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Measurement of peak fluence of neutron beams using Bi-fission detectors

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Abstract. Fission fragments and other charged particles leave tracks of permanent damage in most of the insulating solids. Damage track detectors are useful for personal dosimeters and for flux/dose determination of high-energy particles from accelerators or cosmic rays. A detector that has its principal response at nucleon energy above 50 MeV is provided by the fission of Bi-209. Neutrons produce the largest percentage of hadron dose in most high-energy radiation fields. In these fields, the neutron spectrum is typically formed by low-energy neutrons (evaporation spectrum) and high-energy neutrons (knock-on spectrum). We used Bi-fission detectors to measure neutron peak fluence and compared the result with the calculated value of neutron peak fluence. For the exposure to 100 MeV we have used the iThemba Facility in South Africa.

Keywords. Neutron-induced fission; fission detector; neutron peak fluence; spark counter; track detectors.

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1. Introduction

In most of the high-energy radiation fields, such as those encountered around accelerators or cosmic rays in the atmosphere, neutrons produce the largest percentage of hadron dose. The ^{209}Bi fission track detector gives its principal response to nucleons (protons and neutrons) with energy above 50 MeV [1]. A serious disadvantage of this detector is its low sensitivity to measure the low flux of nucleons present around high-energy accelerators

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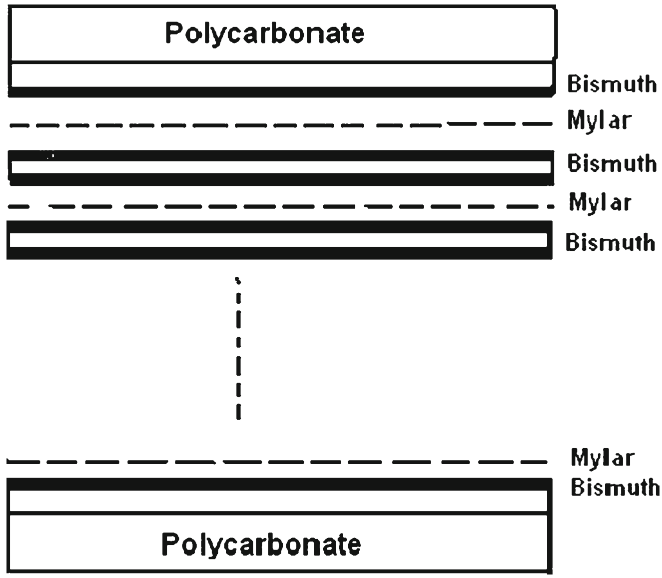

Figure 1. Arrangement of Bi radiators and Mylar detector foils in Bi-fission damage track detectors.

or in cosmic ray fields. The neutron-induced fission can be detected by spark counting of induced fission-fragment holes in Mylar films. A latent track (a track before etching) is made up of an approximately cylindrical hole and a damaged zone around it. In addition to the registration by a nuclear track detector, it is possible to detect the fission fragments by thin film break down counters, which can be considered as a real-time analogue of the spark counter [2]. By using both detector systems, it is possible to achieve a new strategy for calibrating nuclear track detectors, even through the neutron beam is not monoenergetic. This paper reports the result of neutron peak fluence measured using Bi-fission detectors.

2. Detection of high-energy neutrons by fission reactions

Bi-fission detector based on track registration was developed by Tommasino *et al* [3]. The response of the Bi-fission track detectors can be improved using long exposure time and large detector area. Large detector area can be scanned by spark counting of etched-through holes in the polyethylene terephthalate (PET) films [4,5]. To get a better response, the detector – a thin PET film – is sandwiched between two bismuth radiators with infinite thickness, i.e. a thickness greater than the range of the fission fragments in bismuth (figure 1). The use of two Bi-radiators, not only double the registration efficiency, but also remove the front–back asymmetry of the fission track detector [6,7]. The Bi-radiators are made of a 25 mg/cm^2 bismuth film deposited on 100 μm PET film, which acts as a bismuth film support. Spallation residues produced in these materials are not registered, since the lightest detectable particle is the oxygen molecule [8], which is also the heaviest nucleus present in the PET films. Bismuth radiators typically used in the past were obtained by depositing a thin film of bismuth (1–2 mg/cm^2) on a thick aluminium [9] or a copper backing [10].

3. Irradiation of the Bi-foil stack

The peak fluence Φ_0^{res} per unit monitor counts N at a distance of 8 m from the Li target was calculated using a ^{238}U fission chamber by the formula

$$\left(\frac{\Phi_0^{\text{res}}}{N}\right) = 1.33(7)\ \text{cm}^{-2}.$$

The peak fluence was calculated by integrating the spectral fluence in the region of high-energy peak above energy $E_1 = 91$ MeV. The uncertainty corresponds to one standard deviation. The ^{238}U(n, f) reference cross-section (INDC) used for the analysis was measured relative to n–p scattering. Although the primary reference cross-section is the n–p scattering cross-section, the ^{238}U(n, f) cross-section has been preferred for use at iThamba Lab because proton recoil telescopes require much longer measuring times and their operation is more cumbersome than that of a fission chamber. A parallel-plate ^{238}U fission chamber (iTL FC) is part of the permanent instrumentation of the facility. The chamber was manufactured in 1988 at the Institute for Reference Materials and Measurements (IRMM) in Belgium. The $^{238}U_3O_8$ deposits, 76 mm in diameter, were produced by electronic spraying onto both sides of the six tantalum backings. The distance between deposits and electrodes is 5 mm [11]. The contribution of the uncertainty of the n–p cross-section to the uncertainty of the ^{238}U(n, f) cross-section is not included in the uncertainty of the peak fluence. The average energy E_{n} of the peak neutrons was 96.7 MeV. The un-normalized spectral fluence Φ_E is shown in figure 2. The Bi-foil stack (ANPA-stack) was irradiated at a distance of 8.07 m from the Li target. The number of monitor counts N during the irradiation was 59145046. The resulting peak fluence was $\Phi_0 = 7.7(4) * 10^7\,\text{cm}^{-2}$

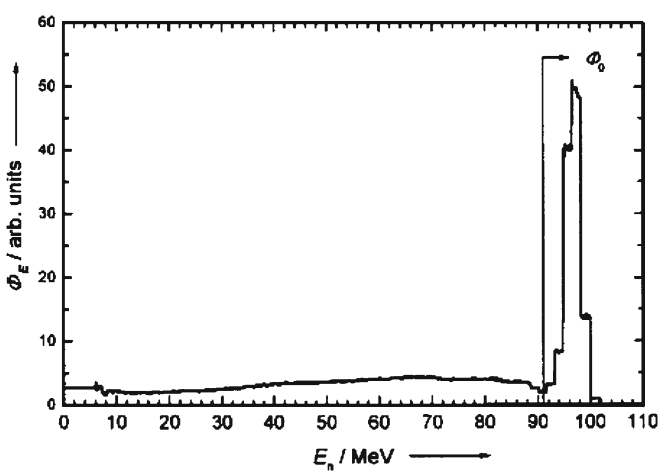

Figure 2. Un-normalized spectral fluence Φ_E measured with ^{238}U fission chamber.

Figure 3. Fission tracks observed with iThemba Facility, South Africa by 100 MeV neutrons.

at the time of irradiation. To increase the detector registration efficiency, a thin plastic film was sandwiched between two bismuth radiators with infinite thickness, i.e. a radiator thickness greater than the range of fission fragment in bismuth. Because of the simplicity and the low weight of the thin bismuth film on plastic backing, large detector areas (>1 m^2) can be conveniently obtained with compact and light stack of many replicate detectors. After irradiation, the PET detector was removed from the stack and etched for 2.5 h in 30% KOH in water at 40°C. The spark counting was carried out at 500 V after a pre-count discharge of 900 V [12].

4. Results and discussion

We obtained density, D, of the events of (22 ± 2) sparks/cm^2 (aluminium-holes/cm^2) with the bismuth stack (figure 3) (background is much less than 0.1 spark/cm^2). With these data we can calculate the peak neutron fluence simply by assuming that the South Africa spectrum will be equal to that of Uppsala, Sweden. The ratio, R, between the number of fissions induced by the 100 MeV peak neutrons and the number of fissions induced by neutrons by the entire spectrum is 0.73 as measured by Smirnov and Prokofiev with time-of-flight spectrometry by thin film.

The thin film breakdown counter (TFBC) was first developed by Tommasino *et al* [2]. It was however Smirnov and co-workers from Khlopin Radium Institute, who developed this novel detector to such an extent that it became useful for practical applications [13,14]. The TFBC technique can be considered as the real-time analogue of solid-state nuclear

Table 1. Measured and calculated neutron fluence.

Energy (MeV)	(Sparks/neutrons)$*10^{-7}$	Sparks/cm^2	Measured neutron peak fluence	Calculated neutron peak fluence
100	2.2 ± 0.2	16 ± 2	$(7.7 \pm 0.4)*10^{-7}$	$(7.3 \pm 0.8)*10^{-7}$

track detector (SSNTD) as they combine the threshold detection properties of SSNTD with good timing characteristics of microelectronic devices. The number of sparks per cm^2 induced only by the peak neutron is

$$R * D = 0.73 * (22 \pm 2)\ \text{sparks/cm}^2 = (16 \pm 2)\ \text{sparks/cm}^2.$$

The calibration, C, of the bismuth ANPA-stack was carried out at Uppsala using 100 MeV neutrons. In Sweden, all the measurements were performed at the Neutron Beam Facility using the Gustaf Werner Cyclotron at The Svedberg Laboratory in Uppsala. The neutrons were produced by the ^{7}Li(p, n) reaction in 4–15 mm thick discs of enriched ^{7}Li. The neutron spectrum consists predominantly of a high-energy peak due to the transitions to the ground state and to the first excited state in ^{7}Be nuclei [15].

$$C = (2.2 \pm 0.2) * 10^{-7}\ \text{sparks/neutron}.$$

The above data were used to calculate the peak fluence at iThemba Facility in South Africa. The ^{7}Li(p, n)^{7}Be reaction is employed to produce quasi-monoenergetic neutrons from 25 MeV to 200 MeV. The ^{7}Li(p, n)^{7}Be reaction proceeds only by the transition to the ground state and first excited state of ^{7}Be since all higher levels are unstable. A quasi-monoenergetic neutron emission which is strongly forward-peaked is obtained in this way. Breakup reactions in lithium cause a low-energy tail to the monoenergetic peak. Also (p, xn) reactions in the more massive nuclei of the target holder generate neutrons of lower energies [11]. The neutron emission from these reactions can be roughly approximated by a phase-space distribution with smaller angular dependence. We obtain the peak fluence

$$\Phi\ (\text{peak fluence}) = R * D/C = (7.3 \pm 0.8) * 10^7\ \text{neutrons/cm}^2.$$

When we compared this value of the peak fluence with that given by Prof. Helmet Schumacher, using iThemba Facility, South Africa (i.e. $(7.7 \pm 0.4) * 10^7$ neutrons/cm^2), we conclude that this value is in agreement with the value we obtained using completely different measurement systems with high-energy neutrons as shown in table 1.

5. Conclusion

Bismuth fission track detectors are the only systems capable of measuring high-energy neutrons selectively and with sufficiently high sensitivity. Neutron peak fluence measured by Bi-fission detectors and calculated by integrating the spectral fluence in the region of high-energy peak at 96.7 MeV is almost the same within the experimental error.

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