Communications in Physics, Vol. 19, No. 1 (2009), pp. 53-58

NEUTRON YIELD FROM (γ, n) AND (γ , 2n) REACTIONS FOLLOWING 100 MeV BREMSSTRAHLUNG IN A TUNGSTEN TARGET

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Abstract. *The photonuclear reactions of (γ, xn) or (γ, xnp) types can be used to produce high-intensity neutron sources for research and applied purposes. In this work a Monte-Carlo calculation has been used to evaluate the production yield of neutrons from the (γ, n) and (γ, 2n) reactions following the bremsstrahlung produced by a 100 MeV electron beam on a tungsten target.*

I. INTRODUCTION

The bremsstrahlung emissions produced by accelerated electron beams are intense and high-energy photon sources. They are widely used in photonuclear reaction research and applied nuclear physics. In electron accelerators, tungsten (W) is often used as a target because it has a large cross section for bremsstrahlung production, a high melting temperature and good heat conductivity [1]. Moreover, for the tungsten isotopes, ^{180,182,183,184,186}W, the cross sections of the (γ, n) and (γ, 2n) reactions are relatively high [2]. Therefore, these reactions can be used to produce secondary neutrons for research purposes during accelerator operation. In this paper we show that such reactions provide a high-intensity neutron source by evaluating the expected neutron yield in the case of the 100 MeV electron beam of the Linear Electron Accelerator (LUE-100 Linac) at the Joint Institute for Nuclear Research (JINR), Dubna, using a 1.5 mm thick tungsten target [3]. In a first step the energy and angular distributions of the bremsstrahlung photons are evaluated, using both theoretical models and experimental data, especially those related to non-zero emission angles [4, 5]. In a second step a folding with the reaction cross sections gives an estimation of the production yield of neutrons from the photonuclear reactions of interest.

II. TOTAL NEUTRON YIELD

Bremsstrahlung photons can be emitted whenever a charged particle experiences a change in momentum under the influence of the Coulomb field of a nucleus. The rate of energy loss due to bremsstrahlung and the cross-section for its production are inversely proportional to the square of the mass of the incident particle [6]:

$$dE_b/dt \sim Z^2 Z_t^2/m^2 \tag{1}$$

$$\sigma_b \sim Z_t^2(e^2/mc^2)^2 \tag{2}$$

where m and Z are, respectively, the mass and the charge of the beam particle, and Z_t is the atomic number of the target. Bremsstrahlung emission is, therefore, a major energy loss mechanism for electrons, the lightest charged particle, especially at relativistic energies greater than a few MeV.

At very low electron energies the angular distribution of bremsstrahlung is maximum in the direction perpendicular to the incident beam [6, 7]. However, as the energy is increased, the maximum occurs at increasingly forward angles and in the limit of very high energies, the emission of bremsstrahlung essentially occurs in a narrow cone in the forward direction. The root-mean-square (rms) angle of emission is then given by [6]:

$$\theta_\gamma \approx m_e c^2/E_e \tag{3}$$

with E_e being the total energy of the incident electron and m_e – its rest mass.

Calculations of the spectral characteristics of bremsstrahlung photons and scattered electrons when the relativistic incident electron beam hits a target have been described earlier [4, 5]. Amongst the secondary interactions induced by bremsstrahlung photons with the target material, photonuclear reactions become possible at energies larger than the reaction thresholds. Fig. 1 shows the spectra of bremsstrahlung photons emitted in the angular range of $0^\circ - 20^\circ$ at the incident electron energy of 100 MeV on a 1.5 mm thick tungsten target [5]. The resulting energy distribution is used in the Monte Carlo calculation to generate randomly photons having the proper energy spectrum.

The reaction yield is expressed by the relation:

$$Y = N_t \int_{E_{th}}^{E_{max}} \sigma(E) I(E) dE \tag{4}$$

where $\sigma(E)$ is the photonuclear reaction cross section and I(E) is the bremsstrahlung-spectral intensity,

N_t being the number of the target nuclei per cm^2:

$$N_t = \zeta(N_{Avog}/A)\rho t \tag{5}$$

Here, ζ is the isotopic enrichment, $N_{Avog}$is Avogadro number,

ρ(g / cm^3) and t (cm) are the density and thickness of the target, respectively.

E_{th} and E_{max} are the reaction threshold and the maximal energy of the bremsstrahlung spectrum.

For each tungsten isotope the yields of (γ, n) and (γ, 2n) reactions are determined by using the simulated bremsstrahlung spectrum (curve 1 in Fig. 1) and the proper reaction cross sections (Fig. 2 for ^{186}W isotope). The neutron yield, $Y_{(\gamma,xn)}$, from the two types of reactions is the sum of the individual yields.

The total yield is obtained by adding the yields of each isotope properly weighted by their fractional abundance.

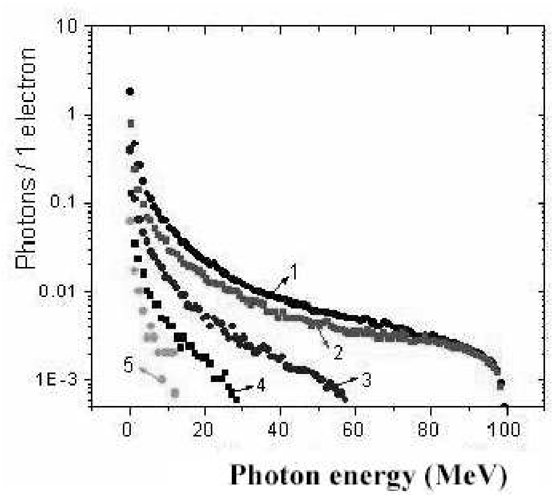

Fig. 1. Bremsstrahlung emission at different angles for the case of using the 100 MeV electron beam incident on 1.5 mm tungsten [5]: (1) total spectrum, (2) from 0 to 5 $^\circ$, (3) from 5 $^\circ$ to 10 $^\circ$, (4) from 10 $^\circ$ to 15 $^\circ$, (5) from 15 $^\circ$ to 20 $^\circ$

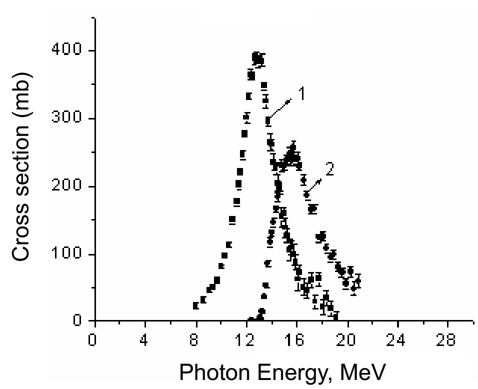

Fig. 2. Excitation functions [2]: (1)^{186}W(γ, n)^{185}W reaction (2)^{186}W(γ, 2n)^{184}W reaction

The uncertainty of the neutron yield was determined on the basis of the uncertainty of the cross section data and the error in determining the photon intensities from simulated bremsstrahlung spectrum.

Fig. 3 shows the simulation results for the production yields of the secondary particles, $Y_{(e,x\gamma)}$ for the bremsstrahlung photons and $Y_{(e,xe')}$ for the emitted electrons as a function of the tungsten target thickness, i.e. number of these secondary particles per one incident electron [5]. For example, at 1.5 mm thickness of the tungsten target the yield values are, respectively, 4.14 and 1.14 for the bremsstrahlung photons and emitted electrons. This consideration is necessary to determine the neutron yields, $Y_{(e,xn)}$, directly from

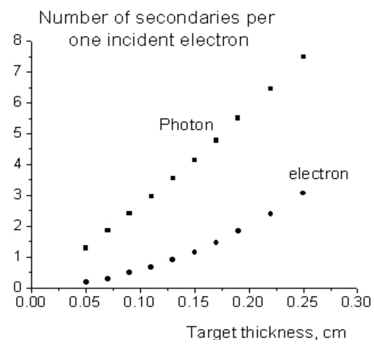

Fig. 3. Production yields of secondary particles as a function of the target thickness [5]

information on the electron current used in accelerator operation:

$$Y_{(e,xn)} = Y_{(e,x\gamma)} x Y_{(\gamma,xn)} \quad (6)$$

The obtained results of the neutron yields $Y_{(e,xn)}$ are summarized in Table 1. As a result, a total yield of about $(1.01 \pm 0.09)10^{-3}$ n / electron was determined for neutron production from the above mentioned photonuclear reactions. For example, at a typical electron current 100 μA, i.e. corresponding to the beam intensity of about 6.2×10^{14} electron / s, we can estimate two following results for the secondary neutron emission:

i) A total neutron intensity of about $(6.26 \pm 0.56)10^{11}$ n / s is able to be produced during the accelerator operation.

ii) If it is supposed that the neutron measurement is performed at a distance 10 m from the target by using a detector with 30 cm radius. The solid angle covered by this detector is about 0.25 mrad. Therefore, the neutron amount which is able to reach the detector is evaluated as:

$$N = (6.26 \pm 0.56)10^{11} \times 0.25 \times 10^{-3}/4\pi = (1.25 \pm 0.11)10^{7} n/s$$

III. NEUTRON ENERGY AND ANGULAR DISTRIBUTIONS

Besides evaluating the total neutron yield, the Monte Carlo method makes it possible to calculate the energy and angular distributions of the produced neutrons once the angular dependence of the photonuclear reaction cross-section is known. In case of the (γ, n) reaction, the energy – momentum conservation relates the neutron energy E_n to its production angle θ_n via:

$$M_r^2 = (\Delta E + M_n)^2 - 2\Delta E(E_n + M_n) + 2E_\gamma(\Delta E - E_n - \cos\theta_n\sqrt{E_n^2 - M_n^2}) \quad (7)$$

where M_r is the mass of the final state nucleus (c = 1), $\Delta E = (M_t - M_r - M_n)c^2$ with M_t the mass of the target nucleus, M_n that of the neutron and E_γ the incident photon energy – Note that the neutron kinetic energy is $T_n = E_n - M_n$.

The angular distribution of the photonuclear cross section is taken from [8, 9]. It has form $P(\theta_n) = A + B^* \sin^2\theta_n$ with $B / A = 2.0 \pm 0.5$ [9]. We justify this choice by remarking that the photons which are active in producing neutrons have energies concentrated above threshold whatever the electron energy.

Table 1. Neutron yields and nuclear data used for yield determination

Abundance (%)	**Reaction**	**Threshold energy (MeV)**	**Yield (n / electron)**
^{186}W (28.60)	^{186}W(γ, n) ^{185}W	7.19	$(1.91 \pm 0.13)*10^{-4}$
	^{186}W(γ, 2n) ^{184}W	12.95	$(1.00 \pm 0.09)*10^{-4}$
^{184}W (30.70)	^{184}W(γ, n) ^{183}W	7.41	$(2.21 \pm 0.14)*10^{-4}$
	^{184}W(γ, 2n) ^{182}W	13.60	$(1.11 \pm 0.09)*10^{-4}$
^{183}W (14.28)	^{183}W(γ, n) ^{182}W	6.19	$(0.95 \pm 0.08)*10^{-4}$
	^{183}W(γ, 2n) ^{181}W	14.26	$(0.38 \pm 0.04)*10^{-4}$
^{182}W (26.30)	^{182}W(γ, n) ^{181}W	8.07	$(1.65 \pm 0.12)*10^{-4}$
	^{182}W(γ, 2n) ^{180}W	14.75	$(0.92 \pm 0.07)*10^{-4}$
^{180}W (0.12)	^{180}W (γ, n) ^{179}W	8.41	$(0.009 \pm 0.003)*10^{-4}$
	^{180}W(γ, 2n) ^{178}W	15.35	$(0.002 \pm 0.001)*10^{-4}$

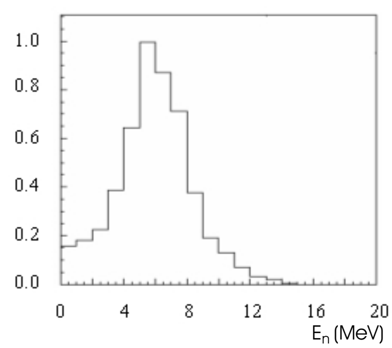

Fig. 4. The energy spectrum of neutrons emitted by the ^{186}W(γ, n)^{185}W reaction

The bremsstrahlung radiation is taken to be exactly forward. The angular distribution of the produced neutrons is therefore the same as [8, 9] while the neutron energy spectrum is displayed in Fig. 4.

IV. CONCLUSION

We have used a Monte-Carlo calculation to evaluate the total neutron yield from photonuclear reactions (γ, n) and (γ, 2n) induced by bremsstrahlung photons radiated by a 100 MeV electron beam incident on a 1.5 mm tungsten target. The bremsstrahlung spectrum was calculated and folded with the cross sections of the (γ, n) and (γ, 2n) reactions for the various tungsten isotopes present in the target. The energy and angular distributions of the produced neutrons were calculated under the assumptions that the bremsstrahlung radiation is exactly forward and the direct interaction model can be used to consider the neutron emission.

In this work we determined the total neutron yield which is about $(1.01 \pm 0.09)10^{-3}$ n / electron. This value makes us possible to evaluate the neutron emission as a secondary source produced when accelerator is operated at a given electron current.

In reality there may be additional contributions to the neutron production from other types of nuclear reactions induced by 100 MeV bremsstrahlung photons such as (γ, np) and (γ, xn) reactions with high neutron multiplicity as well as spallation processes. However, their contribution to the total neutron yield should not exceed a few percents as they imply higher energy incident photons associated with lower bremsstrahlung photon intensities.

ACKNOWLEDGEMENT

This work has been performed with the financial support by the National Research Program on Natural Science under grant No. 403806. We would like to express sincere thanks for this precious assistance.

We are grateful to Prof. Pierre Darrulat for useful discussions to improve the quality of the work.

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Received 20 August 2008.