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A fast neutron spectrometer and its use in determining the energy spectra of some cyclotron-produced fast neutron beams

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ABSTRACT

This paper describes the development of a fast neutron spectrometer and its application to the measurement of the fast neutron spectrum of the beam produced by the Medical Research Council (MRC) Cyclotron. In addition, spectra produced by bombarding thin beryllium targets and a thick carbon target with 16 MeV deuterons have been determined. Spectra of beams produced by bombarding thick targets of beryllium and heavy water with 16 and 11 MeV deuterons have been reported previously (Parnell, Page, and Chaudhri, 1971).

The fast neutron beam produced by the M.R.C. Cyclotron results from the bombardment of a beryllium target with 16·7 MeV deuterons. The thickness of the beryllium is nominally 0·8 mm and is not sufficient to stop the incident deuterons completely. Instead, they are brought to rest in the copper backing on which the beryllium is mounted (Parnell, 1971). The energy spectrum published previously for this beam (Bewley, 1963) requires modification. At that time a thick beryllium target was used; moreover the calculations employed the data of Cohen and Falk (1951) for 15 MeV deuterons, whereas the energy of the deuteron beam is now considered to be 16·7 MeV (Bewley, Field and Parnell, 1967). The neutron beam, as currently used, is subjected to increased filtration by the target backing and water cooling and by a monitoring ionization chamber.

The advantage of using a cyclotron to produce fast neutron beams for radiation therapy is that clinically acceptable dose-rates are easily obtained. For example, the MRC machine routinely gives 40 rads/minute at about 120 cm from the target, the distance at which patients are treated. However, the depth doses are such that deep-sited tumours are not easily treated and hence some improvement would be advantageous. Consequently an examination was made of some other neutron-producing reactions and target configurations in an attempt to produce a more penetrating beam (Parnell *et al.*, 1971; Parnell, 1971).

When a beam of fast neutrons interacts with tissue, energy is deposited in a complex manner. For example, Auxier, Snyder and Jones (1968) have listed 33 possible mechanisms whereby this can occur in the energy range up to 20 MeV. For the fast neutron beam from the M.R.C. Cyclotron, Bewley (1963) has estimated that approximately 85 per cent of the absorbed dose in tissue is due to recoil protons resulting from elastic scattering of the fast neutrons with hydrogen. The remaining 15 per cent is due to heavy recoil nuclei, such as carbon, oxygen and nitrogen, and the products of nuclear reactions with these elements, *e.g.*, α particles from the $^{16}O(n,\alpha)^{13}C$, $^{12}C(n,\alpha)^{9}$ Be and $^{12}C(n,n^1)3\alpha$ reactions. Whilst only approximately 15 per cent of the absorbed dose in tissue is due to reactions other than with hydrogen, the biological effect of this fraction might be greater than its contribution to the absorbed dose suggests, since the particles reponsible can have LET values much higher than those of recoil protons. The cross sections for the reactions are all energy dependent and in some cases are not well known. Hence, in order to assist in the interpretation of biological effects of fast neutron irradiation, it is essential to know not only the cross section for each reaction but also the energy distribution of the neutrons to which the tissue sample is exposed. Similar information is also required in the estimation of neutron dose, especially if this is carried out using ionization chambers which are not constructed with tissue equivalent walls.

APPARATUS AND MATERIALS

A diagram of the fast neutron spectrometer is given in Fig. 1. A beam of fast neutrons 2·5 cm square is incident upon a Polythene foil 2 cm square and 10 μm thick. Recoil protons emitted from this foil at a mean angle of 20 deg. relative to the incident neutron beam pass through a 12·5 μm thick silicon detector (25 mm^2 surface area) into a 2 mm thick (50 mm^2 surface area) detector in which they are absorbed completely.

The energy resolution of the system is determined by three factors. First, a distribution of scattering

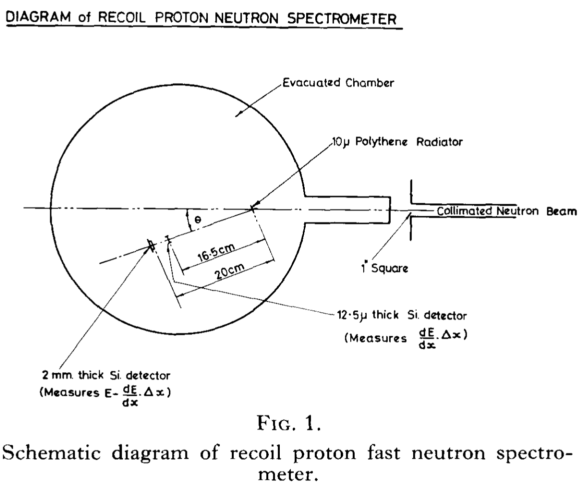

FIG. 1.

Schematic diagram of recoil proton fast neutron spectrometer.

angles exists over which recoil protons will be recorded. This is determined by geometrical factors and introduces a fractional energy spread which is independent of particle energy. Second, protons lose energy within the Polythene foil and this is important at low energies. For example, at 2 MeV a 10 μm thick radiator introduces a spread of about 8 per cent in the energy of the recoil protons, whilst at 10 MeV the corresponding spread is less than 1 per cent. The third factor is the detector resolution, but with silicon detectors this is negligible in comparison with other factors.

The 12·5 μm transmission detector was situated 3·5 cm in front of the thick detector. This position corresponds closely to the point of intersection of the paths of protons which originate at either end of the Polythene foil and are just detected by the thick detector on the opposite side. Since $E_n = E_p \sec^2\theta$, an approximate distribution of $\sec^2\theta$ was calculated, assuming that the neutron beam was parallel, that all protons passed through the centre of the transmission detector and that the scattering angle for a proton originating at the centre of the Polythene and arriving at the centre of the detectors was 20 deg. The resulting distribution was approximately rectangular with a width of 10 per cent. However, the other factors mentioned above and the finite size of the transmission detector would mean that the energy resolution was somewhat worse than this.

The signals from the two detectors were analysed using a Laben multichannel pulse height analyser operated in a bidimensional analysis mode. The signal from the transmission (dE/dx) detector was fed to the Y converter whilst the signal to the X converter was obtained by summing the signals from both detectors to give a pulse corresponding to the total energy of the proton. This circuitry allowed an event in the thick detector to be recorded only if it was coincident with an event in the transmission detector, but pulses from the transmission detector would be recorded even with no corresponding pulse from the thick detector.

Energy calibration of the system was carried out using α particles from a source consisting of a mixture of ^{239}Pu, ^{241}Am and ^{244}Cm and a pulse generator.

The background of the detectors was determined by removing the Polythene foil from the neutron beam.

RESULTS

The neutron beam from the MRC Cyclotron

For these measurements the neutron beam was monitored by an ionization chamber assembly and digital dose integrator system. One thousand divisions on this system correspond approximately to an integrated deuteron beam current incident upon the beryllium target of 30 μA-hours. The neutron beam was collimated to $2{\cdot}5 \times 2{\cdot}5$ cm using steel and paraffin wax in addition to the existing shielding

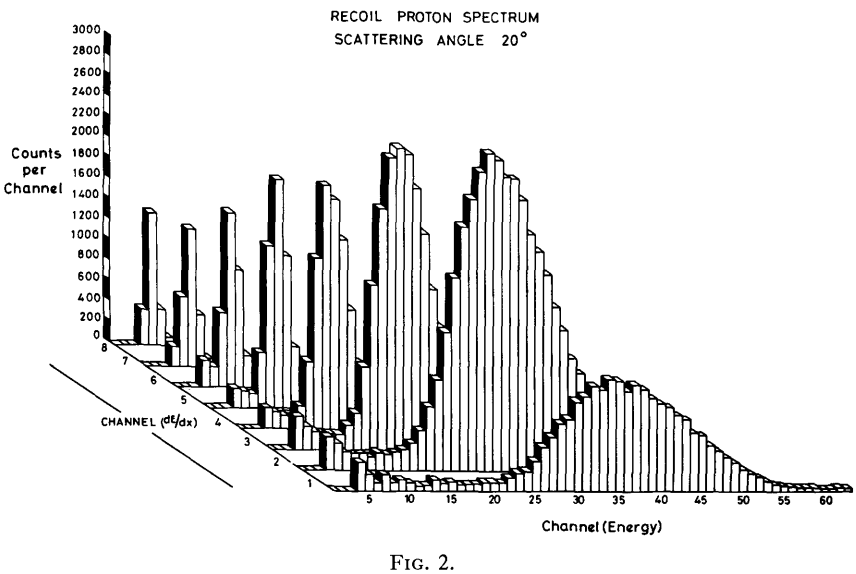

FIG. 2.

Distribution of recoil protons, θ = 20 deg., radiator-to-detector distance 20 cm. Radiator thickness 10 μm.

(Bewley and Parnell, 1969) and the Polythene radiator was approximately 130 cm from the beryllium target. Figure 2 shows a typical distribution of recoil protons obtained after background subtraction using a scattering angle of 20 deg. Examination of the variation of counting rate as a function of energy at constant dE/dx shows a peak corresponding to recoil protons. On the low energy side of this peak the counting rate decreases to a minimum and then increases slightly. In the analysis, channels below this minimum were excluded. To obtain the complete spectrum of recoil protons as a function of energy the counts in Fig. 2 were integrated at constant energy for the various values of dE/dx but excluding those discussed above. Figure 3 compares the proton and background spectra obtained. The addition of the transmission detector improved the signal to background ratio over the entire energy spectrum. For example, at 4 MeV the signal to background ratio was 30:1, an improvement of a factor of 300 over the same system using only a thick detector.

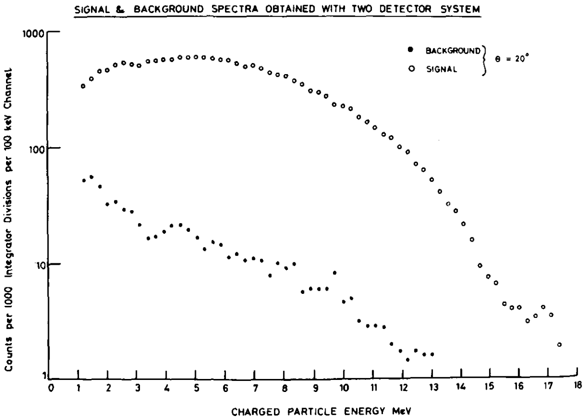

Fig. 3.

Comparison of recoil proton and background spectra. ● background; ○ recoil protons. Signals have been normalized to 1,000 integrator divisions (approximately 30 μA-hours of deuterons) and 100 keV channel width. $\theta = 20$ deg. Radiator-to-detector distance 20 cm. Radiator thickness 10 μm.

The background is shown in more detail in Fig. 4. In this figure the axes have been reversed in comparison with Fig. 2 to achieve greater clarity. The highest background counting rate occurred in channels corresponding to low energy, low dE/dx and there are three possible reasons for this. First, charged particles resulting from nuclear interactions in one detector can cross into the other. Second, the noise level of the thin detector was such that some noise pulses were able to gate the analyser and thus accidental coincidences could occur between one of these and a background pulse from the thick detector. The majority of the background in this detector is of low energy and thus the most

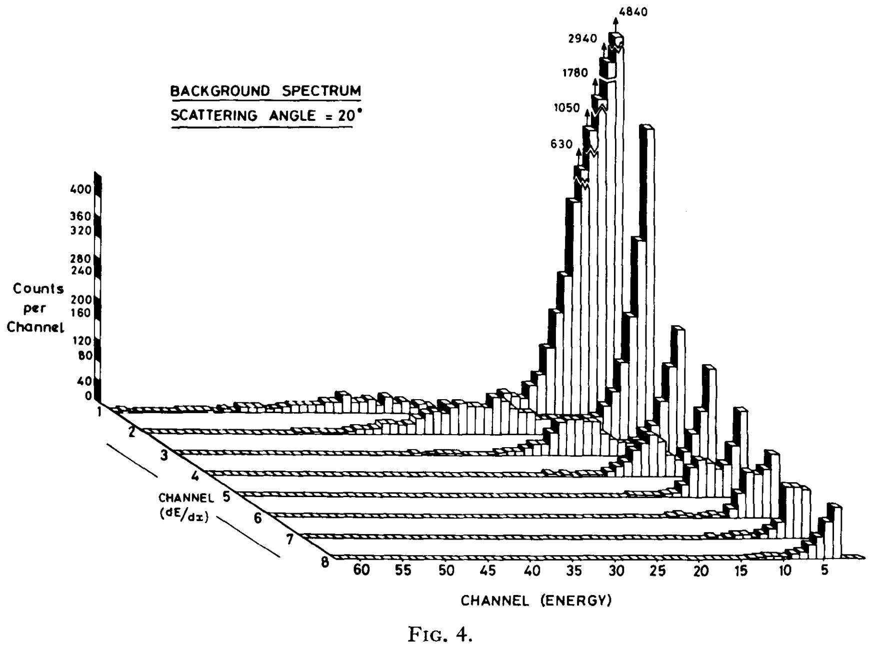

Fig. 4.

Background spectrum. Conditions identical to Fig. 2 but with Polythene radiator removed.

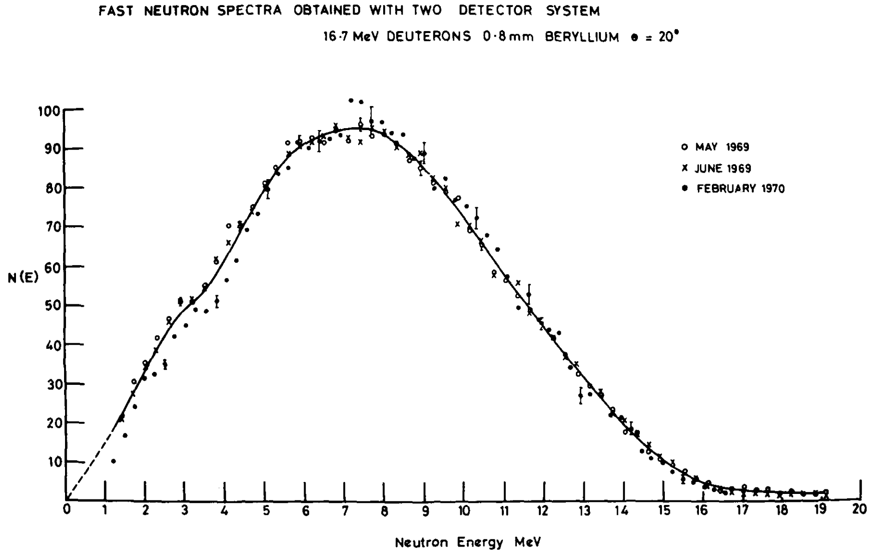

Fig. 5.
Three determinations of the fast neutron spectrum for the M.R.C. Cyclotron. Errors shown are $\pm 1\sigma$ and are due to counting statistics only.

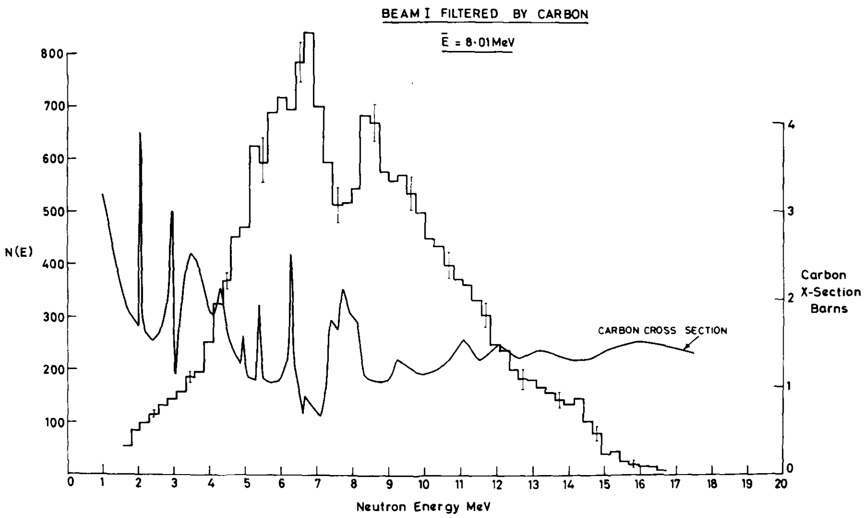

FIG. 6.
Spectrum of fast neutron beam after filtration by 15 cm of carbon.

probable event is a random coincidence between a noise pulse in the thin detector and a low energy pulse in the thick detector. Third, random coincidences between particles which pass through the thin detector but miss the thick detector and the background pulses of the thick detector can occur. However, it is evident that the majority of the background is well separated from the relevant proton signals. To convert the recoil proton spectrum to the neutron spectrum the proton energy, E_p, for each channel was multiplied by $\sec^2\theta$ ($\theta = 20$ deg.) to give the corresponding neutron energy, E_n, and the counts in that channel were divided by the (n,p) cross section for neutrons of energy E_n.

Figure 5 shows three determinations of the neutron spectrum made during a period of nine months. For each measurement a scattering angle of 20 deg. and a radiator-to-detector distance of 20 cm was used. The curves have all been normalized to the same area in the energy range from 3 to 17 MeV.

A final check on the over-all performance of the spectrometer was made by passing the neutron beam through a block of carbon 15 cm thick and determining the spectrum of the transmitted neutrons. Since the total cross section for carbon exhibits a broad increase in the energy range from about 7 to 8·5 MeV, filtration of the beam by carbon should result in a decreased neutron intensity in this region. Figure 6, showing the fast neutron spectrum measured under those conditions superimposed upon the total cross section for carbon, clearly demonstrates the effect of the relevant rise in the cross section. In addition there is also evidence, though not statistically significant, for effects produced by the narrow peaks in the carbon cross section at 5·4 and 6·3 MeV.

Other targets

Since the deuteron beam current on the experimental beam used for these measurements was much smaller than that of the beam previously used, the spectrometer was placed closer to the target and the thickness of collimating and shielding material reduced to approximately 30 cm. With this arrangement the polyethylene radiator was about 50 cm from the target.

The targets were the same as those used in the depth dose determinations (Parnell, 1971).

Figure 7 compares the fast neutron spectra obtained by bombarding three different thicknesses of beryllium with 16 MeV deuterons. The spectrum shown for 209 mg/cm^2 beryllium represents that for a target in which the deuterons are stopped completely and is replotted from the data of Parnell *et al.* (1971). A target of 101 mg/cm^2 of beryllium backed with copper corresponds approximately to that used routinely with the MRC Cyclotron whilst the 51 mg/cm^2 beryllium target backed with gold is that which gave the greatest improvement in depth dose (Parnell, 1971). The three spectra have been normalized in such a manner that the area under the curves is proportional to the respective dose-rates observed with these targets. In this normalization procedure no account has been taken of the variation of the dose per neutron as a function of neutron energy.

The fast neutron spectrum obtained by bombarding a thick carbon target with 16 MeV deuterons is compared with that for a thick beryllium target in Fig. 8. The normalization has been carried out as before.

Figure 9 presents neutron spectra produced by bombardment of thick beryllium targets with deuterons of various energies. The data are from the publications of Bruninx and Crombeen (1969) (7·5 MeV deuterons), Parnell *et al.* (1971) (11 and 16 MeV deuterons), Cohen and Falk (1951) as cited by Tochilin and Kohler (1958) (15 MeV deuterons), Tochilin and Kohler (1958) (20 and 24 MeV

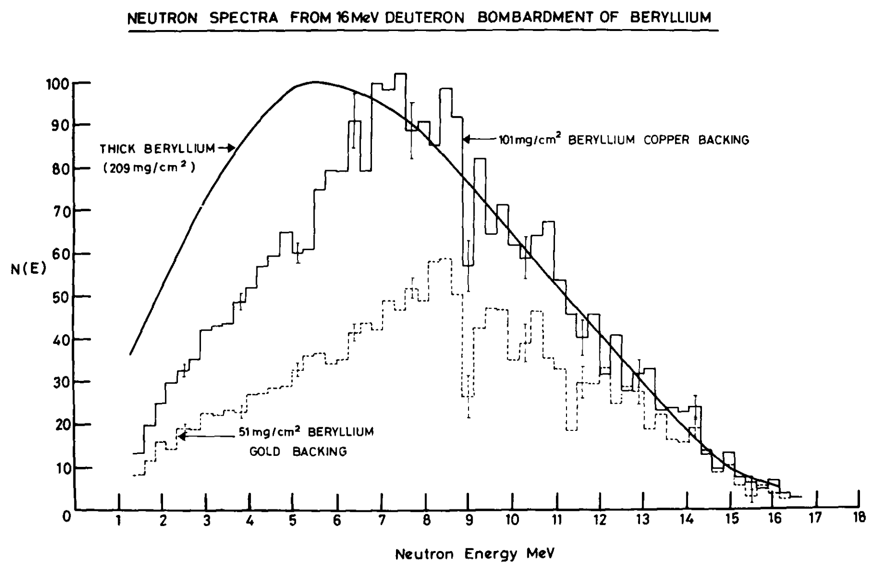

FIG. 7.

Energy spectra of fast neutrons produced by bombarding three different thicknesses of beryllium with 16 MeV deuterons.

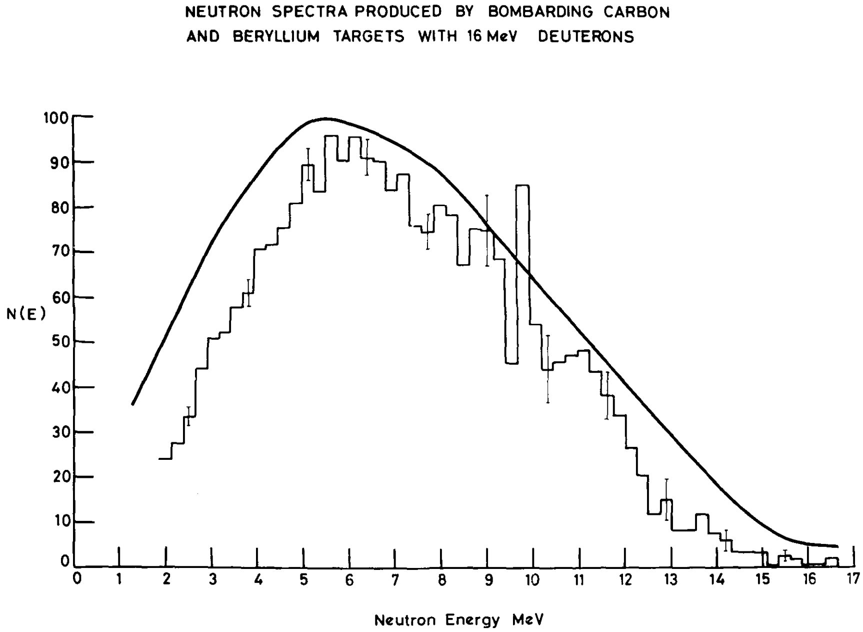

Fig. 8.

Comparison of neutron spectra produced by bombarding thick beryllium and carbon targets with 16 MeV deuterons. Solid curve, beryllium, histogram, carbon.

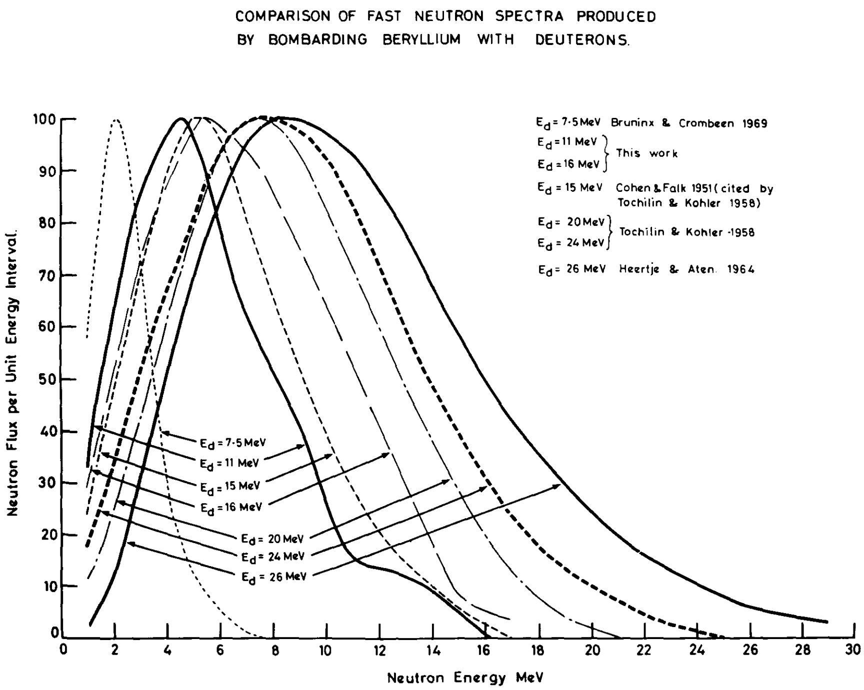

FIG. 9.

Comparison of fast neutron spectra produced by bombarding thick beryllium targets with deuterons of various energies.

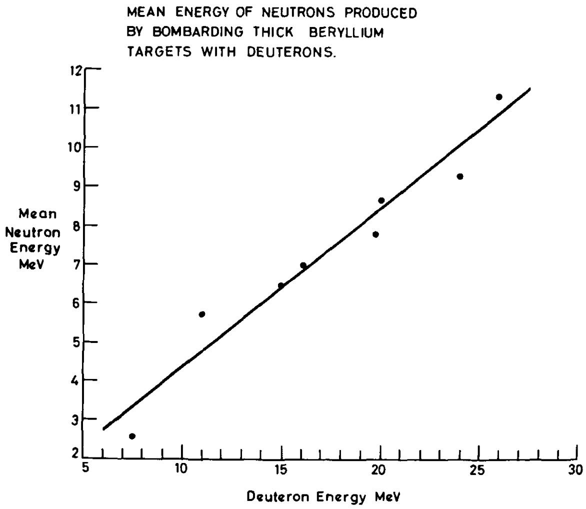

Fig. 10.

Mean energy of neutrons produced by bombarding thick beryllium targets with deuterons of various energies.

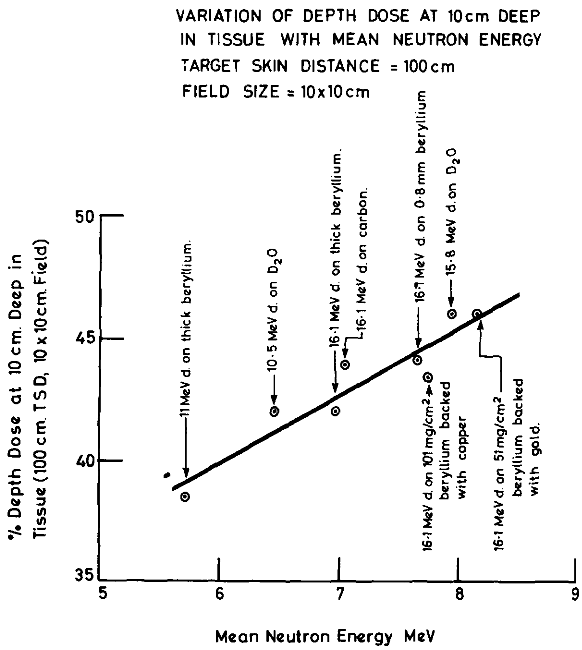

Fig. 11.

Variation of depth dose at 10 cm SSD for a 10 × 10 cm field as a function of the mean energy of the neutrons.

deuterons), and Heertje and Aten (1964) (26 MeV deuterons). The spectrum at 11 MeV was obtained by degrading the energy of the 16 MeV deuterons from the MRC Cyclotron in a gold foil and thus the majority of neutrons above 11 MeV shown in this spectrum are probably due to production in the gold rather than in the beryllium.

The mean energy of each spectrum shown in Fig. 9 has been calculated and is shown as a function of deuteron energy in Fig. 10. Since the experimental data did not extend to zero energy a linear extrapolation was made from the lower limit of the experimental data to the origin. The mean energy $\bar{E}_n$ was then estimated by using the relationship:

$$\bar{E}_n = \frac{\Sigma E\, N(E)}{\Sigma N(E)}.$$

The point at a deuteron energy of 11 MeV is probably too high due to the contribution of neutrons produced in the gold energy degrading foil. An estimate was made of this contribution and the mean energy recalculated when a figure of approximately 5 MeV was found. This is in closer accord with the line shown. An approximate value for the mean energy of the neutrons produced by bombarding thick beryllium targets with deuterons of energies between 7·5 and 26 MeV can be obtained by multiplying the deuteron energy by 0·42.

Figure 11 relates the depth doses for a 10 × 10 cm field at 100 cm SSD to the mean energy of the neutrons. The data for this figure have been taken from the publications of Parnell *et al.* (1971), Parnell (1971) and the present paper. Within the limits of experimental error the relationship is linear over the energy range from 6 to 8 MeV.

Discussion

In estimating the neutron energy spectrum from the experimentally observed distribution of recoil protons no allowance has been made for the energy resolution of the system, the energy absorbed in the Polythene radiator or the anisotropy of the (n,p) scattering which occurs at the higher neutron energies. Since the energy spectrum is observed to be a smoothly varying curve, the allowance for the energy resolution of the system is unlikely to produce any significant effect on the results presented here. Energy absorbed in the radiator is negligible at high neutron energies, but at low energies the neglect of this effect means that there could be some error in addition to the errors shown (Fig. 5) which are due to counting statistics only. The effect of anisotropy in the (n,p) scattering is negligible at energies below 14 MeV. However, since there are few neutrons above this energy the neglect of this effect is unlikely to cause any appreciable error in the determination of the neutron spectrum.

The three spectra shown in Fig. 5 were all made with different beryllium targets prepared by two different manufacturers. In addition they had been in use for different periods of time. Consequently any surface contamination or deuterium deposition within the target could be different for the three targets.

The neutron spectra presented in Fig. 5 have not been corrected for the filtration of the neutron beam. Since the filtration, with the exception of the 0·5 mm (approximately) steel window of the vacuum chamber, is permanently in the beam, the results present a reasonable estimate of the energy distribution of the beam currently used for radiobiology and radiotherapy. This inherent filtration consists of about 3 mm of copper, on which the beryllium is mounted, and approximately 1 mm of cooling water behind the copper and 1 mm of aluminium. In addition the monitoring ionization chamber provides an additional 5 mm of Polythene plus 2–3 mm of aluminium.

In considering the shape of the neutron spectrum, there are few neutrons with energies greater than the energy of the bombarding deuterons. Since these neutrons can only be produced by the ^{9}Be $(d,n)^{10}$B reaction ($Q = 4{\cdot}4$ MeV), this suggests that this reaction contributes relatively little to the neutron beam. Probably the greatest proportion of the neutrons are due to deuteron stripping and this was advanced by Cohen and Falk (1951) to explain the shape of the neutron spectrum observed by them for the bombardment of a thick beryllium target with 15 MeV deuterons.

The mean energy of the neutron beam has been estimated to be 7·65 MeV and this agrees closely with the energy at which the maximum intensity of neutrons occurs. However, it must be remembered that the beryllium target is not of sufficient thickness to stop the incident deuterons and hence the spectrum has a higher mean energy than if a thick target had been used.

The spectra shown in Fig. 7 clearly demonstrate the reduction in the low energy component of the beam resulting from the use of thin targets. For example, a beryllium target of 101 mg/cm^2 reduces the energy of the incident deuterons from 16 to 11 MeV and consequently the high energy region of the spectrum is not altered significantly. However, since the backing material produces fewer neutrons than the beryllium, the reduction in neutron flux from this target is due to a reduction in the number of low energy neutrons. For the thinner target (51 mg/cm^2) the deuteron energy is reduced from 16 to about 13·5 MeV in the beryllium, the remainder being deposited in the gold backing. Consequently the spectrum obtained with this target diverges from that obtained with a thick target at a higher energy.

The mean energy of the neutrons obtained with the two thin targets was estimated to be 7·7 MeV for a target of 101 mg/cm^2 and 8·2 MeV for the 51 mg/cm^2 target in comparison with 7·0 MeV for a thick target. The data of Fig. 10 show that the same mean energies as those obtained with the thin targets could be obtained by bombarding a thick beryllium target with 18·2 and 19·4 MeV deuterons, respectively.

The beam from the MRC Cyclotron which is currently used routinely for radiobiology and radiation therapy (Fig. 5) has a mean energy of 7·65 MeV. This is equivalent to bombarding a thick target with 18 MeV deuterons, *i.e.*, the use of the present target, although not being the optimum thickness in terms of depth dose, is equivalent to an increase of 1·3 MeV in the deuteron energy.

The spectrum obtained by bombarding carbon with 16 MeV deuterons shows an absence of neutrons with energies in excess of that of the incident deuterons. This reflects the small negative Q value of the ^{12}C$(d,n)^{13}$N reaction ($-0{\cdot}3$ MeV) in comparison with the value of $+4{\cdot}4$ MeV for the corresponding reaction with beryllium. The reduced dose-rate obtained with this target in comparison with beryllium appears as a general decrease in the number of neutrons at all energies, but with the largest decrease at low energies. This is probably due, in part at least, to the absence of neutrons produced by the $(d,2n)$ reaction which was not energetically possible.

Over the relatively small range of energies studied the penetration of the fast neutron beams into tissue appears to be related linearly to the mean energy of the neutrons, the penetration being measured by the percentage depth dose at 10 cm deep in tissue. In addition the mean energy of neutron beams produced by bombarding thick beryllium targets with deuterons of energies from 7·5 to 26 MeV appears to be a linear function of deuteron energy within the limits of experimental error, the mean neutron energy being given approximately by multiplication of the deuteron energy by 0·42.

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Book review

La Maladie de Hodgkin. By C. Lagarde, J. Chauvergne and B. Hoerni, pp. vi+150 (illus.), 1971 (Paris, Masson & Cie), 60F.

The aim of this short monograph from the Fondation Begonié, Bordeaux is to summarize current views on the pathology, clinical features, investigation and treatment of Hodgkin's disease and provide an aid to understanding the fundamental concepts underlying management. This aim is realized in some chapters but not in others.

The first chapter summarizes the historical background and the evidence for the neoplastic nature of Hodgkin's disease. The authors conclusion that Hodgkin's disease is a malignancy of reticulum cell origin with the lymphoid population in the node representing a host defence reaction against the cell proliferation is perhaps rather too dogmatic. The suggested use of the SJL/J murine lymphoma as a Hodgkin's model might also be criticized.

Chapter 2 considers diagnostic aspects and modes of clinical presentation. The histological classification modified from the original work of Lukes and Butler is adequately summarized. Differential diagnosis from other malignancies and infections are dealt with in this chapter.

Extra-nodal manifestations are fully described in Chapter 3 although there are no figures indicating the frequency of, for example, bone or lung involvement at presentation. The two main mechanisms of lung involvement by direct infiltration and haematogenous spread are described, but the risk of developing lung involvement when the hilar nodes are enlarged should be stressed since this has therapeutic implications.

Chapter 4 deals with the course of the disease. The concepts of orderly progression and haematogenous spread patterns with discontinuity of nodal involvement are fairly summarized.

In Chapter 5 the assessment of extent of disease is considered. The value of repeat lymphogram films is rightly stressed to assess the involvement or normality of nodes in equivocal cases, but some indication of the results of the lymphographic findings in relation to clinical presentation should have been included.

Laparotomy is mentioned with some reservation and rather inadequately since it is a matter of considerable current interest. It is a pity that the option of dividing Stage I into $I_{(1)}$ and $I_{(2)}$ (two adjacent regions involved) offered in the original Rye staging system is still adhered to since this has been abandoned by most centres.

In Chapter 6, which deals with therapy, the history of radiation therapy is briefly considered and the tumoricidal dose level and the principles of extended field radiotherapy are described. The radiotherapy details are rather skimpy; the dimension of the "Mantle" field is described as being 30×30 cm, but clearly this needs to be individualized. There is no indication of the various steps involved in treatment planning; the diagram indicates that the mediastinal part of the "Mantle" field is treated as a strip with no shaping to take in the hilar regions; other factors such as the necessity to treat the infraclavicular region when supraclavicular and axillary areas are involved are not dealt with.

Combination chemotherapy is dealt with inadequately and it is not stressed that single agent chemotherapy is now obsolete. The place of immunotherapy, which remains purely speculative, is dealt with in as much detail as quadruple chemotherapy. Similarly, a disproportionate amount of space is devoted to symptomatic treatment in relation to the amount of space devoted to the two main methods of radical treatment (extended field irradiation and combination chemotherapy).

Pregnancy in Hodgkin's disease is mentioned, but no guidance is given as to how a pregnant patient who presents with Hodgkin's disease is best managed.

Prognosis and results of treatment are dealt with in Chapter 8. Bearing in mind the different staging systems in use in various centres it is very difficult to compare results and one has considerable sympathy with the authors in trying to arrive at any meaningful conclusion, especially since current methods have only been in use for a limited period of time.

In summary, whereas the first part of the book dealing with clinical and pathological aspects is an interesting and full account, the weakness of the book as a whole lies in the relative disproportion of space allotted to these aspects and to treatment methods and results.

There is a reasonably comprehensive bibliography but there are some curious omissions; for example there are only two references to the clinical work of Kaplan, which is a serious omission when one considers that current practice in most centres has been influenced to a considerable degree by the work emanating from Stanford.

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