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DOSIMETRY STUDIES OF A HIGH-ENERGY NEUTRON BEAM

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A B S T R A C T

The dose distribution in a water phantom from a high-energy neutron beam produced by the CERN 600 MeV Synchro-cyclotron has been measured and the characteristics of the beam investigated. A method for estimating the absorbed dose to biological specimens in a high-energy neutron beam, using thermoluminescent detectors is described. It is shown that the dose to a biological specimen can be estimated to within about $\pm 15\%$ at small depths where the dose is varying rapidly with depth. Radioactivity induced in biological material by high-energy neutrons is shown to make a negligible contribution to the total dose.

1. INTRODUCTION

The estimation of the flux of high-energy neutrons corresponding to the maximum permissible radiation level for radiation protection is based on calculations (ICRP, 1963). These calculations include the absorbed dose per unit particle flux as a function of energy and the assignment of quality factor (QF) (Neary, 1967) to the radiation from a consideration of the calculated LET spectra of secondary charged particles produced (Neufeld, Snyder, Turner and Wright, 1966). There do not appear to be any experimental verifications of these quantities.

The properties of the high-energy neutron beam that can be produced by bombarding an internal beryllium target in the CERN 600 MeV Synchro-cyclotron were therefore investigated to determine the ratio between particle flux density and absorbed dose rate, and also to investigate the dose distribution in an absorber so that the dose to a biological specimen placed in the beam can be determined.

The radiobiological studies carried out using the beam will be described elsewhere.

2. THE NEUTRON BEAM

The beam was produced by bombarding a beryllium target placed in the cyclotron such that the axis of the beam pipe used formed a tangent to the circulating protons at the position of the target. The target position for the beam pipe used was at 175 cm from the centre of the machine; at this radius circulating protons have a kinetic energy of 397 MeV. The beam pipe used to collimate

the radiation was a 21.6 cm diameter channel through the 4 m thick shield of the machine and was evacuated. The exit of the beam pipe was approximately 10 m from the target. The layout of the beam area is shown in Fig. 1.

The collimator accepts all radiation that can have a direction along its axis. Charged particles originating from the target are deflected by the field of the cyclotron magnet and the chance of stray charged particles passing through the collimator is small. Tests with an additional sweeping magnet at the exit of the collimator indicated that the contribution of charged particles to the absorbed dose in the beam was less than 1%. The collimator will accept gamma radiation and evaporation neutrons as well as the high-energy neutrons that are emitted in the forward direction. The upper limit of the gamma component was estimated by exposing personnel monitoring gamma films in the beam, from which it was estimated that gamma rays contribute less than 8% to the absorbed dose. The spectrum of the neutrons was not measured; however, measurements under similar conditions using 480 MeV protons to bombard a beryllium target show a broad peak in the neutron spectrum some 100 MeV below the primary proton energy and a fairly constant distribution at about half the peak intensity down to about 50 MeV (Dzhelepov, 1955). No information exists for the proportion of the spectrum below this energy.

3. INSTRUMENTATION AND METHODS

The beam was monitored by a thin walled ionization chamber attached to the end of the beam pipe. This chamber had the same diameter as the beam pipe and presented a total mass in the beam of 35 mg/cm^2 . The ionization current was measured by an electrometer which was used to drive a digital integrator. All measurements in the beam were normalized using this monitor.

The intensity profile across the beam and its divergence was checked using a 30 cc ionization chamber mounted on a remote-controlled XY scanner. A series of horizontal scans at various heights, taken at 4 m from the exit of the beam pipe is shown in Fig. 2. The beam had about 26 cm diameter and the intensity varied by about 20% across the beam. The profile was expected to be uniform as the beam originates from a target 14 m away. The distortion could be due to inhomogeneities in the material in the beam path, or to inexact alignment of the plane of the circulating protons and target position with the axis of the beam pipe. A sufficient area of constant beam intensity was found at about 6 cm to the right of the beam axis and subsequent measurements were made with detectors centred on this line. The intensity in the beam varied by about 14% per metre along the beam path; this coincides with the expected divergence of the beam from geometrical considerations.

The measurements of absorbed dose were made using a parallel-plate ionization chamber with collector and polarization plate made from tissue-equivalent plastic (Shonka, Rose and Failla, 1958). The chamber has a collector of 6 cm diameter and a spacing of 3 mm and can be filled with tissue-equivalent gas up to about 6 kg/cm² (Sullivan and Baarli, 1968). This form of construction allows the dose to be estimated at a precisely determined depth. The pressure casing around the chamber is of aluminium which is 1 mm thick on the front surface. The total thickness of the window of the chamber is 570 mg/cm². The construction of the chamber is shown in Fig. 3. The absorbed dose was calculated from a relation:

$$R = 1.29 \frac{i}{P}$$

where R is the dose rate in rad/h, i is the mean measured current using positive and negative polarization in units of 10⁻¹² A, and

P the absolute pressure in kg/cm^2 . This relation is calculated from the dimensions of the chamber and assumes 33 eV absorbed per ion pair formed in tissue-equivalent gas. The calculated sensitivity of the chamber agrees to within about 2% with the value obtained by exposing the chamber to a known gamma ray source. The chamber was operated at $3.6 \text{ kg}/\text{cm}^2$ pressure and a polarizing voltage of 312 V. The voltage and pressure were varied in order to estimate any correction for initial recombination that may be necessary (Sullivan, 1968). This correction was estimated to be between 3 and 5%. The chamber was mounted on a remotely operated movable arm such that it could be moved along the beam axis when immersed in a water phantom.

The flux density measurements were made from an estimation of the production of carbon-11 from carbon-12 in plastic phosphors. These phosphors were 5 mm thick and 10 cm in diameter and the activity produced was counted with the phosphor placed directly on a photomultiplier tube. A cross-section of 22 mb was assumed for the $^{12}\text{C}(n,2n)^{11}\text{C}$ reaction, independent of the neutron energy above 20 MeV (Goebel, 1964).

4. THE ATTENUATION OF THE BEAM IN A WATER PHANTOM

The depth-dose distribution was made by moving the 3 mm parallel-plate ionization chamber through a water phantom contained in a 32 x 32 x 45 cm rectangular tank. Measurements were also made in front of the tank to determine the dose rate at the minimum depth. Flux density measurements were made outside the absorber and at various depths in the water tank so that an extrapolation could be made to zero depth to obtain the primary high-energy neutron flux density in the beam. The depth-dose distribution for the 22 cm diameter beam, described above, is shown in Fig. 4. Also shown in this figure is

the measured variation of high-energy particle flux density with depth. The apparent build-up of particle flux density is due to both the nuclear cascade and to the fact that the contribution of protons produced in the cascade increases with depth, where the carbon-11 production cross-section may be considerably greater than the assumed 22 mb (Goebel, 1964).

The measured parameters of the beam are given in Table 1. The results obtained from an earlier experiment are included for comparison. Basically the same conditions were used in this experiment except that a small error was afterwards discovered in the target alignment, and the beam channel then had a 13 cm diameter compared to 22 cm for the beam described.

It is of interest to note that the depth at which the maximum dose rate occurs appears to be a function of the diameter of the beam, indicating that an extrapolation is required when comparing with data calculated for broad beam conditions. The ratio between the primary flux density and the maximum dose rate in the absorber was 18 and 20 $\text{n/cm}^2/\text{sec}$ per mrad/h for the two beams. The degree of build-up and the absolute value of flux per unit dose indicate that the 22 cm diameter beam behaves approximately as a monoenergetic 150 MeV neutron beam (Neufeld, Snyder, Turner and Wright, 1966). The smaller diameter beam appeared to have a slightly lower effective energy.

5. DOSIMETRY FOR BIOLOGICAL IRRADIATIONS

The composition of the radiation changes markedly over the first few g/cm^2 of absorber due to the production of secondary

particles with different equilibrium depths. At very small depths the short-range spallation products make an important contribution to the absorbed dose; as the depth increases the dose from long-range secondary protons becomes an important contribution. It would therefore be of interest to compare the biological effects of the radiation at the smallest possible depth and at a point somewhere in the region of the maximum dose rate.

As both the dose rate and composition initially vary very rapidly with depth of absorber, the problem of estimating the dose to a biological object in the beam becomes severe. Measurements in phantoms are therefore necessary for the evaluation of the absorbed dose at the point of interest. For this reason a small thermoluminescent detector (TLD) was calibrated against the parallel-plate tissue-equivalent chamber as a function of absorber depth. The TLD could then be used in a phantom of any biological object to estimate the dose at a particular site.

The TLD sample was 42.1 mg of LiF-7 powder in a plastic capsule with 1 mm wall thickness. The sensitivity, expressed relative to the sensitivity to ^{60}Co gamma radiation, is shown in Fig. 5 as a function of absorber depth in the two beams used.

The efficiency of TLD appears to increase with depth as the proton contribution to the dose increases. The relatively high efficiencies found indicate that lightly ionizing secondaries are a significant contribution to the dose after a few g/cm^2 of absorber. The sensitivity of the TLD appears to be about 20% different in the two sets of measurements.

No explanation could be found for the systematic difference in sensitivity other than the difference in beam diameter and the fact that the LiF powders used were obtained at different times.

The dose to the biological specimens was estimated from the TLD reading and a knowledge of the mass in the beam in front of the dosimeter.

Although the difference in sensitivity of the TLD in the two experiments appears to be real, the possibility exists that it is due to systematic differences in the measurement of the absorbed dose. Also, the ionization chamber used to estimate the dose is effectively calibrated for gamma rays and will underestimate the dose by up to about 5% due to differences in the energy required to form an ion pair in the gas by the different types of charged particles that will be produced. Systematic errors of up to $\pm 15\%$ therefore appear to be possible in an estimation of the absorbed dose to biological samples. Random variations in the apparent sensitivity of TLD add a further 5% uncertainty to a single estimation of the dose.

6. DOSE FROM INDUCED RADIOACTIVITY

Samples irradiated in a high-energy particle beam become radioactive and the energy from the subsequent decays needs to be added to the dose received from direct radiation. Calculations of the induced-activity dose to tissue irradiated by 600 MeV protons (Barbier, Hutton and Pasinetti, 1966) indicate a dose from induced activity of 2×10^{-4} rad per 2.7×10^7 p/cm². This figure can be applied directly to the case of high-energy neutrons as nuclear interaction cross-sections are of the same order. Such a calculation

indicates that the induced-activity dose integrated over a long time will never exceed 1% of the dose received in the neutron beam.

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Table 1

The measured parameters of the beams

Diameter of beam pipe cm	Dose rate at 1 g/cm ² rad/h	Dose rate at max. build-up rad/h	Depth of max. dose rate g/cm ²	Build-up from 1 g/cm ² to max.	Beam flux density n/cm ² /sec above 20 MeV
20	5.1	10.0	22	1.95	2.0 x 10 ⁵
13	2.54	4.45	17	1.75	8.0 x 10 ⁴

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FIGURE CAPTIONS

1. The layout of the neutral beam area.
2. Horizontal scans across the beam at different distances from the beam centre. The arrow indicates the position selected to make the irradiations.
3. The 3 mm variable-pressure tissue-equivalent ionization chamber.
4. The variations of the dose rate and the high-energy particle flux density with depth in water.
5. The sensitivity of (LiF-7) TLD powder relative to that for gamma rays as a function of depth in absorber.

Fig.1

Fig. 2

Fig. 3

- aluminium alloy
- polyethylene
- TE plastic
- brass

Fig. 4

Fig. 5