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NEUTRON RADIATION PRODUCED BY THE 32 MeV ROENTGEN BEAM OF A MEDICAL BETATRON

by

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Nowadays, medical betatrons are used mainly for the production of high energy roentgen rays, and most radiotherapeutic treatment is given with the maximum energy of the machine.

Neutron radiation is created when the energy of the roentgen rays exceeds the threshold energy for a (γ, n)-reaction; this is unwanted radiation when patients are treated with either roentgen rays or electrons from a betatron. The most important reactions concerned in the irradiation of human tissue are those in ^{12}C, ^{14}N and ^{16}O, with the threshold energies 18.72, 10.55 and 15.67 MeV, respectively. When the betatron beam strikes heavy materials of the collimating systems, or other parts of the machine, neutron radiation is also produced.

Difficulties have been encountered in earlier investigations of the neutron radiation, in view of the strong electron or roentgen radiation that affects the measurements. These difficulties can be overcome by application of a detection method that is not disturbed by other radiations. The solid state track detectors used in this study are suitable in this respect.

The purpose of this investigation was to develop a solid state track detector,

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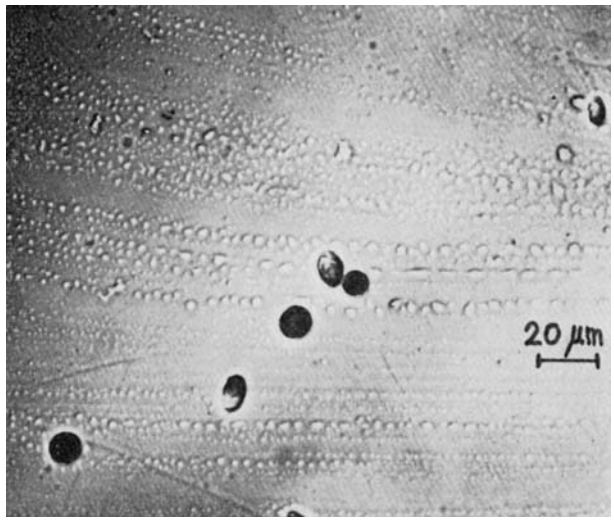

Fig. 1. Etched tracks in soda-lime-silica glass.

intended especially for measurement of the neutron contamination in the beam of the medical betatron and in the neighbourhood of the machine. Furthermore, a great deal of care was given to the determination of the neutron radiation to the patient under treatment.

Solid state track detectors. When heavy particles, such as fission fragments or atomic nuclei, traverse certain insulating solids they leave trails of radiation damage, which become evident as tracks when examined under a transmission electron microscope (FLEISCHER et coll. 1965). The trails of radiation damage are chemically attacked much more rapidly in an etching solution than is the undamaged part of the solid (PRICE & WALKER 1962). After the etching procedure, the tracks are visible under an optical microscope; they appear black in normal bright-field illumination and white when viewed on a dark field.

The solid state detector also provides a possibility of detecting neutrons by allowing them to traverse a neutron fissionable material which is put close to a track-detecting solid in which the resultant fission fragments cause damage.

The solid state track detector is usable as a radiation dosimeter, as the track intensity, that is, the number of tracks per unit area, is a measure of the radiation. Consequently, the detector can be calibrated by the aid of known neutron sources.

After experiments with a number of different materials (e.g. biotite, muscovite, polycarbonate resin) glass was found to be the best material for these measurements. The detector material consisted of an ordinary soda-lime-silica glass, in which uranium oxide had been mixed to the amount of 1 % uranium. The detectors were prepared at the Nuutajärvi-Notsjö Glass, Wärtsilä Corporation. The detectors measured 17 mm × 30 mm × 2 mm.

The etching was effected in 38 to 40 % hydrofluoric acid for 12 seconds. The temperature of the etching solution was 65° C. A criterion in the determination of the etching parameters was that the tracks should be clearly visible under an optical microscope with a magnification of × 900. In counting the tracks, only those with a sharp base were accepted. An example of the tracks is reproduced in Fig. 1.

Detection method. The following formula is valid for the number of fissions K

$$K = \sigma_f N x \Phi \tag{1}$$

where σ_f is the fission cross-section, N is the number of fissionable atoms within depth x of the detector material, x is the mean path of a fission fragment for producing a track visible after etching, and Φ is the total neutron fluence.

The track density T, i.e. the number of tracks per cm^2, is given by the formula

$$T = \beta K = \beta N x \sigma_f \Phi = F \sigma_f \Phi \tag{2}$$

where β is the efficiency of the detector and F $(= \beta N x)$ in this paper is called the detector constant (which is mainly dependent upon the etching parameters: reagent, time, temperature, and type of glass). It has been found that the efficiency of glass detectors is about 0.40 (DEBEAUVAIS et coll. 1964).

The detector constant can be determined experimentally by irradiation of the detectors by monoenergetic neutrons of known energy. By determination of the track density, the F-value is obtained from formula (2). When the neutron energy varies, the effective cross-section $\bar{\sigma}_f$ and the integrated fluence Φ have to be determined from the energy distribution of the neutrons.

The detectors were calibrated against two Am-Be-sources (Department of Physics, University of Helsinki and Institute of Radiation Physics, Helsinki). With the neutron source placed in water, the neutrons are in thermodynamical equilibrium with the water when the distance is greater than 2 cm, and it can be assumed that the spectrum consists of a Maxwell distribution and a tail, which is $1/E$-distributed, where E is the neutron energy (BECKURTS & WIRTZ 1964). A temperature of 293° K, corresponding to a neutron energy of 0.025 eV, was used in calculation of the Maxwell distribution. The cross-sections for

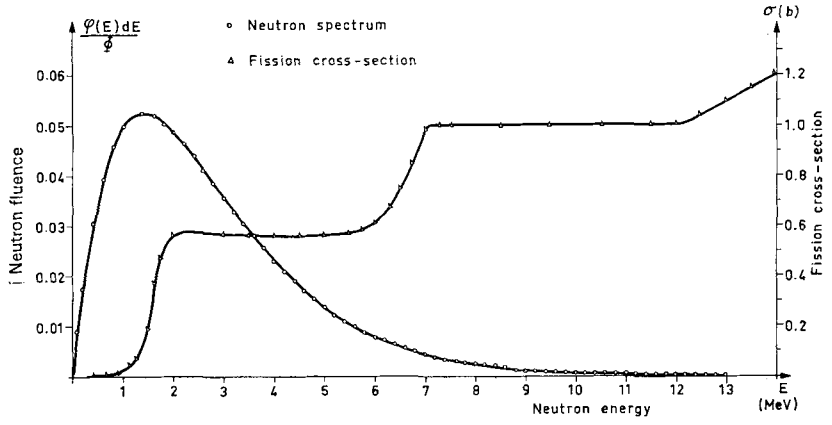

Fig. 2. Spectrum of the neutron radiation from the betatron and cross-sections for natural uranium, calculated with the aid of the values published by SCHMIDT (1962).

natural uranium (Fig. 2) have been calculated with the aid of the values published by SCHMIDT (1962) and HALPERN (1959).

When the integrated neutron fluence Φ and the effective cross-section $\bar{\sigma}_f$ are known, the detector constant F is determinable by the application of formula (2). The numerical integrations were made in accordance with the Weddles rule (MARGENAU & MURPHY 1964), and $F = (0.66 \pm 0.10)$ tracks/(neutrons · barn) was obtained.

It is now possible to determine the total neutron fluence Φ_m measured with the detectors concerned. The following formula is valid

$$\Phi_m = \frac{T_m}{\bar{\sigma}_{fm} \cdot F} = k \cdot T_m \tag{3}$$

where $\bar{\sigma}_{fm}$ is the effective cross-section for the neutron fluence under investigation, F the detector constant obtained above, T_m the measured track density, and $k = 1/\bar{\sigma}_{fm} \cdot F$.

The effective cross-section $\bar{\sigma}_{fm}$ must be determined separately for every measurement if the measuring conditions are changed. The calculations in this study were based upon values reported by SCHMIDT (1962), and the cross-sections obtained are given in Table 1.

In the application of formula (3), a correction for spontaneous fission in ^{238}U must be taken into consideration, as the spontaneous fission decay constant

Table 1

Results of measurements in a water phantom

Depth (cm)	$\bar{\sigma}_{fm}$ (mb)	$\bar{R}_c$ (rem/(n/cm²))	$\overline{QF}$ (rem/rad)	Neutron dose equivalent (mrem/rad roentgen dose*)		Neutron dose (mrad/roentgen dose*)	
				Inside beam	Outside beam	Inside beam	Outside beam
0.3	116	$8.06 \cdot 10^{-9}$	7.6	0.021 ± 0.005	0.021 ± 0.006	0.0028 ± 0.0007	0.0028 ± 0.0008
5.5	52.5	$3.58 \cdot 10^{-9}$	5.0	0.029 ± 0.007	0.024 ± 0.006	0.0058 ± 0.0002	0.0048 ± 0.0002
13.5	55.9	$3.35 \cdot 10^{-9}$	4.8	0.023 ± 0.005	0.019 ± 0.005	0.0048 ± 0.0001	0.0040 ± 0.0001
20.5	55.9	$3.35 \cdot 10^{-9}$	4.8	0.022 ± 0.005	$0.027 + 0.004$	0.0046 ± 0.0001	0.0056 ± 0.0001

*Roentgen dose measured in water at the maximum point of the depth dose curve.

$\lambda_f = (6.9 \pm 0.2)\ 10^{-17}\ a^{-1}$ (FLEISCHER & PRICE 1964). This implies about 25 fissions per hour in one gram of ^{238}U.

The final formula for the neutron fluence is

$$\Phi_m = k \cdot T_m - T_{sf} \tag{4}$$

where T_{sf} corresponds to the track density caused by spontaneous fissions.

If photon energies that exceed 5 MeV are used, photofission reactions are also possible, although the cross-sections for these reactions are so low that the reactions do not disturb the measurements. An estimate indicates that only about 3 per thousand of the tracks originate from these reactions.

Finally, when the neutron fluence is determined, the corresponding dose equivalent DE (rem) can be calculated:

$$DE = \bar{R}_c \cdot \Phi_m \tag{5}$$

and the corresponding dose D (rad):

$$D = \frac{DE}{\overline{QF}} = \frac{\bar{R}_c \Phi_m}{\overline{QF}} \tag{6}$$

where effective values of the conversion factor R_c (rem/(neutrons/cm²)) and the quality factor QF must be used in view of variations in the neutron energy. The $\bar{R}_c$-calculations were effected with the neutron energy spectra determined and the R_c-values based upon information given in NBS Handbook No. 63 (1957). The effective quality factor was calculated with the aid of values given in this handbook as well as in ICRP No. 4 (1964).

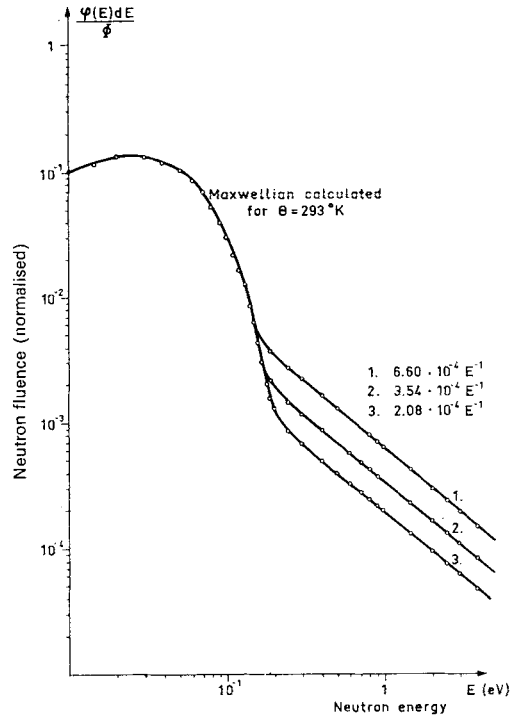

Fig. 3. Calculated neutron spectra in water at (1) 5.5 cm, (2) 13.5 cm and 20.5 cm depths, and (3) at a distance of 7.0 cm from an Am-Be-source.

Measurements

All the measurements were made with SSD = 80 cm, field 10 cm × 10 cm and a roentgen energy of 32 MeV. In every single measurement, the roentgen dose corresponded to a dose of 860 rad measured in water at the maximum point of the depth dose curve.

Measurements in air. The neutrons originate from (γ,n)-reactions in the betatron collimator and other heavy material of the machine. The energy spectrum must be calculated theoretically (BLATT & WEISSKOPF 1952). It is assumed that the spectrum is Maxwell distributed, with a temperature of $\Theta = 1.4$ MeV ($\pm$ 7 %), where the errors shown are the possible maximum deviations, by reason of the approximations made in the calculations (Fig. 2). The effective cross-section $\overline{\sigma} = 86.9$ mb, $\overline{R_c} = 7.66 \cdot 10^{-9}$ rem/(n/cm^2), and $\overline{QF} = 7.4$ were determined.

An average value of 0.014 $\pm$ 0.006 mrem/R was obtained, with the exposure measured at the central ray 80 cm from the anticathode. This corresponds to a neutron fluence of $(1.8 \pm 0.7)10^3$ (n/cm^2)/R. It should be observed that

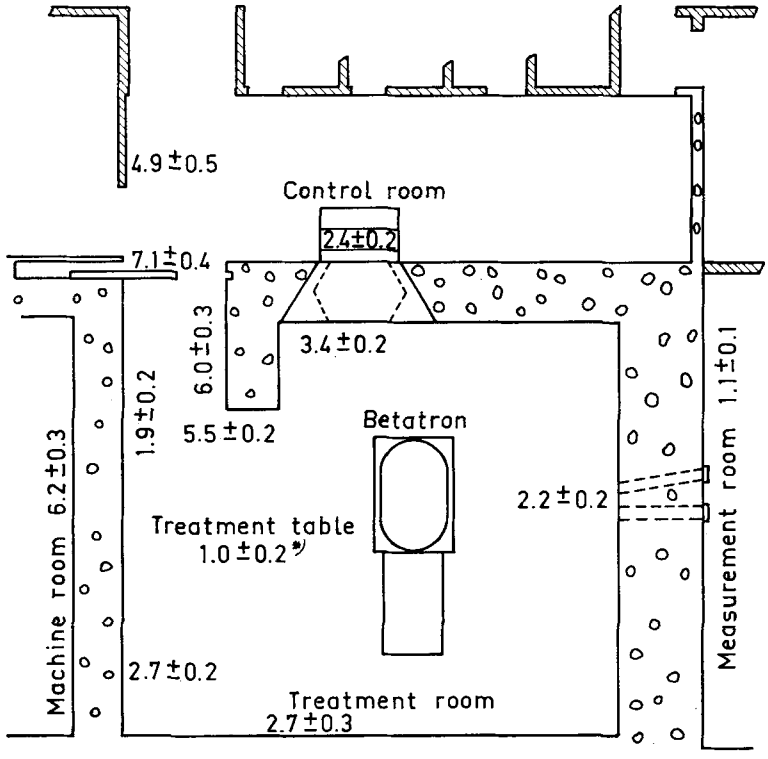

Fig. 4. Schematic figure illustrating the neutron dose equivalents in mrem/h measured at different points in the surroundings of the betatron. Asterisk indicates measurement under the treatment table.

the same value was obtained both inside and outside the beam. The measurements were made up to a distance of 7 cm outside the field used. The values were higher at the central ray, i.e. 0.039 ± 0.006 mrem/R and $(5.1 \pm 0.7)10^3$ $(n/cm^2)/R$ respectively.

Measurements in a water phantom. The neutron dose in water — tissue-equivalent material — consists of the neutrons measured earlier together with the neutrons originating from (γ,n)-reactions in tissue, mostly from the $^{16}O(\gamma,n)^{15}O^*$ reactions.

The neutron spectrum used for the calculation of $\bar{\sigma}_{fm}$, $\overline{R_c}$ and $\overline{QF}$ was a sum of a Maxwell distribution and a neutron spectrum of the $^{16}O(\gamma,n)^{15}O^*$ reaction presented by FUCHS et coll. (1965). The neutron spectrum varies for different depths in the water (BECKURTS & WIRTZ 1964). When the depth exceeds 10 cm, it can be assumed constant.

Table 2

Measurements of neutron radiation in the roentgen ray beam of a betatron

Investigation	Energy (MeV)	Neutron dose equivalent per roentgen exposure (mrem/R)	Neutron fluence ((n/cm²)/R)	Betatron
WÄFFLER	31	2.8	$1.3 \cdot 10^4$ at 1 m	BBC-31 Medical
LAUGHLIN (1951)	23	3.0	$4.2 \cdot 10^4$ at 0.84 m	University of Illinois Medical
POHLIT (1960)	31	2.4	$3.1 \cdot 10^5$	BBC-31 research
FROST & MICHEL (1964)	34	15	$1.7 \cdot 10^5$ at 1 m	Asklepitron
BRENNER (1965)	32	1.0 . . . 1.3*	$(1.3 \ldots 1.7)10^5$ at 1 m	Asklepitron
Present	32	0.039	$5.1 \cdot 10^3$ at 0.8 m	Asklepitron

Asterisk denotes: calculated with an effective value of $R_e = 7.66 \cdot 10^{-9}$ rem/(n/cm²).

The spectrum at a depth of 0.3 cm is assumed to be a Maxwell distribution, with $\Theta = 1.4$ MeV and an added tail of photoneutrons. For depths of 5.5, 13.5 and 20.5 cm, the distribution consists of a Maxwell distribution ($\Theta = 0.025$ eV $= 293°$ K), and an $1/E$-tail. These spectra are shown in Fig. 3, together with the spectrum used for the Am-Be-source in water. The influence of neutrons from ^{16}O (n) $^{15}O^*$ reactions is accounted for in the $1/E$-tail, since these neutrons have not reached thermodynamical equilibrium with the water.

All the values obtained for $\bar{\sigma}_{fm}$, $\bar{R}_c\overline{QF}$ and the measurements made with the solid state detectors, are contained in Table 1. The neutron doses and dose equivalents correspond to a roentgen dose of 1 rad at the maximum point of the depth dose curve, i.e. at a depth of 5 cm in water.

Table 1 illustrates that the neutron radiation is inclined to be similar within and outside the beam. It can be said that on the average the neutron dose equivalent is 0.0045 ± 0.0004 mrem per 1 rad roentgen dose at the dose maximum. It must be emphasized that the measurements are made only to a depth of 20.5 cm in water, and to a distance of 7 cm outside the beam, i.e. the irradiation field.

Measurements during treatment. Detectors were placed at different points in and outside the treatment room. A schematic figure of the room, the betatron, and the surroundings is reproduced in Fig. 4. The detectors were kept there for three weeks, with 40 hours treatment time per week. The results of

measurement are indicated in the figure. Most of the results are of the order of the allowed maximum dose equivalent 2.5 mrem/h, which of course also includes all other types of irradiation. No one is allowed to stay in the neighbourhood of the door of the treatment room or in the machine room during the irradiation.

Discussion

The results obtained in this study are compared in Table 2 with those published earlier. The differences in the results are difficult to explain. Of course, all the other measurements are based upon activation analysis, and at least some of them are influenced by the strong roentgen, beta or proton radiation present during the measurements. The solid state track detector should not be affected by radiation other than neutron.

The results presented here have moreover been checked with a BF_3 proportional counter (ANDERSSON & BRAUN 1964), developed by AB Atomenergi, and made by 20th Century Electronics. With this counter 115 ± 5 mrem/h was obtained in air at the central ray 80 cm from the anticathode. The corresponding value deduced from the measurements with the detectors employed was 98 ± 16 mrem/h. Measurements made behind 8.2 cm water gave 80 ± 10 mrem/h (proportional counter) and 75 ± 18 mrem/h (SST-detectors). The SSTD-measurements are also in agreement with scintillator counter (boron enriched scintillator) measurements made by RYTILÄ (1962).

The dose equivalent to the patient caused by the neutron radiation is 0.11 ... 0.16 rem during a treatment of 6 000 rad. This is a small value (0.0037 ... 0.0053 rad, $QF = 30$) even for the eyes which are sensitive to neutron radiation.

Acknowledgement

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SUMMARY

Solid state track detectors, consisting of 1 % uranium soda-lime-silica glass, have been used for investigation of the neutron fluence and the corresponding neutron doses and dose equivalents inside, outside and in the neighbourhood of the roentgen beam of the medical betatron.

ZUSAMMENFASSUNG

Kernspurendetektoren aus festem Material, bestehend aus 1%-igen Uran Soda-Kalk-Kiesel-Glas, wurden für Untersuchungen der Flussdichte von Neutronen und der entsprechenden Neutronendosen und der Dosis-Äquivalente innerhalb, ausserhalb und in der Nähe des Strahlenganges eines medizinischen Betratrons verwendet.

RÉSUMÉ

Des détecteurs à l'état solide, faits de verre de silicate, de soude et de chaux à 1 % d'uranium ont été utilisés pour étudier la fluence des neutrons et les doses correspondantes des neutrons ainsi que les doses équivalentes à l'intérieur, à l'extérieur et dans le voisinage du faisceau d'un bétatron médical.

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