Available online at www.sciencedirect.com
ScienceDirect
Radiation Measurements 43 (2008) S215–S218
Radiation Measurements
www.elsevier.com/locate/radmeas

Preliminary results on neutron production from a Pb/U target irradiated by deuteron beam at 1.25 GeV/amu

M. Fragopoulou[a,*], M. Manolopoulou[a], S. Jokic[b], M. Zamani[a], M. Krivopustov[c], A. Sosnin[c], S. Stoulos[a]

[a] *School of Physics, Aristotle University of Thessaloniki, Greece*
[b] *Vinca Institute, Belgrade, Serbia and Montenegro*
[c] *High Energy Laboratory, JINR Dubna, Russia*

Abstract

A spallation neutron source consisted of a cylindrical Pb target and surrounded by uranium blanket was irradiated by deuteron beam 1.25 GeV/amu provided from the Nuclotron accelerator at High Energy Laboratory, JINR, Dubna. For radiation protection purpose a polyethylene shielding was placed around the spallation neutron source. Neutron distributions along the surface of the U-blanket were measured by using solid state nuclear track detectors (SSNTDs) as particle and fission detectors. The neutron distributions appear to be similar to those obtained by proton irradiations. Applying a fitting procedure to the experimental data the inelastic cross section of deuteron in Pb was estimated. The escaping neutron distribution from the polyethylene shielding and parallel to the target was also measured and presented to be two orders of magnitude less than that over the U-blanket surface.

Keywords: Neutron distribution; Spallation sources

1. Introduction

Spallation reactions have been thoroughly investigated during the last decades using energetic proton beams (Pienkowski et al., 1997; Letourneau et al., 2000). Such experiments have also been performed in Dubna using a large cylindrical Pb target surrounded by a paraffin moderator or a U-blanket (Westmeier et al., 2005; Zamani et al., 2003, 2005). From the accumulated knowledge it is concluded that the average number of generated neutrons depends mostly on the target mass and secondarily on the projectile mass and bombarding energy. The prospect of building new facilities providing high-intensity fast neutron beams for transmutation or incineration purposes via (n,xn) and (n,f) reactions has prompted to a renewal of interest in data related to spallation reactions induced by energetic light particles, such as deuterons. Therefore, a spallation neutron source consisted of a cylindrical Pb target surrounded by uranium rods (U-blanket) was irradiated by 1.25 GeV/amu deuterons. The irradiation was carried out at the Nuclotron accelerator at the High Energy Laboratory of Joint Institute of Nuclear Research (JINR) in Dubna, Russia. Around the spallation neutron source a polyethylene shielding was placed for radiation protection purposes. Measurements of the neutron distribution along the spallation source surface (U-blanket) and over the polyethylene shielding were performed using solid state nuclear track detectors (SSNTDs). The results of this experiment are presented in the current work.

2. Experimental

The spallation neutron source consists of a cylindrical Pb target 50 cm in length and 8.4 cm in diameter. Around the Pb target U-rods were placed hexagonally. Four sections of natural uranium blankets constitute the spallation source. Each section consists of 30 U-rods with 10.4 cm in length and 3.6 cm in diameter. The whole system is surrounded, for radiation protection purpose, by a polyethylene moderator covered with 1 mm thick Cd (Fig. 1).

---

[*] Corresponding author. Tel.: +30 231 099 8082; fax: +30 231 099 8176.
E-mail address: fragom@auth.gr (M. Fragopoulou).

1350-4487/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.radmeas.2008.03.014

Neutron distributions were studied along the surface of the U-blanket and on the top of the shielding using SSNTDs. PADC foils acting as particle detector were placed parallel to the target axis. One part of the detector was in contact with a neutron converter (Kodak LR115 type 2B, containing $Li_2B_4O_7$). This converter provides information about neutron fluence, detecting the alpha particles' tracks from $^{10}B(n,\alpha)^7Li$ and $^6Li(n,\alpha)^3H$ reactions. Another part of the detectors was in contact with the converter and was covered on both sides with 1 mm Cd foils detecting likewise the epithermal neutrons. The thermal neutron component (up to about 1 eV) was calculated by subtracting the measured track density of the Cd-covered from the Cd-uncovered region of the CR39 detector. The fast neutrons were determined by proton recoil tracks on the detector itself (neutron elastic scattering on H of the detector). The neutron energy region detected by proton recoils is between 0.3 and 3 MeV due to limitations in the proton registration efficiency (Harvey et al., 1998). The dosimeters were calibrated in the frame of EURADOS actions for fast and thermal neutron dosimetry. SSNTDs were also used as fission detectors. The fissioning target of approximately 100 μg/cm^2 was evaporated on Makrofol E detector. Targets of ^{235}U and ^{232}Th were used in order to study the thermal (up to about 1 eV) and fast neutron (above 2 MeV) distributions over the U-blanket (Remy et al., 1970).

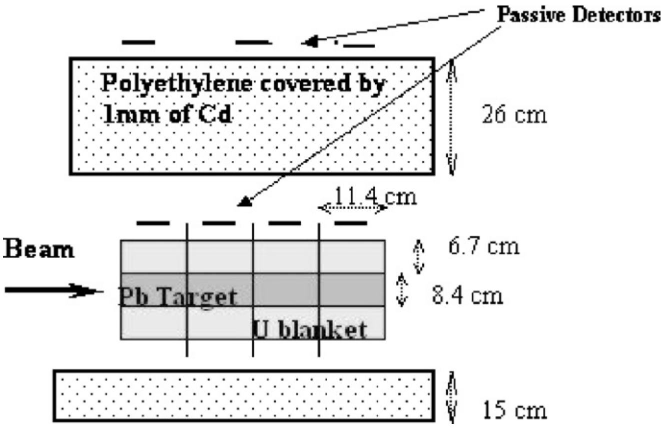

Fig. 1. A cross section of the Pb/U-blanket set-up.

3. Results and discussion

The neutron fluence on the U-blanket surface reflects neutron production along the Pb target from spallation reaction produced by primary and secondary particles and also neutron production in U-blanket by secondary particles, keeping in mind that the beam diameter is smaller than the Pb target diameter.

According to the experimental data, thermal neutrons were not detected because no difference between the track density on the Cd-covered and the Cd-uncovered region of CR39 with $Li_2B_4O_7$ converter was observed. The measured track density corresponds mainly to epithermal neutron (up to 10 keV) fluence, which presented to be one order of magnitude less than intermediate-fast neutron fluence (between 0.3 and 3 MeV) detected from the proton recoil on the detector itself. Thus, it is obvious that the specific spallation neutron source produces mostly fast neutrons. Fission detectors with ^{232}Th converter were also used in order to measure fast neutron fluence above 2 MeV. The fast neutron distribution along the U-blanket measured by both methods is presented in Fig. 2. Fast neutron production increases up to about 15 cm from the beam entrance and then decreases along the target.

In order to study further the spallation neutron distribution along the U-blanket as a function of the distance x from the

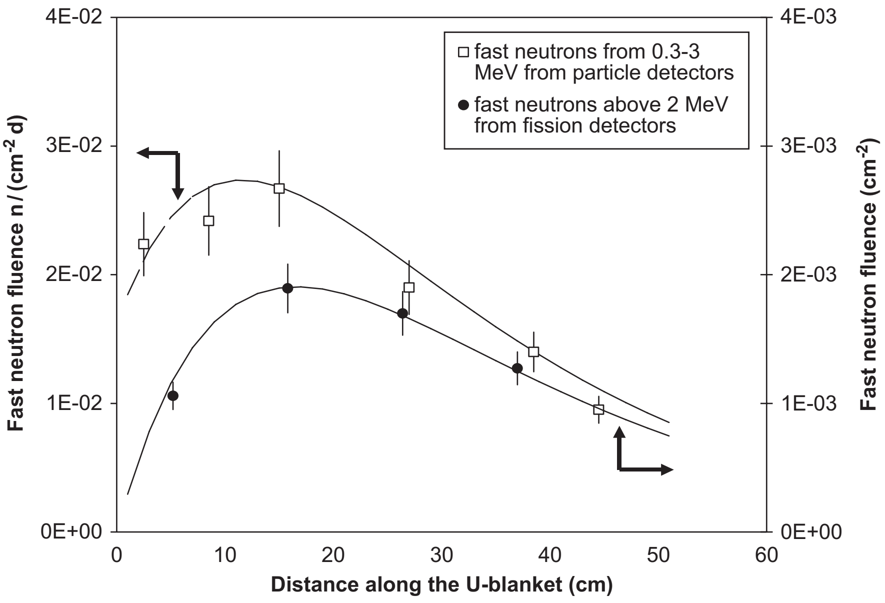

Fig. 2. Fast neutron fluence per incoming deuteron measured along the surface of U-blanket using SSNTDs as particle and fission detectors.

beam entry in the Pb target, a fitting procedure was applied to the fast neutron fluence per incident deuterons (ρ_n, n/cm^2 d^1) measured over the U-blanket surface. The following equation was used (Fragopoulou et al., 2006):

$$\rho_n = C(1 - \alpha e^{-bx})e^{-dx} \tag{1}$$

where C is a parameter with units neutrons per cm^2 per deuteron. The first part of the equation was set to describe the build-up effect having build-up parameter α and build-up coefficient b. The second part represents the beam attenuation along the target as was observed over the U-blanket surface. The values of the above fitting parameters, applied to the data obtained by particle and fission detectors, are presented in Table 1.

According to the fitting procedure on the data obtained by particle detectors, the maximum of the build-up effect for intermediate-fast neutrons, from 0.3 to 3 MeV, takes place up to 12 ± 3 cm from the beam entrance into the target. While for fast neutrons above 2 MeV, the build-up effect seems to go deeper up to 16 ± 3 cm into the target (Fig. 2). The calculated attenuation coefficient (d, cm^{-1}) is related to interaction length (λ, cm), so it is possible to calculate the specific interaction length ($\lambda = I/d$) of the 1.25 GeV/amu deuterons in Pb. Additionally, the inelastic cross section (σ, b) of deuterons in Pb can be estimated using the relation $\sigma = A/N\lambda p$, where A is the Pb atomic number, N is Avogadro's number and p is the Pb target density (g/cm^3). Consequently, the interaction length of deuterons with energy 1.25 GeV/amu in Pb presented to be 19.2 ± 1.5 cm and 18.5 ± 2.8 cm from the data obtained by particle and fission detectors, while the corresponding inelastic cross section was found to be equal to 1.58±0.21 b and 1.64±0.15 b, respectively. These values are close to the inelastic cross section of protons in Pb at the same energy region, as it is presented in the literature (Letourneau et al., 2000).

Table 1
Fitting parameters applied to the data along the U-blanket obtained by particle and fission detector

Fitting parameters	Particle detectors	Fission detectors
Parameter C	0.18 ± 0.02	0.024 ± 0.002
Build-up parameter a	0.91 ± 0.02	1.00 ± 0.02
Build-up coefficient b (cm^{-1})	0.020 ± 0.005	0.013 ± 0.004
Attenuation coefficient d (cm^{-1})	0.052 ± 0.004	0.054 ± 0.006

Moreover, the fluence of epi thermal and intermediate-fast neutrons escaping the shielding was measured using detectors. The fast neutrons escaping the polyethylene are presented to be two orders of magnitude less than that on the U-blanket surface (Fig. 3), while less than the half of these neutrons are in the thermal-epithermal energy range. Therefore, the polyethylene shielding proves to be an efficient moderator thermalizing a large amount of the intermediate-fast neutrons produced by the specific spallation neutron source (Fig. 3).

4. Conclusion

Neutron distributions along a Pb (U-blanket) spallation source were measured by SSNTDs. Comparison between measurements with particle detectors and fission detectors was performed. The specific spallation neutron source presented to be an efficient producer of high fast neutron fluences, while the epithermal neutron fluence is one order of magnitude less than fast. The fast neutron distributions along the U-blanket surface show an increase up to about 15 cm of Pb and then decrease along the target. Applying a fitting procedure to the experimental data of fast neutron fluence, the interaction length and the inelastic cross section of deuterons in Pb were calculated and presented to be 19 ± 3 cm and 1.6 ± 0.2 b. According to the measurements of the escaping neutrons from the polyethylene shielding surrounded the spallation source, the number of fast

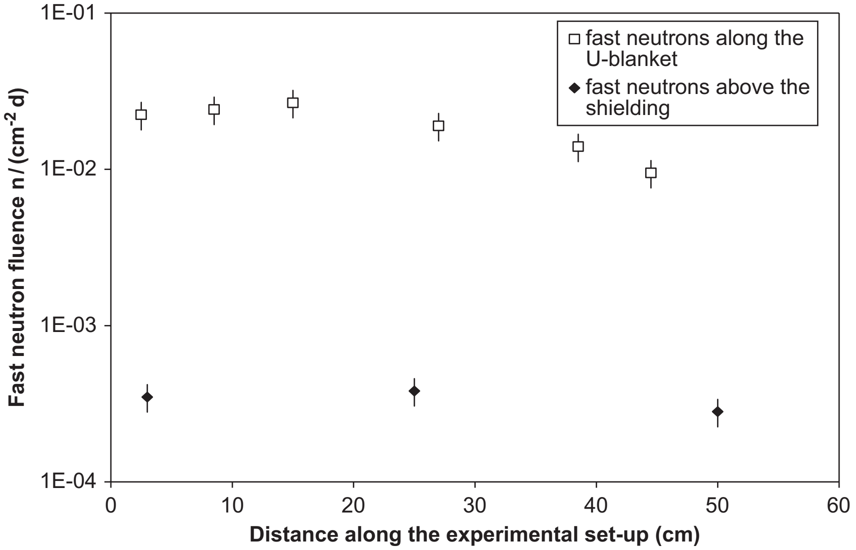

Fig. 3. Fast neutron fluence per incoming deuteron measured over the polyethylene shielding in comparison with fast neutron measured along the surface of U-blanket.

neutrons behind the shielding is presented to be two orders of magnitude less than that over the U-blanket surface.

References

Fragopoulou, M., et al., 2006. Spatial distribution of moderated neutrons along a Pb target irradiated by high energy protons. Nucl. Instrum. Methods A 560, 571–576.

Harvey, J.R., et al., 1998. The contribution of Eurados and Cendos to track etch neutron dosimetry: the current status in Europe. Radiat. Prot. Dos. 77, 267–304.

Letourneau, A., et al., 2000. Neutron production in bombardments of thin and thick W, Hg, Pb targets by 0.4, 0.8, 1.2, 1.8 and 2.5 GeV protons. Nucl. Instrum. Methods B 170, 299–322.

Pienkowski, L., Goldenbaum, F., Hilscher, D., Jahnke, U., Galin, J., Lott, B., 1997. Neutron multiplicity distributions for 1.94 to 5 GeV/*c* proton-, antiproton-, pion-, kaon-, and deuterons-induced spallation reactions on thin and thick target. Phys. Rev. C 56, 1909–1917.

Remy, G., Ralarosy, J., Stein, R., Debeauvais, M., Tripier, J., 1970. Heavy fragment emission in high energy reactions on heavy nuclei. J. Phys. 31, 27–34.

Westmeier, W., et al., 2005. Transmutation experiments on ^{129}I, ^{139}La and ^{237}Np using the Nuclotron accelerator. Radiochim. Acta 93, 65–73.

Zamani, M., et al., 2003. Spallation neutron production in the new Dubna transmutation assembly. Nucl. Instrum. Methods A 508, 454–459.

Zamani, M., et al., 2005. Neutron yields from massive lead and uranium targets irradiated with relativistic protons. Radiat. Meas. 40, 410–414.