

ANALYSIS OF THE BREMSSTRAHLUNG BEAM WITH
EMPHASIS ON THE NEUTRON CONTAMINATION

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The neutron component of the hardened bremsstrahlung beam of a 42 MeV betatron has been examined. Using nuclear emulsions as radiator and detector both the gamma ray intensity as well as the neutron spectrum and fluence have been measured and dose equivalent for the fast neutron contamination of the beam has been deduced.

1. Introduction

The hardening of the gamma ray beams used in radiotherapy by filtering through various materials introduces neutron contamination, neutrons being produced mainly via γ , n reactions in the target, collimation system and filters¹⁾. Even though the fluence of neutrons is small in comparison with the photon intensity, the presence of neutrons may add to the dose absorbed in tissue because of the large quality factor for neutrons. The latter depends on neutron energy and a knowledge of the neutron energy spectrum is necessary for dose calculation. On the

other hand direct neutron dosimetry in a mixed field possess some problems because the large γ intensity makes the use of some typically neutron dosimeters (like fission *SSNTD*) difficult in the direct beam²⁾.

The γ ray spectrum itself is of interest when depth dose due to gamma rays is being determined. Moreover, if the filtered beam is used as a high energy γ source for experiments studying photonuclear reactions, the form and intensity of the γ spectrum is needed. In recent years precise methods have been developed to determine bremsstrahlung spectra by measuring protons or neutrons from the break up of the deuteron³⁾. However, these methods require an elaborate apparatus. Nuclear emulsions loaded with heavy water were also employed by several authors, but this method, though rather simple, is less reliable because soaking in water and exposing wet emulsions reduces considerably the emulsion sensitivity.

In the present paper a simple method using nuclear emulsions as radiator and detector is applied. The fast neutron spectrum is measured simultaneously with the photon fluence via the n, p scattering and γ, p reaction, respectively. Knowing the fast neutron spectrum it is possible to calculate the neutron dose in the mixed γ and neutron field.

2. Experimental procedure

The bremsstrahlung beam from a Siemens-Reiniger Werke betatron at an end-point energy of 42 MeV was examined. The beam was allowed to pass through a 160 g cm^{-2} aluminium filter consisting of two narrow cylinders of equal length with diameters of 4 cm and 6 cm, respectively. The shape of the γ spectrum of the unfiltered beam being known⁴⁾, the filtered spectrum can be calculated. The shape of the computed »hardened« spectrum is shown in the inset to Fig. 1.

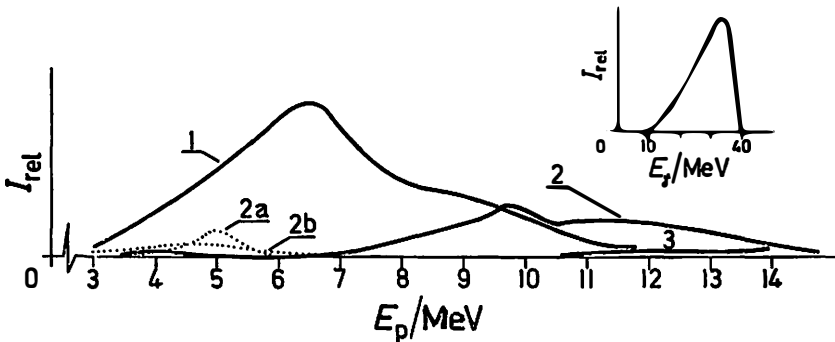


Fig. 1. The expected relative proton yield in the emulsion due to the following reactions: $^{12}\text{C}(\gamma, p_0) \dots$ (1), $^{16}\text{O}(\gamma, p_0) \dots$ (2), $^{16}\text{O}(\gamma, p_{1,2}) \dots$ (2a), $^{16}\text{O}(\gamma, p_3) \dots$ (2b) and $^{14}\text{N}(\gamma, p_0) \dots$ (3). The incident γ spectrum is shown in the inset.

After passing through the filter, the beam fell on an Ilford K2 nuclear emulsion plate wrapped in black paper, situated at 20 cm from the aluminium cylinder and inclined at 30° to the incident beam. The total distance from the source to the detector was 120 cm. By cutting the low part of the bremsstrahlung spectrum, the thick filter considerably reduced the fogging of the emulsion.

When the beam impinges on the emulsion, any constituent nucleus acts as a target. A list of the most probable (γ , charged particle) reactions on light nuclei of the emulsion (C, N, O) is given in Table 1. For heavy nuclei (Ag, Br), the Coulomb barrier inhibits the emission of charged particles at giant resonance energies⁵¹. Table 1 gives the peak value of the differential cross section at 90° (column 5) and the following energies: the threshold energy (E_{th}), the energy at the peak value of the cross section (E^M), the corresponding energy of the emitted particle (E_b) and, for particles other than protons, the energy assigned to the emitted particle according to the length of its track as if it were a proton (E_p).

TABLE 1

Reaction	emitted particle	E_{th} MeV	E^M MeV	(90°) mb/sr	E_b MeV	E_p MeV	Ref.
$^{12}\text{C}(\gamma, b)$	p_0	16	22.7	1.4	6.4	6.4	6)
	p_2	20.4	29	0.12	7.9	7.9	7)
	p_3	21	30	0.12	8.8	8.8	7)
	d	25	33	0.002	6.5	3.5	8)
$^{16}\text{O}(\gamma, b)$	p_0	12.1	22.5	0.75	9.7	9.7	9)
	$p_{1,2}$	17.4	23	0.7	5	5	9)
	p_3	18.2	23	0.35	5.1	5.1	9)
	t	25	30	0.08	4	2.8	10)
$^{14}\text{N}(\gamma, b)$	p_0	7.6	22	0.26	13.8	13.8	11)
	p_2	11.2	23	0.08	10.9	10.9	11)

The last column gives the reference from which the data have been taken.

We have computed the expected relative yield of protons emitted at 90° for the five most probable reactions cited in Table 1 taking into account the shape of the γ spectrum, the known differential cross sections and the relative abundance of various elements in the emulsion. The yield as a function of proton energy is shown in Fig. 1.

It is evident that the most probable reaction is $^{12}\text{C}(\gamma, p) ^{11}\text{B}_{g.s.}$. Moreover, the bulk of protons emitted in this reaction is comprised between 2.5 and 9 MeV, i. e. outside the region in which protons from other reactions are emitted in an appreciable amount.

If the incident beam is contaminated with fast neutrons, the predominant reaction is n, p scattering. In this reaction the proton is emitted in the forward hemisphere, its energy being zero at 90°. On the other hand, the γ, p process, occurring with highest probability in the giant-resonance region, has an angular distribution peaked at 90°. For that reason, the plates were scanned for proton tracks in a narrow »pyramid« oriented alternately so that the protons emitted in the forward direction, in the backward direction and at 90° to the incident beam been detected separately. The »pyramid« was defined by a maximum angle of $\pm 10^\circ$ in the plane of the emulsion and a dip angle of $\pm 13^\circ$. The length of each track emitted in the given direction inside given angular limits has been measured and the proton energy deduced.

The experiment was monitored with a *PTW* duplex ionization chamber dosimeter (0.1 ccm) covered with plexiglass 6 cm thick and exposed to the filtered beam at the same distance from the target as the emulsion. All results are therefore normalized to a gamma ray dose of 1 Gy as defined by the conditions described above.

3. Results

i) *Energy spectra.* The measured proton spectrum in the forward direction is shown in Fig. 2. The bars (thick lines) are statistical errors. This spectrum has a broad peak at 1.5 MeV, cut sharp at low energies, and a prolonged »tail« toward higher energies. The spectrum of protons emitted backward (Fig. 2. — thin bars) has a similar shape, but much lower intensity.

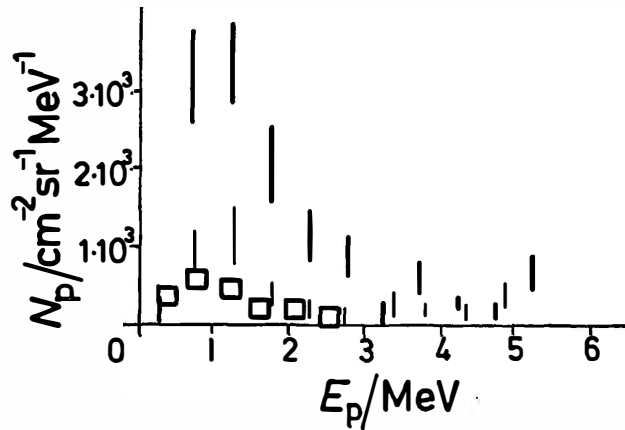


Fig. 2. Proton spectrum — lower energy portion — measured in the forward direction (thick bars), backward direction (thin bars) and at 90° (open squares).

The ratio $[\int N_p(E) dE]_{\text{forward}} / [\int N_p(E) dE]_{\text{backward}}$ equals 4, the integration limits being 0.5 and 2.5 MeV. The predominance of forward emitted protons suggests that they are emitted in n, p scattering, neutrons being contained in the incident beam in the direction of the primary radiation. About 25% of protons emitted in this energy region in the forward direction is attributed to a component not dependent on the angle of emission; namely the same spectrum appears at backward angles and at 90° (open squares in Fig. 2.) with approximately the same intensity. This »background« arises from secondary reactions and backscattering on the walls, etc. of the accelerator room. It is subtracted from the forward spectrum by reducing the statistical weight of each track in the ratio $(N_f - N_b)/N_f$, where N_f and N_b are the number of tracks in 0.5 MeV intervals in the forward and backward direction, respectively. The neutron spectrum has been deduced from the protons emitted in the forward direction by computing the neutron energy for each track. This spectrum, representing the fast neutron contamination of the direct beam, is shown in Fig. 3.

The dotted line is the photoneutron spectrum for 25 MeV bremsstrahlung on tantalum, as given by Wilenzick²⁾. Both spectra have a similar shape, but our spectrum is removed toward higher energies. It must be emphasized, however, that the end-point energy in the two cases is different, namely 25 and 40 MeV, respectively.

At 90° to the incident beam, the proton spectrum can be divided into three groups: as already mentioned, the first group at 0.5—2.5 MeV belongs to secondary effects; the second, most intensive group at 2.5—10 MeV is assumed to arise predominantly from the $^{12}\text{C}(\gamma, p)^{11}\text{B}_{g.s.}$ reaction; the third group extending from about 10 MeV to higher energies is due to protons emitted in various (γ, p) reactions which cannot be separated. The proton spectrum measured in the 2.5—14 MeV interval is shown in Fig. 4. The dashed line is the expected yield for the $^{12}\text{C}(\gamma, p)^{11}\text{B}_{g.s.}$ reaction taken from Fig. 1 and normalized to the same area as the measured one. The corresponding photon energy scale is also indicated on the abscissa.

ii) *Fluence and dose.* The fluence of incident particles in a definite energy range is computed from the measured number of protons emitted per target particle in a definite direction and from the known differential cross section for the particular reaction between the incident particle and the target nucleus. In case of the incident gamma ray the target nucleus is ^{12}C and the reaction in question is $^{12}\text{C}(\gamma, p)^{11}\text{B}_{g.s.}$. The photon fluence in the gamma energy interval 19—25 MeV amounts to $(8.8 \pm 1.1) \cdot 10^9 \text{ cm}^{-2}$, the quoted error being statistical. This value can be used to calibrate the spectrum from Fig. 1. By comparing the area under the computed curve in the measured energy region to the total area the fluence of photons between 10 and 42 MeV has been deduced (Table 2).

The measured fast-neutron fluence amounts to $(4.12 \pm 0.4) \cdot 10^7$ neutrons per cm^2 . This value may be compared with $7.3 \cdot 10^7$ neutrons per cm^2 obtained by Wilenzick et al.²⁾. Their measurements were performed on the unfiltered beam from a 19 MeV Siemens betatron by means of a silicon diode dosimeter. Other properties pertaining to the fast neutron component of the 42 MeV bremsstrahlung beam are displayed in Table 2. They have been deduced from the neutron spectrum of Fig. 3, where the number of neutrons per cm^2 is given as a function of neutron energy. Kerma has been computed for a small mass of tissue in free space as given by Auxier et al.¹²⁾.

The quality factor (QF) needed to calculate the dose equivalent (DE) has been taken from the ICRP data¹³⁾. The estimated fluence of γ radiation is also given in Table 2 for comparison. The corresponding γ energy fluence has been computed taking the mean energy of 27 MeV.

TABLE 2

Rad. type.	Energy (MeV)	Fluence (cm^{-2})	Energy fluence (Jm^{-2})	Kerma (Gy)	Dose (Gy)	DE (Sv)	Error statistical
Fast n	0.5	$4.12 \cdot 10^7$	0.267	$2.5 \cdot 10^{-3}$		0.02	10%
γ	10—40	$4.64 \cdot 10^{10}$ *)	$2 \cdot 10^3$ **)		1		

*) Estimated from the fluence measured between 18 and 25 MeV.

***) Calculated for the mean energy of 27 MeV.

4. Conclusion

The absolute energy spectrum of neutrons in the mixed gamma and neutron field as measured in this experiment (Fig. 3) enables one to calculate the dose equivalent due to the neutron contamination (Table 2). The ratio of the neutron *DE* to the γ ray dose as measured using the ionization chamber is $2 \cdot 10^{-2}$. This number is an estimate of the additional radiation dose absorbed by the patient due to the fast neutron contamination of the bremsstrahlung beam.

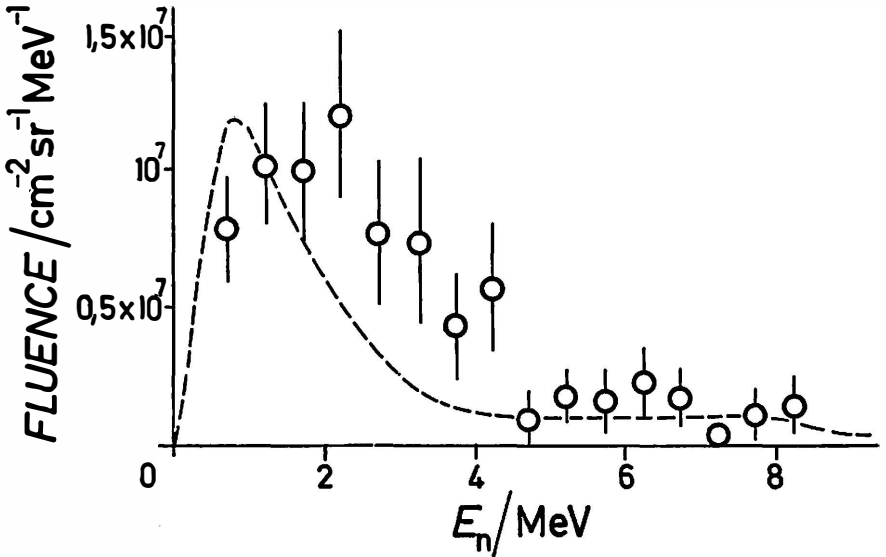


Fig. 3. Neutron spectrum, errors are statistical. The dashed line corresponds to the neutron spectrum as given in Ref. 2.

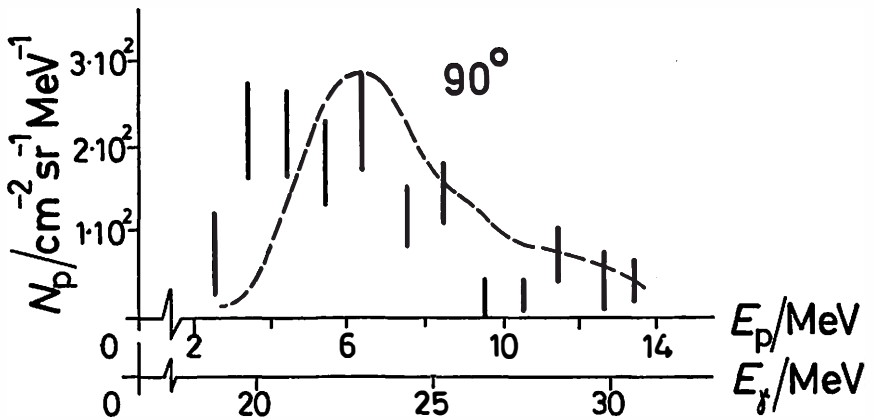


Fig. 4. Proton spectrum at 90° in the 2—14 MeV energy interval. The dashed curve is the expected spectrum for reaction (1) in Fig. 1.

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ISPITIVANJE NEUTRONSKE KOMPONENTE BETATRONSKOG SNOPA

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Analiziran je betatronski snop dobiven zakočnim zračenjem elektrona energije 42 MeV, filtriranim kroz filter od aluminija. Korištena je nuklearna emulzija kao radijator i detektor i to za mjerenje neutronske spektra — preko n, p raspršenja — i za određivanje intenziteta gamma zraka — preko γ, p reakcija u emulziji. Izračunata je kerma i ekvivalent doze za neutronske komponente snopa.