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Measurement with Bonner spheres spectrometer in pulsed neutron fields

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ABSTRACT

Paper presents results of measurements of neutron spectra with Bonner spheres spectrometer around radiotherapeutic linac producing undesirable photoneutrons and around plasma focus device PF-1000 in which neutrons are generated in $^{2}H + ^{2}H \rightarrow n + ^{3}He$ reaction. In the Bonner spheres an active detector, proportional counter filled with ^{3}He, was replaced by passive one to avoid overloading of the active detector during very short period of neutrons generation. For the measurements around linac track detectors with ^{10}B radiator were used and around plasma focus device pairs of TLDs (^{6}LiF and ^{7}LiF).

1. Introduction

For the specification of neutron fields for radiation protection purposes, and for various other applications, the Bonner spheres spectrometer (BSS) is one of the most frequently used instruments. An active detector of thermal neutrons, usually a proportional counter filled with ^{3}He, is placed in the centre of polyethylene spheres of different diameters. To avoid problems with overloading during measurements around neutron sources working in pulse mode, the active detector of thermal neutrons in the BSS must be replaced by a passive one, e.g. gold foils, track detectors with ^{10}B radiator or pairs of TLDs (^{6}LiF and ^{7}LiF). Each of these passive detectors has some advantages and also limitations. Gold foils have low sensitivity, track detectors have good sensitivity, but a very narrow dynamic range and complicated processing while TLDs offer good sensitivity and a wide range of responses, but the reproducibility of their responses is small and this often leads to undesirable scatter of the values measured.

Both TLD's and track detectors were chosen for the measurements around radiotherapeutic linacs, however, TLD's readings were unacceptably scattered and the cause was not found, so the measurements continued with track detectors only. Another reason for the use of track detectors was a short distance of the laboratory where the irradiated track detectors were processed from the linac facility. It was easy to carry out preliminary irradiation with the aim of selecting the optimal exposure for each Bonner sphere. Previous results (Kralik et al., 2008) taken into account, the goal was to specify the main source of photoneutrons in the linac gantry. For the specification of neutron field around the plasma focus device (Z-pinch), which is installed at the Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland, only TLD pairs were selected, as it was easier to transport the TLD reader. To manage all the measurements within the time allotted to the experiment, it was necessary to use faster evaluation of TLDs instead of time consuming processing of track detectors.

2. Experiment

The Bonner spheres spectrometer, PTB design (Wiegel et al., 1994), produced by Centronic Ltd., UK, consists of a set of polyethylene spheres (density 0.946 g/cm^{3}) with the following diameters usually given in inches (1 inch = 2.54 cm): 3, 3.5, 4, 4.5, 5, 6, 7, 8, 10, and 12. A spherical (3.2 cm active diameter) proportional counter of type SP 9, filled to the pressure of 202 kPa ^{3}He and 101 kPa Kr, normally serves as the thermal neutron detector at the

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centres of the spheres. This so called "active" detector was replaced in pulsed neutron fields by track detectors and TLDs.

The track detector was a sandwich of four CR-39 foils (Page Mouldings Ltd., UK) with boron BE10 radiators (DOSIRAD Company, France); the volume of the sandwich was 1.4 × 1.4 × 0.3 cm^3. Two inner CR-39 were in contact with boron, two outer served as the control ones. The outer foils registered recoil protons and other charged particles only, the inner ones registered in addition alpha particles and ^{7}Li nuclei from ^{10}B radiator. The difference between the responses of inner and outer detectors corresponds to alphas and ^{7}Li nuclei from ^{10}B(n,α) ^{7}Li reaction. For the visualization of tracks, electrochemical etching (Tommasino, 1970) in 30% solution of KOH at 30 °C, 25 $kV_{peak}\cdot cm^{-1}$, 8 kHz, for 5.5 h was adopted, because this method allows easy track counting. The high-resolution (4800 dpi) scanner EPSON Perfection 4990 Photo was used instead of visual counting with a microscope.

During measurements around the plasma focus device the SP 9, the detector was replaced by five ^{6}LiF: Mg, Cu, P (TLD-600H) and four ^{7}LiF: Mg, Cu, P (TLD-700H) chips (Krása et al., 2008). In the polyethylene holder, nine holes for TLD chips were drilled: one hole was exactly in the centre of the Bonner sphere and the remaining eight holes were equidistantly placed around the circle whose centre was identical with the centre of the sphere and whose radius was 9 mm; see Fig. 1. The dimensions of the TLD chips were 3.2 mm × 3.2 mm × 0.9 mm, the holes for their placement had the radius 2.4 mm and depth 1 mm.

TL signals were read-out at a heating ramp 3 °C/s from 50 °C to 240 °C followed by a reader annealing at 240 °C for 120 s in an N_2 atmosphere using a PC-aided Harshaw Model 3500 reader. The response of a pair of the above mentioned chips to a mixed field of thermal neutrons and gamma photons is determined by the relation

$$R^{n}_{TLD600} = R^{n+\gamma}_{TLD600} - k\ R^{n+\gamma}_{TLD700}, \quad (1)$$

where $R^{n+\gamma}_{TLD600}$ is the response of a TLD-600 chip to the mixed field and

$$R^{n+\gamma}_{TLD700} = R^{n}_{TLD700} + R^{\gamma}_{TLD700} \approx R^{\gamma}_{TLD700} = R^{\gamma}_{TLD600} k^{-1} \quad (2)$$

is the response of a TLD-700 chip in the same field. The parameter k was measured in the ^{137}Cs photon beam.

Volumes of TLDs and track detectors are small compared with the volume of SP 9, so the holes in the Bonner spheres, which normally hold the SP 9 counter, were filled with extra polyethylene. Thus the effective thickness of polyethylene was changed and this effect could not be neglected especially for spheres of smaller diameters. Fig. 2 shows ratios of SP 9 readings to the readings of the track detectors in ^{252}Cf field normalized to the ratio obtained for 12 inch sphere. A similar dependence was obtained for TLDs. It was obvious that the response matrix calculated for BSS with SP 9 counter (Wiegel et al., 1994) could not be used, therefore a new response matrix was calculated by means of the MCNP5 code (MCNP5, 2005). The geometrical arrangement specified in the MCNP input file corresponded to those with TLDs. For each ^{6}Li TL chips in the polyethylene sphere the response $R(E)$ was calculated for mono-energetic neutrons with energies E from the interval (10^{-9} ÷20) MeV according to formula (3)

$$R(E) = \int_{E_{min}}^{E} \Phi(E_n)\sigma(E_n)\mathrm{d}E_n, \quad (3)$$

where $\Phi(E_n)$ is neutron energy distribution at the TL chip and $\sigma(E_n)$ cross section of neutron capture reaction ^{6}Li(n,t)^{4}He. Differences between responses of individual chips were negligible. An adjustment of the calculated response matrix to absolute values was made experimentally in the ^{252}Cf neutron field.

The same calculated matrix as for BSS with TLDs was used for BSS with track detectors and its scaling to absolute values was also carried out in ^{252}Cf field. The decision to utilize the same response matrix was based on two assumptions:

- Volumes of TLD chips and track detectors are comparably small, so the differences in the effective thicknesses of polyethylene were negligible;
- Cross sections of both reactions, ^{6}Li(n,t)^{4}He and ^{10}B(n,α)^{7}Li, follow "$1/v$ law" in the low energy region.

2.1. Measurements around radiotherapeutic linac

Measurements with BSS were performed on the therapeutic coach of the linear accelerator Varian Clinac 2100 C/D. For all collimator settings, the centre of the BSS was at 50 cm distance from the isocentre on the longitudinal axis of the treatment coach. The basic parameters of the irradiation were as follows: the width of the linac pulse 4.5 μs, the repetition rate 90 Hz and the dose rate 3 Gy/min at the isocentre. Two ionization chambers built into the linac head, see Fig. 3, served as monitors of the delivered dose with uncertainty less

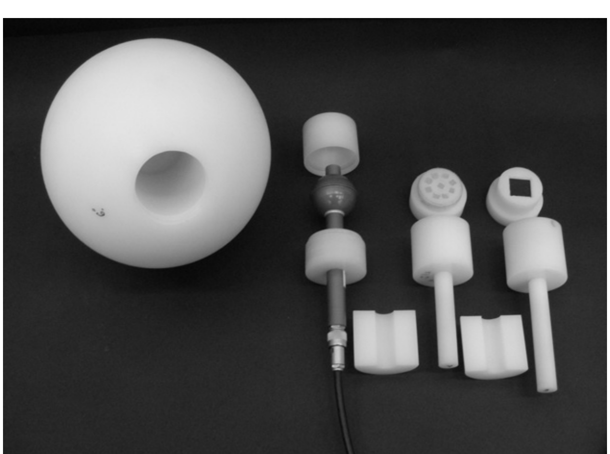

Fig. 1. Holders of SP 9 counter, TL chips and track detectors used in Bonner spheres.

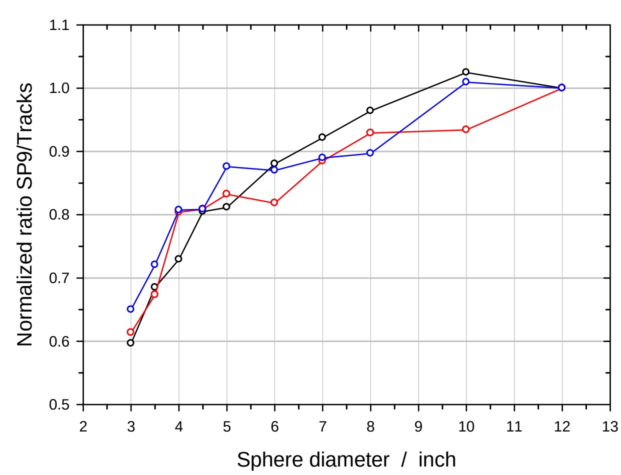

Fig. 2. Normalized ratios of SP 9 readings to the readings of track detectors measured in 252Cf neutron field normalized to the ratio for 12 inch sphere. Ratios were obtained in three independent experiments.