\omega)$$

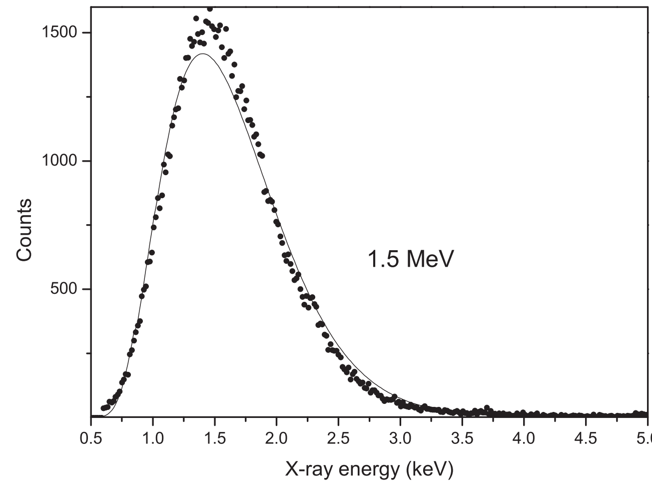

Fig. 5. Bremsstrahlung spectrum produced by 1.5 MeV protons in a bulk carbon target. Dots: experimental spectrum measured with a Si(Li) detector; line: prediction given by the proposed model.

where $\hbar\omega$ is the energy of the generated photon, the coefficients P are constants for each incident energy. The two exponentials consider the contributions of K and L atom shells.

As mentioned before, in this case only the K-shell is considered. Then the following model is proposed for predicting the continuous spectrum:

$$\log(B_g) = A + B\hbar\omega \tag{4}$$

where A and B are constants and log is the base-10 logarithm.

The modified spectra plotted in Fig. 3 in logaritmic scale were properly fitted by linear functions according to the behavior assumed in Eq. (4). The A and B parameters show a smooth behavior with E_0 (see Fig. 4).

Although the expression proposed by Murozono et al. is based on continuous spectra produced by thin targets, it was observed that the trend may be extended to bulk samples if the spectrum is modified as stated in Section 3.

It is interesting to perform a comparison between the measured spectra and the ones predicted here. To this end, the spectra generated within the target, predicted by Eq. (4), must be multiplied by the attenuation factor $A(z)$, defined below Eq. (2), the intrinsic

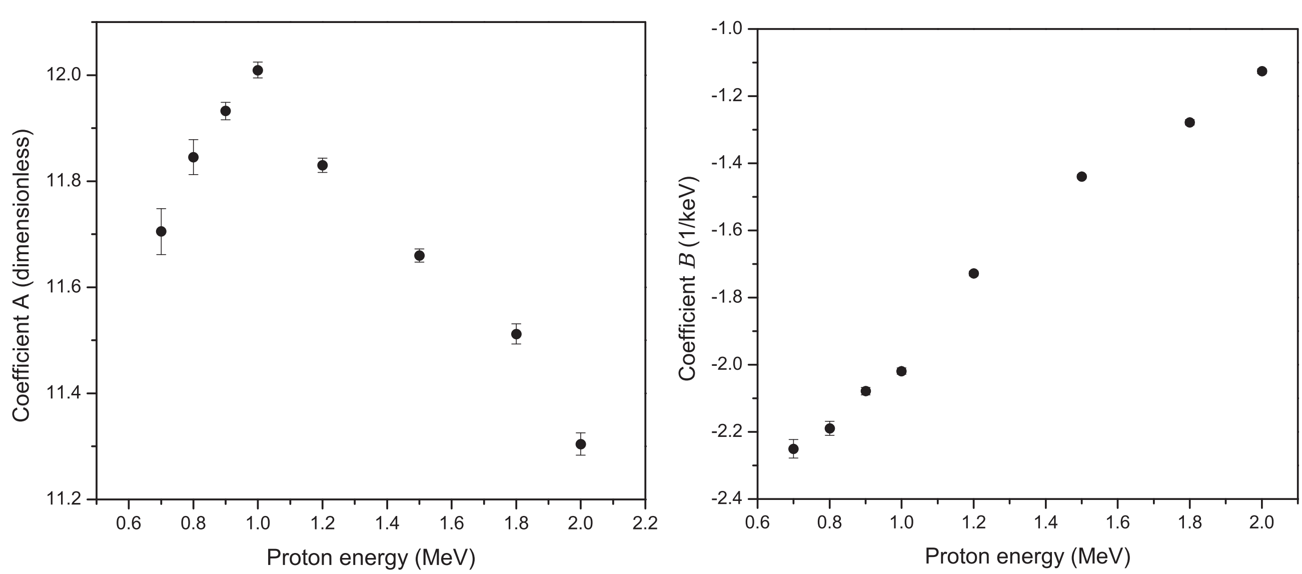

Fig. 4. Coefficients A and B of Eq. (4) as function of incident energy. Error bars are taken from fitting deviations and when missing they are smaller than the point size.

detection efficiency ε, given by Eq. (3), the measured solid angle $\Delta\Omega/4\pi$, and the incident total charge Q. In Fig. 5, both experimental and predicted spectra are shown for 1.5 MeV proton incidence, as an example. As can be seen, the agreement is very good. It must be emphasized that no additional factor was introduced to scale the predicted spectrum.

5. Conclusion

A semi-empirical model for predicting bremsstrahlung in bulk carbon targets induced by proton irradiation was developed. This model requires the continuous spectrum to be corrected to consider detection artifacts and X-ray attenuation in the sample. After a parameterization of coefficients A and B, the continuous spectrum can be predicted analytically.

The results obtained here for carbon can be useful for the common case of thin samples supported on carbon substrates. Other low atomic number elements or compounds often used as substrates should be investigated to generalize the present model to different experimental configurations.

Acknowledgements

This work has been supported by the *Coordenação de Aperfeiçoamento de Pessoal de Nivel Superior*-CAPES (Brazil) and the *Secretaría de Políticas Universitarias del Ministerio de Educación*-SPU (Argentina).

The authors acknowledge the details about detection geometry provided by SGX Sensortech Ltd.

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