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Fast Neutron Yields and Spectra from Targets of Varying Atomic Number Bombarded with Deuterons from 16 to 50 MeV

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ABSTRACT. Neutron production from targets of Be, C, Mo, Cu, Ta and Au bombarded with deuterons of 16, 33 and 50 MeV has been studied at the isochronous cyclotron at Louvain-la-Neuve. Neutron spectra were measured by the time of flight method. The yields of neutrons and gamma rays were also measured, and the greatest ratio of neutrons to gamma rays in the forward direction was found to occur with 50 MeV deuterons on a Be target. The angular distribution of neutrons from Be was measured at 16, 33 and 50 MeV, and neutron spectra were measured as a function of angle with 50 MeV deuterons on Be.

1. Introduction

The production of high intensity fast neutron beams for radiobiological and radiotherapeutic purposes has attracted much interest in recent years. The ^{9}Be(d, n) reaction is usually employed with cyclotrons in preference to the reaction ^{3}H(d, n)^{4}He, which is used with low energy electrostatic accelerators. Although the energy spectrum of the neutrons produced by the first reaction is continuous as opposed to the monoenergetic 14 MeV neutron spectrum of the second reaction, the neutron yield is higher and the problem of the lifetime of the tritium target is avoided. Nevertheless, information about the energy spectra and the neutron yield obtained from (d, n) reactions above 16 MeV deuteron energy (Parnell 1972) remain scarce.

This work concentrates on the (d, n) reactions performed on different targets of light mass nuclei (^{9}Be, ^{12}C), medium mass nuclei (^{nat}Cu, ^{nat}Mo) and high mass nuclei (^{181}Ta, ^{197}Au) at 16, 33 and 50 MeV deuteron energy. Angular distributions of the neutrons emitted at those energies are also discussed.

2. Experimental procedure

The isochronous cyclotron of the Université de Louvain accelerates deuteron beams up to 50 MeV with typical intensities of 20–25 μA. The extracted beam is transported through a switching magnet to different experimental areas outside the cyclotron vault; the targets and the target holder were located on the unanalysed or zero degree beam line. The following thick targets were used: ^{9}Be (1·85 g cm^{-2}), ^{12}C (3·2 g cm^{-2}), ^{nat}Cu (2·58 g cm^{-2}), ^{nat}Mo (5·1 g cm^{-2}), ^{181}Ta (3·3 g cm^{-2}) and ^{197}Au (8·8 g cm^{-2}). Moreover, two thin ^{9}Be targets (0·20 g cm^{-2}) were mounted on a copper and on a gold backing. The highest energy deuterons are completely stopped in the thick targets and lose 2 MeV in the thin ^{9}Be targets.

The neutrons were detected at a zero degree angle in an open geometry by a NE111 fast plastic scintillator (5·1 cm diameter and 2 cm thick) coupled to a 56 AVP photomultiplier. The time of flight method with a 1 m long flight path has been used. The width of the beam bursts can be reduced to 0·7 ns by a half turn collimator. The overall resolution was typically 1·2 ns which allowed the separation of the γ-rays from the neutrons originating at the target. The time of flight spectra were recorded and converted into energy spectra averaged over 1 MeV intervals.

The absolute efficiency of the neutron detector has been measured between $E_n = 6$ MeV and $E_n = 14$ MeV by means of the D(d, n)^{3}He reaction where the ^{3}He and its associated neutron are detected in coincidence; these results have been compared with the efficiency calculated by a Monte Carlo program written by Stanton (1971); the agreement was found to be sufficiently satisfactory for extrapolating the method to higher energies (Leleux, Macq, Meulders and Pirart 1974).

A comparison of the neutron spectrum from the ^{9}Be(d, n) reaction with the detector threshold set at different energies up to $E_\gamma = 540$ keV has been measured at 16, 33 and 50 MeV incident deuteron energy. All spectra were found reliable from $E_n = 4$ MeV to the maximum energy of the neutrons produced (see fig. 1). Below 4 MeV, the shape of the spectrum changes with the setting of the threshold; this must be attributed to an inaccurate evaluation by means of Monte Carlo calculations of the efficiency of the detector for low

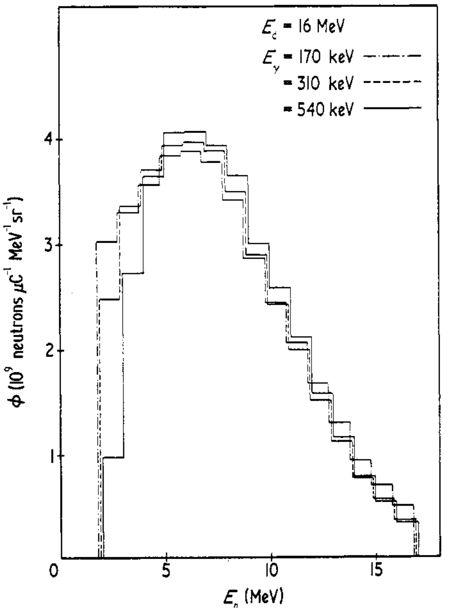

Fig. 1. Neutron energy spectra produced in the (d, n) reaction on a thick ^{9}Be target at $E_d = 16$ MeV, with detector thresholds at $E_\gamma = 170$, 310 and 540 keV.

energy neutrons; this has also been observed by Edelstein *et al.* (1972). This is the reason why all the reported fluxes are obtained by integration of the energy spectra from 4 MeV to the maximum neutron energy.

The angular distribution of the neutrons emitted by the $^{9}Be(d,n)$ reaction have been measured at the three above mentioned deuteron energies. The thick ^{9}Be target was placed in the centre of an aluminium scattering chamber, 60 cm in diameter. The time of flight path was 1 m. Measurements were taken in 5° steps from 0 to 64°. The neutron flux was corrected for absorption in the wall of the scattering chamber.

3. Neutron spectra and yield

The energy spectra of the neutrons obtained with 16, 33 and 50 MeV deuteron beams are displayed in figs. 2, 3 and 4 respectively. The threshold of the neutron detector was fixed at $E_{\gamma} = 60$ keV for the 16 MeV deuteron beam and at $E_{\gamma} = 110$ keV for the 33 and 50 MeV deuteron beams.

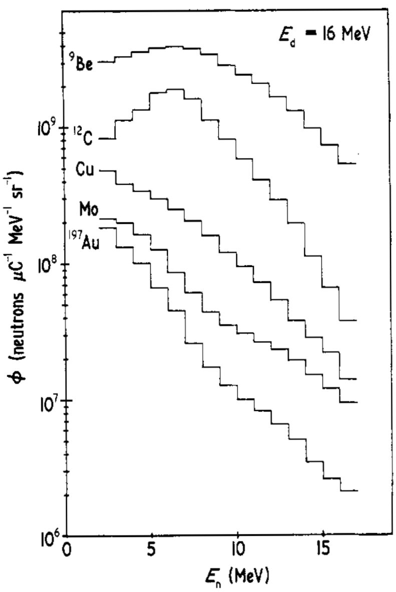

Fig. 2. Neutron energy spectra produced in the (d, n) reaction on thick targets with a 16 MeV-deuteron beam.

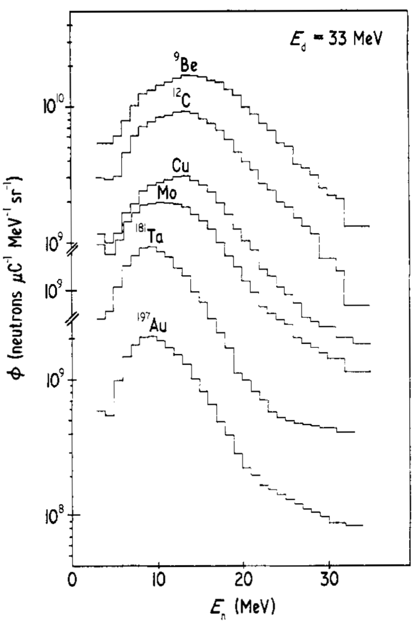

Fig. 3. Neutron energy spectra produced in the (d, n) reaction on thick targets with a 33 MeV-deuteron beam.

At 16 MeV deuteron energy and with targets of Be and C (see fig. 2), the spectra show maxima at about 6·5 MeV in good agreement with the results of Parnell (1972). Targets of higher atomic number give spectral shapes falling steadily with increasing neutron energy. The yield of the neutrons decreases with targets of higher atomic number (table 1). For this reason, it is more appropriate to use thin ^{9}Be with a gold backing instead of a copper backing, if one tries to improve the depth dose by increasing the mean energy of the neutrons.

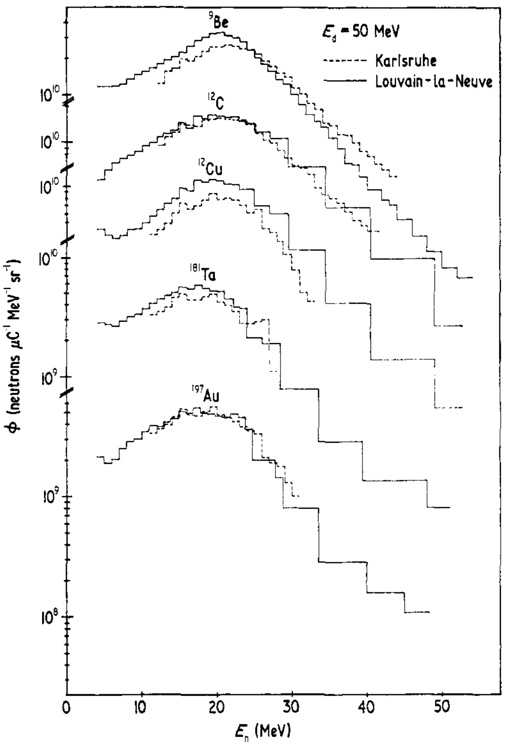

Fig. 4. Neutron energy spectra produced in the (d, n) reaction on thick targets with a 50 MeV-deuteron beam compared with those obtained at Karlsruhe by Schweimer (1969) at 53·8 MeV.

At $E_d = 33$ MeV (fig. 3), the fluxes obtained are 10 to 100 times higher than at 16 MeV, with a similar variation as a function of the atomic mass of the target; the energy spectrum from the ^{9}Be(d, n) reaction has a maximum at 14 MeV.

A comparison of our data obtained at 50 MeV with the data obtained at 53·8 MeV by Schweimer (1969) at the Karlsruhe cyclotron is shown in fig. 4. Taking into account the 4 MeV difference of the incident deuteron beam, the overall shape of the neutron spectra is in good agreement in the energy range where the data overlap. The maximum in the energy spectrum of the neutrons from the thick ^{9}Be target lies at $E_n = 21$ MeV. At this energy again, the highest neutron flux is obtained with ^{9}Be rather than with targets of higher atomic number.

Fig. 5 shows the spectra of the neutrons obtained by bombardment of a thin ^{9}Be target on different backings in comparison with the spectrum from the

Table 1. Neutron and gamma yield produced by the (d, n) reaction on thick targets in the forward direction

Target (thickness)	E_d = 16 MeV		E_d = 33 MeV		E_d = 50 MeV	
	Neutron[a] yield (10^9 μC^{-1} sr^{-1})	Gamma[b] yield (10^9 μC^{-1} sr^{-1})	Neutron[a] yield (10^9 μC^{-1} sr^{-1})	Gamma[c] yield (10^9 μC^{-1} sr^{-1})	Neutron[a] yield (10^9 μC^{-1} sr^{-1})	Gamma[c] yield (10^9 μC^{-1} sr^{-1})
^{9}Be (10 mm)	30·7	3·34	275	13·7	580	14·3
^{12}C (20 mm)	10·3	3·30	128·4	13·2	358	16·9
^{nat}Cu (3 mm)	1·72	5·58	41·7	46·8	214	77·6
^{nat}Mo (3 mm)	0·65	2·32	26·5	33·3	—	—
^{181}Ta (2 mm)	0·28	1·37	20·8	20·6	103	39·8
^{197}Au (4·5 mm)	0·30	1·37	20·6	19·0	97	38·2
^{9}Be (1·1 mm) + Cu	26·4	4·48	130	36·7	—	—
^{9}Be (1·1 mm) + Au	22·7	4·29	111·4	17·4	187	33·6

[a] Obtained by integration of the energy spectra from 4 MeV to the maximum neutron energy.
[b] $E_\gamma > 60$ keV.
[c] $E_\gamma > 110$ keV.

thick target. The mean energy ($\bar{E}_n$) of the neutrons increases from 15·3 to 17·0 MeV and 17·5 MeV respectively; this should improve the penetration but at the expense of the dose rate.

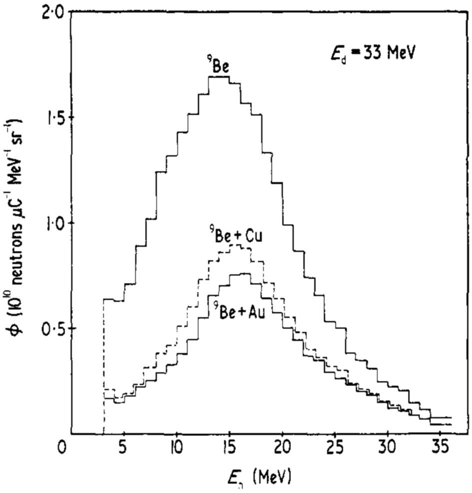

Fig. 5. Neutron energy spectra produced in the ^{9}Be(d, n) reaction on a thick target (10 mm) and on a thin target (1·1 mm) with a copper and a gold backing (E_d = 33 MeV).

4. Gamma yield

The gamma yield has been estimated by assuming a 10% mean efficiency above the energy threshold of the detector. A glance at table 1 shows that if the gamma flux is increasing between E_d = 16 MeV and E_d = 50 MeV, by a factor of 4 or 5 for the low Z targets, this factor reaches 30 for the high mass targets. A particularly important contribution appears in the copper region. The high gamma flux present in the case of a thin ^{9}Be target on a copper or a gold backing offers a significant argument against the use of thin ^{9}Be targets on these backings.

Most encouraging is the fact that the gamma fluxes produced by the 33 and 50 MeV deuteron beams on a thick ^{9}Be target are almost the same while the neutron flux increases by 210%. The ratio ϕ_γ/ϕ_n = 2·5% found at 50 MeV has been confirmed by dosimetric measurements with ionization chambers, as mentioned by Parmentier *et al.* (1974).

Comparison of the neutron and gamma yield obtained with different targets also gives information about the materials which should be used for the collimation of charged particle beams or for the design of Faraday cups for experiments which require a low background.

5. Angular distributions

The angular distributions of the neutrons from the ^{9}Be(d, n) reaction are shown in fig. 6. Each data point is the result of the integration of the energy spectrum from $E_n = 4$ MeV to the maximum neutron energy. It clearly shows that the angular distribution of the emitted neutrons becomes more and more

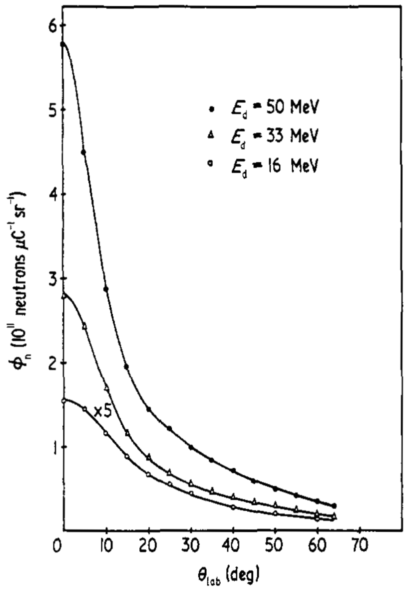

Fig. 6. Angular distribution of the neutrons from the ^9Be(d, n) reaction at E_d = 16, 33 and 50 MeV.

forward peaked on increasing the incident deuteron energy. Table 2 gives the angle where the neutron flux, ϕ, falls to half of its zero degree value, ϕ_0; by increasing the energy of the incident deuteron beam, one diminishes rapidly the

Table 2. Angle at which the flux, ϕ, of the neutrons produced by the ^9Be(d, n) reaction falls to half its zero-degree value, ϕ_0

E_d (MeV)	Angle where $\phi = \phi_0/2$ (deg)
16	18
33	12·5
50	10

size of the irradiation field which has a homogeneity suitable for radiotherapeutic purposes.

Fig. 7 displays the neutron spectra obtained at different angles with the 50 MeV deuteron beam. The decrease of the total flux is mainly due to shrinkage of the peak at 21 MeV, which becomes negligible at angles greater than 10°. As table 3 shows, this implies a decrease in the mean energy of the neutrons and emphasizes the importance of using the forward direction for radiobiological applications.

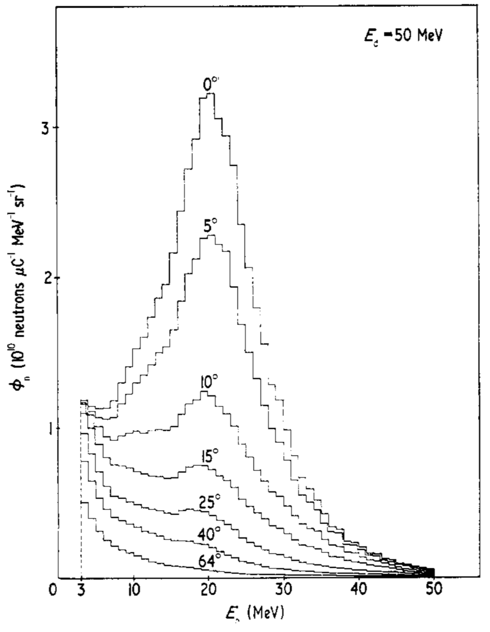

Fig. 7. Energy spectra of the neutrons emitted at different angles, θ, from the $^9Be(d,n)$ reaction at E_d = 50 MeV. Values of θ are given for each spectrum.

Table 3. Mean energy of the neutrons produced in the $^9Be(d, n)$ reaction at E_d = 50 MeV at the forward angles

θ_{lab} (deg)	$\bar{E}_n$ (MeV)
0	19·8
5	19·4
10	18·4
15	17·0
20	16·7
25	16·4
30	15·8

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Résumé

Les rendements en neutrons rapides et les spectres obtenus des cibles ayant des nombres atomiques variés et bombardées de deutérons de 16 à 50 MeV

On a étudié à l'aide du cyclotron à Louvain-la-Neuve la production des neutrons obtenus des cibles en Be, C, Mo, Cu, Ta et Au, bombardées par des deutérons de 16, 33 et 50 MeV. Les spectres neutroniques ont été mesurés par la méthode du temps de parcours. On a aussi mesuré les rendements en neutrons et en rayons gamma, et on a trouvé, que le rapport maximum neutrons/rayons gamma dans la direction en avant a lieu avec des deutérons de 50 MeV sur la cible en Be. On a mesuré la distribution angulaire des neutrons obtenus de Be pour 16, 33 et 50 MeV, et les spectres neutroniques ont été mesurés en fonction de l'angle avec des deutérons de 50 MeV sur Be.

Zusammenfassung

Ausbeuten und Spektra schneller Neutronen aus den Targets verschiedener Kernladungszahl, die mit Deuteronen von 16 bis 50 MeV bombardiert wurden

Man untersuchte bei dem isochronen Zyklotron in Louvain-la-Neuve die Neutronenerzeugung aus den mit Deuteronen von 16, 33 und 50 MeV bombardierten Targets aus Be, C, Mo, Cu, Ta und Au. Die Neutronenspektra sind nach dem Laufzeitverfahren gemessen worden. Es wurden gleichfalls die Ausbeuten von Neutronen und Gammastrahlen gemessen, und es wurde gefunden, dass das grösste Neutronen/Gammastrahlen-Verhältnis in der Vorwärtsrichtung im Falle der 50-MeV-Deuteronen auf einem Be-Target stattfand. Man mass die Winkelverteilung der Neutronen aus Be bei 16, 33 und 50 MeV, und die Neutronenspektra sind als Winkelfunktion mit 50 MeV auf Be gemessen worden.

Резюме

Выходы и спектры быстрых нейтронов из мишеней разных атомных номеров, бомбардируемых дейтронами с энергией от 16 до 50 Мэв

Генерация нейтронов из Be, C, Mo, Cu, Ta и Au мишеней, бомбардируемых дейтронами с энергией в 16, 33 и 50 Мэв, исследовалась на изохронном циклотроне в Лувэн-ла-Нёв. Нейтронные спектры измерялись по методу времени пролета. Измерялись также выходы нейтронов и гамма-лучей, причем оказалось, что максимальное отношение нейтронов к гамма-лучам в направлении вперед имело место в случае дейтронов в 50 Мэв на Be мишени. Угловое распределение нейтронов из Be измерялось при 16, 33 и 50 Мэв, а нейтронные спектры измерялись как функция угла для дейтронов в 50 Мэв на Be.

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