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NEW BEAM MONITORING TOOL FOR RADIOBIOLOGY EXPERIMENTS AT THE CYCLOTRON ARRONAX

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The ARRONAX cyclotron is able to deliver alpha particles at 68 MeV. In the frame of radiological research, a new method is studied to infer *in situ* the deposited dose: it is based on the online measurement of the bremsstrahlung (>1 keV) produced by the interaction of the incident particle with the medium. Experiments are made using bombarded poly(methyl methacrylate) (PMMA)-equivalent water targets in order to characterise this continuous X-ray spectrum. The intensity of the bremsstrahlung spectrum allows for the beam monitoring. A simulation code of the bremsstrahlung has been built, and a good agreement is found with the experimental spectra. With this simulation, it is possible to predict the sensibility of this method: it varies with the target thickness, showing a good sensibility for thin target (<1000 µm) and saturation for thicker ones. Bremsstrahlung spectrum also shows a sensibility on the target's chemical composition.

INTRODUCTION

The ARRONAX (Accélérateur pour la Recherche en Radiochimie et Oncologie à Nantes Atlantique) cyclotron in Saint Herblain, France, is a facility that delivers protons and α particles up to 68 MeV[(1)]. One of ARRONAX's objectives is to become a platform for radiobiological studies, in particular for the irradiation of wells containing cells. At ARRONAX, radiobiological studies with alpha particles evolve around two axes: the low energy range [α emitters energy range: ^{211}At (5.867 MeV), ^{212}Bi/^{212}Po (6.08/8.78 MeV)] in order to optimise radio-immunotherapy treatments (RIT)[(2)] and the high energy range (30–68 MeV)—which is exclusive to ARRONAX—in order to determine the fundamental mechanisms generated by cells in response to ionising radiations (relative biological effectiveness, bystander effect, oxygen effect, etc.).

This study is a proof of the feasibility to use bremsstrahlung signal emitted from an irradiated medium as a method to infer *in situ* the deposited doses in cell medium. It is based on the online measurement of the bremsstrahlung spectrum (>1 keV) produced by the interaction of the incident particle with the medium. This method has the advantage to be non-perturbative for the beam and for the sample. The X-ray continuum spectrum is mainly formed by the secondary electrons bremsstrahlung (SEB). Other components such as quasi-free electron bremsstrahlung (QFEB) and atomic bremsstrahlung (AB) are negligible. A detailed explanation of these processes is given by K. Ishii[(3)].

The experimental bremsstrahlung spectra are compared with the results of the simulation code developed on this bremsstrahlung theoretical models. The purpose of this study is to determine the bremsstrahlung X-ray number per unit dose (gray) to find the sensitivity of this method and to verify the evolution of the bremsstrahlung signal according to the thickness and the chemical nature of irradiated medium.

First, the experimental set-up and simulation code of the bremsstrahlung effect are described. Then, results are presented. In conclusion, statements are made regarding the benefit of this new method for radiobiology experiments.

MATERIALS AND METHODS

Experimental bremsstrahlung set-up

The ARRONAX cyclotron provides an alpha particle beam of 68 MeV. The beam spot size is observed from the fluorescence on an alumina (Al_2O_3) foil[(4)] to optimise the transverse size and to centre the beam at the needed location. The beam intensities were in the range of 1–10 pA, and the diameter of the beam was <1 cm. Energy losses of alpha particles were calculated using the SRIM/TRIM program[(5)].

Figure 1 shows a schematic view of the experimental set-up dedicated to the bremsstrahlung studies. The experiments are made in air at standard pressure and temperature conditions. For practical consideration and convenience, poly(methyl methacrylate) (PMMA)-equivalent water target is used.

The target is located 25 cm downstream the window (a 75-µm-thick Kapton foil called vacuum window) that separates the vacuum from the outside air. After getting out in air, the beam first passes through a 2-µm-thick monitor copper foil and then a

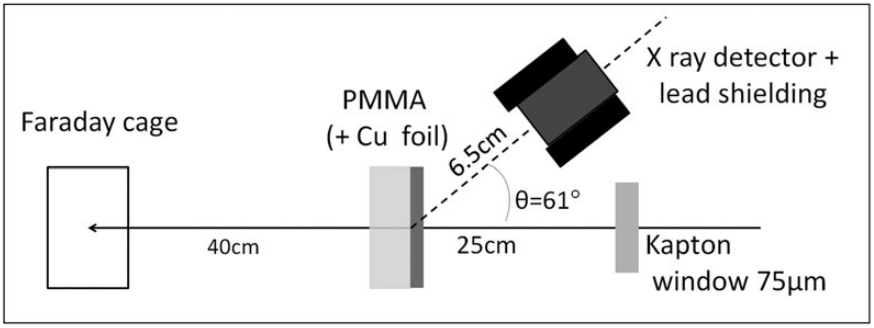

Figure 1. Schematic drawing of the experimental set-up for detection of the bremsstrahlung spectrum.

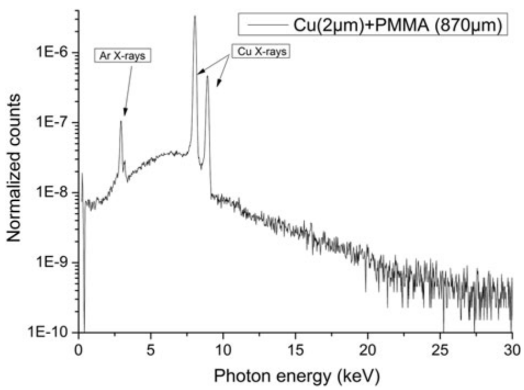

Figure 2. Experimental X-ray spectrum emitted by the PMMA target (870 μm) and the Cu monitor foil (2 μm) irradiated with alpha particles of 63 MeV.

870-μm-thick PMMA target. Both copper and PMMA foils, with a purity of >99 %, were bought from Goodfellow SARL (France). The beam intensity is measured by a faraday cup located 40 cm further away in the air. This faraday cup is placed in vacuum and equipped with electrostatic guard rings to avoid the escape of ejected electrons produced by incident particles interacting with the faraday cup.

The ion energy on the target is 63 MeV after crossing the vacuum window, the 25 cm of air and the copper foil. Produced X rays are detected by a high-purity germanium (HPGe) detector from Canberra (France) (see the spectrum on Figure 2). The detector is placed in front of the target at 61 degree with respect to the beam axis as it will be in the case of the future set-up for cell irradiation. The distance between the detector and the target is 6.5 cm (minimum distance allowed with the current set-up) to limit the absorption of low-energy X rays in the air. The detector is shielded using 5-cm-thick lead bricks.

Detector efficiency

A theoretical model is used to determine the efficiency ε of the detector[6]. The parameters included in the calculation are the thickness of the germanium crystal, the dead layer around the surface and the input window of the detector (data provided by the manufacturer). This model is adjusted to reproduce the experimental efficiency, measured using three radioactive sources with calibrated activities (CERCA LEA, France) and energy peaks: ^{55}Fe (X-ray energy: 5.89 keV), ^{109}Cd (X-ray energy: 22.16 keV) and ^{241}Am (gamma energy: 59.54 keV).

Measuring the beam intensity

In the case of thin target, the whole beam interacts with the faraday cup, and its signal gives directly the beam intensity. In the case of thick target, the beam footprint could be larger than the size of the faraday cup entrance window due to angular straggling (verified using a radiosensitive film at the entrance window of the faraday cup device). To address this loss of beam particles, a thin copper foil monitor is placed in front of the target and intercepts the whole beam. The copper X rays detected by the HPGe detector are proportional to the number of beam particles crossing through the monitor. These are calibrated using the faraday cup when the PMMA target is removed from the set-up.

Bremsstrahlung simulation code

To simulate the bremsstrahlung, the ion energy dependence of the emission cross section σ of a photon with energy $\hbar\omega$ at an angle θ was taken into account. The cross sections given by K. Ishii *et al.* and J.E. Miraglia *et al.*[3, 7] were used in this study, calculated from the semi-classical models in a non-relativistic case. The number of detected bremsstrahlung photons N with energy $\hbar\omega$ at an angle θ is given by the following formula:

$$N(\hbar\omega) = N_p.\varepsilon.\left(\int_0^{d_{\mathrm{PMMA}}} \sigma.\exp\left(-\mu_{\mathrm{PMMA}}\cdot\frac{x}{\cos(\theta)}\right)dx\right) \times exp\left(-\mu_{\mathrm{Cu}}\cdot\frac{d_{\mathrm{Cu}}}{\cos(\theta)}\right) -$$

where $\sigma = \sigma_{\mathrm{SEB}} + \sigma_{\mathrm{QFEB}} + \sigma_{\mathrm{AB}}$ is the total cross section; N_p is the number of α particles; d_{PMMA} and d_{Cu}, respectively, are the thicknesses of the PMMA target and the copper monitor foil; and μ is the linear attenuation coefficient (in PMMA and copper) given by National Institute of Standards and Technology[8]. The first exponential term takes into account the absorption of photons in PMMA and the second one the attenuation of photons in the monitor copper foil.

RESULTS

In Figure 2, the X-ray spectrum emitted by the target formed with the copper monitor foil and 870 μm of PMMA is presented, irradiated with alpha particles (spectrum normalised by the incident particle number). This spectrum shows characteristic peaks of argon present in the air (2.9 keV) and the characteristic peaks of copper. The continuous part of the spectrum is essentially the bremsstrahlung emitted by the target (PMMA+Cu foil) and a low contribution of the Compton scattering from gamma rays of various nuclear reactions. To remove the characteristic X rays and bremsstrahlung emitted by the monitor, the spectrum of Figure 2 is subtracted with that obtained by irradiating the copper foil without PMMA. The obtained spectrum (Figure 3) corresponds to the bremsstrahlung of the PMMA target attenuated with the 2-μm copper foil.

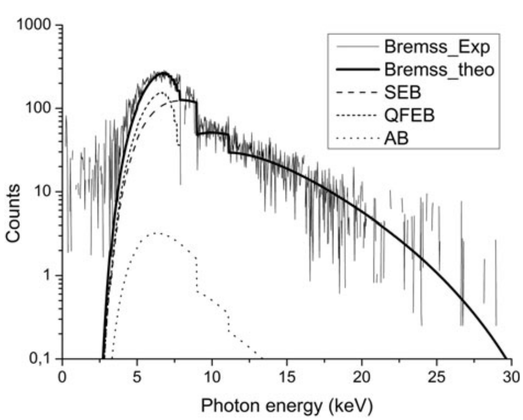

Figure 3. Experimental bremsstrahlung spectrum emitted by PMMA target (870 μm) irradiated with alpha particles of 63 MeV. Theoretical spectrum with its different components (SEB, QFEB and AB) is also presented.

Characteristic peaks of copper and argon have disappeared. The contribution of bremsstrahlung is of the order of background noise for energy higher than 25 keV. For low-energy photons <7 keV, decrease in bremsstrahlung spectrum is due to the reduction in the detector efficiency and the increase in absorption in air.

In Figure 3, also the experimental spectrum emitted by the PMMA target (870 μm) bombarded is compared with alpha particles of 63 MeV and the simulated spectra obtained using the formula (1). The simulated spectra with the three contributions of bremsstrahlung highlight the importance of each process. The SEB contributes to the majority of the spectrum even if QFEB is important at low energy. The theoretical description of bremsstrahlung is in good agreement with the experimental results with a difference of about 15 % over the whole spectrum. The errors can be assigned to the experimental determination of the projectile number, the detector efficiency and the approximations of the theoretical models of bremsstrahlung cross sections considered[7].

With the current experimental set-up, there are not enough bremsstrahlung photons (90 photons per 1 Gray); to increase the efficiency of photon detection, the HPGe detector will be replaced with a silicon drift detector (SDD). The latter has a smaller volume than the HPGe; thus, it can be located closer to the target at a distance of 2 cm. This will enlarge the detection solid angle and lower the attenuation made by air. In addition, the intrinsic efficiency is better than the HPGe for photons between 11 and 15 keV (because of escape peak). It is expected, based on simulations, to have around 10^3 bremsstrahlung photons (integral of the total spectrum) for 1 Gray delivered. Therefore, with this good sensitivity, the bremsstrahlung could be used to check the delivered dose directly in the medium.

Figure 4 presents the integral bremsstrahlung yield as a function of the PMMA thickness for 1 Gray

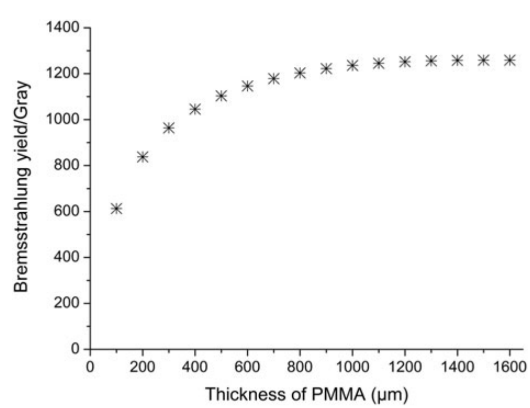

Figure 4. Bremsstrahlung yield in function of the PMMA thickness for 1 Gray delivered with alpha particles.

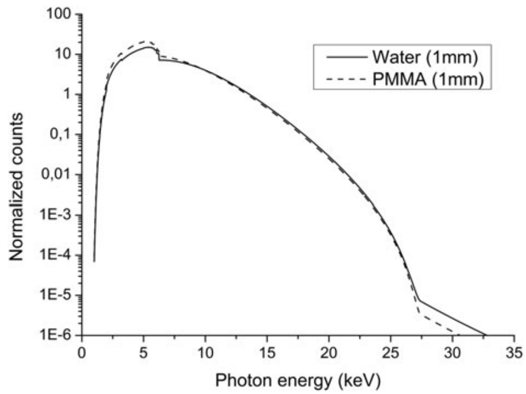

Figure 5. Simulated bremsstrahlung spectra for water and PMMA targets of 1 mm irradiated with alpha particles (1 Gray). These simulations were made considering the use of an X-ray SSD. The distance between the detector and the target is 2 cm.

delivered at the entrance medium. First, it varies quickly with thickness and then saturates after 1000 μm PMMA. On one hand, this is due to an increase in the photons absorption. On the other hand, this saturation comes from the energy decrease of alpha particles, which causes the shifting to low-energy part of X-ray spectrum emitted from deeper layers.

In addition to the beam intensity verification and the sensitivity with the target thickness, the bremsstrahlung contains also information on the irradiated medium. Figure 5 shows simulated bremsstrahlung spectra in the case of water and PMMA targets of 1 mm.

Although these two medium are quite close, their bremsstrahlung spectrum is different especially for photons <10 keV. This is due to photon absorption that is sensitive to the chemical nature. Indeed, the photoelectric component has a dependence in Z^5 (with Z the atomic number). Hence, the bremsstrahlung could provide information about the chemical composition of the medium.

CONCLUSION

The experiment aimed at developing a dosimetry device adapted to our beam lines and allowing online beam monitoring directly on the sample.

The bremsstrahlung emitted during irradiation of a PMMA target by a beam of light ions (68 MeV alpha) was studied. Experiments have shown that the bremsstrahlung spectrum can be detected with non-negligible amplitude in comparison with background noise. It was possible to validate a simulation code based on the theoretical cross sections of three different phenomena at the origin of the continuous spectrum (SEB, QFEB, AB) using the collected experimental data. The model shows satisfactory results, with only 15 % mean difference with respect to experimental data over the whole energy range.

In this study, this simulation code allows to improve the geometrical configuration to optimise bremsstrahlung detection. Replacing the HPGe detector with an SDD permits to be closer to the target, promoting the detection of bremsstrahlung (~1000 counts per Gray). This would enable to measure the beam intensity directly on the target without the use of disturbing medium (ionisation chamber, monitor, etc.).

Finally, the bremsstrahlung depends on the chemical composition of the target. It is possible to differentiate small variations as the difference between the water and the PMMA. Information on the chemical nature of the medium could be necessary for precisely modelling the dose evolution in medium in the beam direction. Future advanced simulations could connect the bremsstrahlung and the delivered dose since the bremsstrahlung is the image of the secondary electron energies created by the ions beam in the medium. This is a promising tool for radiobiology experiments.

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