International Atomic Energy Agency

INDC(CCP)-37/U
(LA-TR-73-32)

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

PROBLEMS OF MEASURING NUCLEAR CONSTANTS FOR THERMONUCLEAR REACTORS*

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May 1973

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* Paper IAEA/SM-170/22 presented at the IAEA Symposium on the Use of Nuclear Data in Science and Technology, Paris, 12-16 March 1973

IAEA NUCLEAR DATA SECTION, KÄRNTNER RING 11, A-1010 VIENNA

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ABSTRACT

From the available nuclear data it appears that a tritium breeding coefficient greater than unity can be obtained in a thermonuclear reactor using the D-T cycle and with a breeding zone consisting of a mixture of lithium isotopes. However, the present inaccuracies in the nuclear data may considerably influence tritium breeding and the optimum relationship between breeder and construction materials. A fairly extensive program of neutron research in the neutron energy range 7-14 MeV is therefore necessary. The main feature of neutron measurements within this range is that there are no monoenergetic neutron sources available. The authors consider the possibility of using normal sources: the reactions D + D, D + T, T + p. Measurement data are presented on the continuous neutron spectrum in the reaction T + p, which limits the use of this reaction as a source of monoenergetic neutrons. Neutron sources based on the use of alpha particles and ^{3}He ions are considered, and currently available sources of continuous-spectrum neutrons are discussed. It is shown that the optimum source of a continuous spectrum of neutrons in the required energy range is deuteron disintegration at $E_d \simeq$ 25-40 MeV. The authors consider which nuclear constants can be used in continuous neutron spectrum measurements.

1. Introduction.

Thermonuclear reactors of the future require information on the nuclear constants to solve two basic problems: determination of the fuel characteristics in a plasma and rational use of the penetrating radiation formed in fusion reactions. Although the plasma parameters necessary for thermonuclear reactions to take place have still not been obtained and a means of obtaining energy from a fusion reaction has not been chosen, there has already been wide discussion of different models of thermonuclear reactors.[1]

An analysis of the contemporary state of data on the reactions occurring between light nuclei in a plasma shows[2] that the characteristics are known fairly completely only for the d + d, d + t, and d + ^{3}He processes.

With rare exception, such as the ^{3}He + d reaction, all the fusion reactions, at least in one of the branches, lead to the formation of fast neutrons. At the present time it is considered that a plasma cycle based on the burn-up of an equal-component mixture of deuterium and tritium is the most easily attainable. In this primary reaction, neutrons are formed with an energy of about 14 MeV. However, due to the secondary processes, neutrons of even higher energies can be present in the plasma. In the plasma and in the materials surrounding the plasma the neutrons lose their energy as a result of elastic and inelastic collisions, create significant fluxes of γ-radiation, breed a fuel component used in fusion reactions which is lacking in nature, create other isotopes, etc. It is necessary to know the characteristics of the indicated processes, such as the angular distributions of elastically scattered neutrons, the angular and energy distributions of secondary neutrons for the processes of inelastic scattering and the (n, 2n) reaction, the cross sections for the formation of γ-rays and their energy spectra, the cross sections of the breeding reactions and of the competing processes, the cross sections of the formation of different isotopes, and others, for a wide range of elements and isotopes for the rational use of neutrons in thermonuclear reactors.

The requirements for nuclear data for an initial stage of study of thermonuclear reactors have been discussed in detail in Refs. 2, 3, and 4. Although a certain part of these requirements is in common with the requirements of fission reactors, the significantly wider range of neutron energies used in thermonuclear reactors introduces important new problems in measuring nuclear constants. Data on the interaction of neutrons with different nuclei are especially not sufficient for the neutron energy region of 7-14 MeV. At the same time, measurements with neutron beams in this region are very complicated. A characteristic of the measurements is that for almost all vaues of neutron energy here there are not, in the usual sense, any beams of monoenergetic neutrons, which are widely used for measurements of nuclear data, primarily for the study of the angular and energy distributions of secondary neutron radiation.

This paper is devoted to a discussion of the peculiarities of measuring nuclear constants mainly in the neutron energy region of 7-14 MeV.

2. Sources of monoenergetic neutrons.*

For monoenergetic neutron sources in different parts of the energy range 7-14 MeV the reactions $T(p,n)^3He$ ($Q = -0.764$ MeV), $D(d,n)^3He$ ($Q = 3.27$ MeV), and $T(d,n)^4He$ ($Q = 17.59$ MeV) occurring between hydrogen isotopes are usually used. Figures 1-3 show the differential cross sections of the formation of neutrons using hydrogen isotopes at 0^o in the laboratory system of coordinates as a function of the energy of protons and deuterons.[5] Detailed information on these reactions, including tabular data on the energy of the emitted neutrons as a function of the energy of the incident particles and the angle of emission of the neutron, is given in Refs. 6 and 7. The ^3He and ^4He nuclei do not have low-lying levels of excitation; therefore,

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*The reactions considered below are arbitrarily called monoenergetic sources.

the emitted neutrons are strictly monoenergetic. However, beginning at certain energies of the charged particles, neutrons of lower energies appear in the beam of monoenergetic neutrons, as a result of processes of break-up at first into three (and then into more) particles by the reactions T(p,pn)D, D(d,pn)D, and T(d,pn)T. The neutrons of the break-up are primarily in the direction of motion of the accelerated particles. In planning the experiments, as well as in the treatment of the data obtained, information is needed on the cross sections of the break-up processes and on the angular distributions and energy spectra of the emitted neutrons.

2.1 Neutrons from reactions of protons with tritium.

The differential cross sections of the $T(p,n)^3He$ reaction are known at present in the proton energy region from the threshold value (E_{thr} = 1.019 MeV) to approximately 13.5 MeV with an accuracy of about 15%. The effective cross section at 0° has been measured with an error of 5-7%.[8,9] At a proton energy of 8.36 MeV, the threshold of the break-up reaction for tritium T(p,pn)D (Q = -6.26 MeV) is reached, and a group of neutrons with a continuous energy distribution appears. With a proton energy above 11.34 MeV, neutrons from the reaction T(p,p 2n)H can be present in the beam. Until recently, published data on the value of the cross section of the process of the break-up of tritium into hydrogen were lacking.

References 10 and 11 give only an estimate of the upper limit of the cross section at proton energies of 11-12 MeV.

To study the characteristics of a neutron beam arising in the interaction of protons with tritium over the whole region of interest for thermonuclear reactors, pertinent work was carried out at the cyclotron at the I. V. Kurchatov Institute of Atomic Energy in 1972. The differential cross sections at 0° were determined for the reaction $T(p,n)^3He$ in the range of proton energies of 6-15.3 MeV, and the cross sections of the process of the formation of break-up neutrons and the energy spectra of these neutrons were determined also at an angle of 0° for proton energies of 11.2 MeV, 14.2 MeV, and 15.3 MeV. The cross section was measured by the time-of-flight method; the threshold of recording of neutrons was 1.5 MeV. The absolute values of the cross section of the $T(p,n)^3He$ reaction were determined by normalization over the data of Ref. 9. Figure 1 shows the results of measurements for $T(p,n)^3He$ and for the break-up process for tritium. The data of the Institute of Atomic Energy (IAE) with the experimental errors (6% for $T(p,n)^3He$) are shown by circles, the data of Ref. 10 by crosses, and the data of Ref. 5 by the line. The upper limit of the cross section of tritium break-up at a proton energy of 11.2 MeV is estimated as

3.5 mb/sr; at proton energies of 14.2 MeV and 15.3 MeV the cross sections are 10.1 ± 1.6 mb/sr and 10.0 ± 1.4 mb/sr, respectively. The energy spectra of the neutrons of the break-up of tritium into hydrogen at 0° (for neutrons with an energy above 2 MeV) are shown in Fig. 4. The spread of the experimental values of the cross sections in all regions of averaging 0.5 MeV in width, with the exception of the high-energy boundary region, did not exceed 20%. On the basis of the data obtained it is possible to say that for proton energies above approximately 11 MeV no additional difficulties arose in the use of a monoenergetic beam of neutrons from the $T(p,n)^3He$ reaction due to the additional presence in the beam of neutrons of the break-up of tritium, the fraction of which is about 20%.

A variant of this situation is the use of the same reaction, $H(t,n)^3He$, but with acceleration not of the protons, but of the tritium nuclei.[11] Although the acceleration of tritium nuclei is associated with known technological difficulties, the use of the indicated reaction as a source of neutrons has its advantages: the neutron yield at 0° increases significantly and the threshold of the $H(t,np)D$ reaction is here reached at a triton energy of E_{thr} = 25.03 MeV; therefore the neutrons from the $H(t,n)^3He$ reaction are free from the presence of break-up groups up to a neutron energy of 17.5 MeV. The threshold value of the energy of the tritium nuclei in the $H(t,n)^3He$ reaction is $E_{thr} = 3.06$ MeV; neutrons at 0° have an energy of 0.575 MeV. Above the threshold the neutrons are contained in a cone with a value of the half angle at the apex determined from the relation $\sin \theta = (E_t - E_{thr})^{\frac{1}{2}} E_t^{-\frac{1}{2}}$. With increasing E_t, θ converges to the limit, 90°. Due to the movement of the center of mass, at each angle in the laboratory system of coordinates neutrons of two different energies are emitted. Figure 5 shows the cross section of formation of neutrons in the direction 0° and the energies of the corresponding neutron groups. The neutrons of the low-energy group have a very low energy and intensity; therefore their presence in the beam can be unimportant for a number of experiments. The yield of high-energy neutrons at 0° is far greater than the yield in the reactions $T(p,n)^3He$ and $D(d,n)^3He$. Thus, for example, for $E_t = 15$ MeV the energy of the neutrons of the high-energy group is 10 MeV and the neutron yield is 450 mb/sr, while the energy of neutrons of the low-energy group is about 0.03 MeV. The reactions $T(p,n)^3He$ and $D(d,n)^3He$ for neutrons with an energy of 10 MeV have yields of 28 mb/sr and 83 mb/sr, respectively.

2.2 Neutrons from the interaction of deuterons.

The reaction D(d,n)^{3}He is widely used as a source of monoenergetic neutrons with an energy up to about 7.5 MeV. The characteristics of the reaction have been studied in detail up to deuteron energies of 19 MeV. The differential cross sections have been measured with an accuracy of about 2.5% in the region of deuteron energies of 2-6 MeV[12] and with an error of 4-5% for higher energies.[13,14] With a deuteron energy of 4.45 MeV, the threshold of the reaction of break-up of a deuteron, D(d,np)D ($Q = -2.23$ MeV), is reached and a group of neutrons with a continuous energy distribution appears in the beam. The energy dependence of the cross section of the reaction D(d,np)D at 0° is shown in Fig. 2. The yield of break-up neutrons increases rapidly with increase in the deuteron energy, and at an energy of about 9.5 MeV becomes greater than the yield of the monoenergetic group. The energy spectra and the angular distributions of neutrons from the reaction D(d,np)D have been studied by the time-of-flight method for deuteron energies of 7.5-11 MeV.[15] Figure 6 shows the neutron spectra for the break-up of deuterons at 0° in the laboratory system of coordinates. The error in the determination of the cross section is about 10%. With increase in the angle of emission, the neutron spectra become softer. Figure 7 shows the change in the spectral composition of neutrons as a function of the angle of emission in the laboratory system of coordinates at a deuteron energy of about 10 MeV. The spectra have a smooth bell shape, analogous to that seen in Fig. 6, even at higher deuteron energies of 12-19 MeV.[14]

Attempts to separate the beam of neutrons from the $D(d,n)^3He$ reaction from the break-up neutrons have been made. In Ref. 16 the possibility of recording the coincidences of pulses from neutrons with the pulses from the ^3He nuclei associated with the neutrons was investigated. A number of serious difficulties arise in this procedure. With deuteron energies greater than 3.27 MeV the ^3He nuclei are emitted in the laboratory system of coordinates only in the forward direction, while the direction of emission is limited to a cone with a value of the half angle at the apex determined by the relation $\sin^2 \theta = 1/3(1 + 6.54/E_d)$, where E_d is the energy of the deuterons in MeV. At each angle two groups of ^3He particles will be observed, having different energies. The ^3He nuclei having the slower energies correspond to neutrons with a higher energy also emitted in the forward direction. In absolute values, the energies of the ^3He nuclei are approximately 1-2 MeV. Recording of the ^3He nuclei must be conducted under conditions of an enormous background from scattered deuterons. Using a scheme for coincidences with a resolving time of 3.5 nsec and a target of deuterated polyethylene about 25 microns thick, Schuster[16] succeeded in obtaining narrow beams of monoenergetic neutrons with an energy of 2-12 MeV and an intensity of $2.2 \cdot 10^3$ n/μC·msr. Thus, at the present time reassuring results have been obtained in the investigation of possibilities of separating out the monoenergetic part of the beam, which corresponds to the reaction $D(d,n)^3He$; however, following this method there is still much to be done in order to put the method of associated particles into practice.

2.3. The $T(d,n)^4He$ reaction.

The basic thermonuclear reaction $T(d,n)^4He$ is also widely used as a source of monoenergetic neutrons with an energy of about 14 MeV and above. The resonance in the curve of the cross section (σ_{max} = 5 barns) at a deuteron energy of about 110 keV determines the importance of this reaction as a neutron source mainly in operation with low-voltage accelerators. It is relatively simple to carry out the recording of the α-particles, with an energy of about 3.5 MeV, associated with the neutrons. This method is widely used here both for monitoring and for an absolute determination of the neutron flux. Figure 3 shows the dependence of the cross section at 0° of the reactions $T(d,n)^4He$ and $T(d,np)T$. However, the process of break-up of the deuteron on the tritium nucleus becomes noticeable for those neutron energies (E_n = 20 MeV) which are outside the limits of the basic interests of this paper. Let us note that to obtain monoenergetic neutrons with an energy in the range of 12-14 MeV it is possible to use neutrons emitted in the backward direction from the reaction $T(d,n)^4He$ at deuteron energies of several MeV. However, the use of neutron beams going in the backward direction is very inconvenient in application and, in addition, the cross section of the reaction in this region of deuteron energies is small. Use of the $T(d,n)^4He$ reaction does not encounter special difficulties for the main mass of measurements of nuclear constants for thermonuclear reactors at points with an energy of about 14 MeV. However, for example, in carrying out the whole experiment in study of (n,2n) reactions when the energy and angular characteristics of both neutrons are determined experimentally, the neutron yield from the usual apparatus is insufficient and even in the case of large cross sections of the (n,2n) reaction the time of exposure at one angular location occupies several days.[17] In this respect the investigations of Ref. 18, conducted with the goal of building powerful neutron sources for use in the study of radiation injuries and cancer therapy, are very interesting.

2.4. The interaction of lithium with hydrogen.

The reaction $^7Li(p,n)^7Be$ ($Q = -1.64$ MeV) is one of the most studied and widely used neutron sources for proton energies of 1.9-2.4 MeV. A feature of the reaction is the presence of a low-lying excitation level in the ^7Be nucleus ($E^* = 0.43$ MeV); therefore for proton energies above 2.4 MeV an additional line, corresponding to this excited state of the ^7Be nucleus, appears in the neutron beam. Measurements show[7,19] that for proton energies below 6 MeV the intensity of the neutrons of the second group is not greater than 15% of the intensity of the main group. With increase in the proton energy the cross section of the reaction with the formation of the ground state of the ^7Be nucleus rapidly decreases, and therefore the intensity of the neutron groups becomes comparable.[20,21] In addition, at proton energies above 7 MeV the second excited state of ^7Be ($Q = -6.29$ MeV) also makes a definite contribution. For example, for a proton energy of 14 MeV, the neutron yield of this group at 0° in the center-of-mass system is smaller by a factor of only approximately 2.5 than the total neutron yield from the ground and first excited states of beryllium.[21] All this limits the applicability of this reaction to the region of neutron energies lying outside the range under consideration.

A calculation analogous to the calculation of the characteristics of the $^{1}H(t,n)^{3}He$ reaction was carried out by the authors of this paper for the $^{1}H(^{7}Li,n)^{7}Be$ reaction. The region of neutron energies from 7 MeV to 14 MeV requires acceleration of the lithium ions in a range of energies of approximately 23-40 MeV. The neutrons formed in the reaction are included in a cone with a half angle at the apex determined by the relation $\sin^{2} \theta = 1 - 13.2/E_{Li}$, where E_{Li} is the energy of the ^{7}Li ions in MeV. Figure 8 gives the effective cross sections of the reactions $^{1}H(^{7}Li,n)^{7}Be$ and $^{1}H(^{7}Li,n)^{7}Be^{*}$ (0.43 MeV) for 0°, calculated from the data of Ref. 19. In the same figure are shown the neutron energies corresponding to the ^{7}Be nucleus in the ground and first excited states for a neutron emission angle of 0°. The neutron energies for the indicated groups differ approximately by 1 MeV; in the region of neutron energies of 12 MeV the intensities of the indicated groups are in a ratio of approximately 5:1. Such a non-monoenergetic condition of the neutron beam can be completely acceptable for certain problems of determining the nuclear constants in a region of neutron energies greater than 10 MeV. A concentration of the neutron flux within the limits of a relatively narrow cone of angles and a weak dependence of the neutron energy on the energy of the lithium ions, permitting work with relatively thick targets, can ensure realtively powerful fluxes of fast neutrons with an intensity of about $4 \cdot 10^9$ n/sr with a current of single-charged lithium ions of 1 μA. The second excited state of ^7Be is reached here for a lithium ion energy of about 50 MeV, which lies outside the limits of the range considered. In the neutron beam there will also be neutrons emitted in the center-of-mass system in the backward direction. The energy of these neutrons, as is seen from Fig. 8, does not exceed several hundred keV, and their cross sections of formation are small. For an energy of lithium ions greater than 25.8 MeV the $^1H(^7Li,n,\alpha)^3He$ reaction is energetically possible; the neutrons from this reaction will have a continuous energy spectrum.

2.5. Reactions with helium ions.

The reactions $^{12}C(^3He,n)^{14}O$, $^{16}O(^3He,n)^{18}Ne$, $^{12}C(^4He,n)^{15}O$, and $^{13}C(^4He,n)^{16}O$ give monoenergetic neutrons in limited energy ranges, which are outside the region of interest. Below are cited the maximum values of the energy of monoenergetic neutrons at 0^o at energies of the helium ions equal to the threshold of the reaction at the first excited state of the final nucleus: $^{12}C(^3He,n)^{14}O$ -- 6.4 MeV, $^{16}O(^3He,n)^{18}Ne$ -- 2.4 MeV, $^{12}C(^4He,n)^{15}O$ -- 7.5 MeV, $^{13}C(^4He,n)^{16}O$ -- 7 MeV.

3. Sources of continuous-spectrum neutrons.

Beams of fast neutrons of a continuous spectrum in the majority of cases are created by acceleration of deuterons bombarding thick targets of different elements. Recently linear electron accelerators[22] with targets of special constructions of a collection of determined elements have begun to be used for these goals. However, the yield of neutrons with energies in the range of 7-14 MeV from photoneutron reactions is significantly less than the yield from the (d,n) reaction. The neutrons arising in the (d,n) reactions are caused mainly by two processes: evaporation from a strongly excited nucleus and break-up of a deuteron in the field of the nuclear and coulombic forces of the nucleus of the target. The neutron energy spectrum in the first case is evaporative, and the angular distribution is symmetric with respect to 90° and close to isotropic. The break-up neutrons are characterized by a wide bell-shaped energy spectrum with maximum intensity at neutron energies approximately equal to half the deuteron energy. The break-up neutrons are directed principally along the motion of the deuteron. The energy and angular distributions of these neutrons are satisfactorily described by the expressions:[23]

$n(E)dE = (1 + y^2)^{-3/2}dy$, $y = (E - 1/2\ E_d)/\sqrt{E_d B}$, and

$n(\theta)d\theta = (1 + x^2)^{-3/2}dx$, $x = \theta\sqrt{E_d/B}$. Here E and E_d are the energies of the neutron and deuteron, respectively; B is the binding energy of the deuteron (2.23 MeV); and Θ is the angle of neutron emission.

The spectra from targets of different elements are close in shape and change smoothly with change in the deuteron energy. A general feature of the spectra is also a decrease in the neutron energy with increase in the charge of the nucleus-target.[24] The total neutron yield from thick targets increases rapidly with increase in the deuteron energy and decreases with increase in the charge of the nucleus-target. Thick targets of deuterium, tritium, and beryllium give the greatest yield. Figure 9 shows the effective cross sections of the d-^{2}H, d-^{3}H, and d-Be processes, for emission of neutrons at 0° in a range of deuteron energies up to 20 MeV.[18] Although the cross sections of the d-Be processes exceed the corresponding cross sections on heavy hydrogen isotopes, the calculated neutron yields from thick gaseuos deuterium and tritium targets for deuteron energies of 10-16 MeV are larger than the yields from beryllium.[25] The fast neutron spectra in d-^{2}H processes have a property very attractive for neutron measurements: a sharp break in the distribution on the side of high energies. Figure 10 shows the calculated neutron spectra from a thick gaseous deuterium target for deuterons with energies of 8, 10, 11.75, and 16 MeV.[25]

Such a shape of the spectrum leads to a decrease in the background for measurements in a limited energy range, due to the absence of undesired neutrons with high energies, and facilitates the construction of shielding and collimation of the neutron beam. However, due to the high value of the range of a deuteron in deuterium (200 mg/cm^2 at E_d = 12 MeV, which corresponds to a range of about 11 m under normal conditions), the practical use of thick gaseous or liquid targets is associated with great technological difficulties.

The use of a thick beryllium target has great possibilities. Figure 11 shows the change in the neutron flux at 0^o in the deuteron energy range from 8 to 30 MeV from the data of a number of authors.[16,25,26] Values of the neutron yield from a deuterium target[25] are given in the same figure for comparison. As is seen from this drawing, the neutron yield from a beryllium target at a deuteron energy of about 28 MeV is greater than 10^{11} n/μC·sr. A detailed comparison of high-energy neutrons from thick beryllium targets for deuteron energies of 15, 20, 24, 40, and 53.8 MeV shows that the energy spectra have a geometric similarity and can be characterized by the location of the maximum of the intensity and the half width of the distribution, $\Delta E_{\frac{1}{2}}$.[27] On the basis of such a similarity the authors propose a practical method of constructing the energy distributions of neutrons for deuteron energies of 15-50 MeV. Figure 12 shows the thus calculated spectrum for a deuteron energy of 28.4 MeV. The neutron energy distribution, in the first approximation, remains unchanged for all angles of emission. However, for large angles the spectra are somewhat depleted in high-energy neutrons.

Important possibilities for measuring nuclear constants in continuous spectra have been demonstrated in the use of isochronous cyclotrons,[28] in which together with a short duration of the current pulse on the target, a relatively high average current has been successfully maintained. The neutron source is a target inside the cyclotron chamber, on which after 1-2 nsec the deuterons, accelerated over several tens of orbits, are incident by deflection. Figure 13 shows the neutron spectrum obtained in a thick uranium target irradiated by deuterium ions with energies in the range of 40-50 MeV. The neutron flux at 0° was $5 \cdot 10^{11}$ n/μC·sr.

It should be noted that to obtain intense neutron fluxes in the energy region of 7-15 MeV, the deuteron energy cannot exceed 30-35 MeV. At the I. V. Kurchatov Institute of Atomic Energy a similar system was developed,[29] which can be used for a two-D isochronous cyclotron with a maximum deuteron energy of 30 MeV. A pulse repetition frequency of 110 kHz has been obtained, and estimates show that for a pulse duration of 1.5 nsec the neutron flux from a beryllium target at 0° will be about $3 \cdot 10^{12}$ n/sr·sec.

The advantages of using continuous spectra -- a "white" beam -- are seen more clearly in a systematic study of the energy dependences of the cross sections over a wide range of neutron energies. The use of monoenergetic neutron sources in such measurements requires very large expenditures of time. The energy resolution attained in a "white" beam from an isochronous cyclotron over a wide range of neutron energies (0.5-30 MeV) is record-breaking and is ≤ 1.7 keV for 0.8 MeV and ≤ 110 keV for 13 MeV.[30] This permits a number of cross sections to be determined in one experiment during a relatively short time, such as the total cross section,[31] the cross section of formation of γ-rays,[30] the fission cross sections,[32] and others. The cross sections of formation of γ-rays by inelastic scattering of neutrons with a low resolution, but sufficient for practical applications, are also measured in "white" beams from linear electron accelerators.[33,34] The same is also true for studies of total cross sections in the region of neutron energies up to approximately 40 MeV.[35] Van de Graaf accelerators are also used for measurements of the total cross sections, in a more limited range, for example, in Refs. 36 and 37. The energy resolution here bows to that obtained in a cyclotron, and the neutron intensity in comparable energy regions is, according to the estimate of the authors of Ref. 37, approximately 0.1 the intensity of a "white" beam from an isochronous cyclotron.

A "white" neutron beam in conjunction with time-of-flight technology is used in many laboratories of the world to study the total cross sections for fast neutrons. However, as was pointed out in Ref. 38, with the characteristic statistical errors of the results of approximately 1%, the divergence of the data of different authors is about 10%. The systematic errors, apparently, are related to difficulties in accurate determination of the background and to inaccuracies caused by the high counting rates. In a comparison of the results obtained using monoenergetic sources and in "white" beams, divergences of (0.1-1%) in the energy scale are also observed.

Investigation of the secondary neutron spectrum arising from the processes of elastic and inelastic scattering of neutrons and reactions of the type (n,2n) and such are being conducted at the present time using monoenergetic neutron sources. Definite information on the process of inelastic neutron scattering can also be obtained using a "white" beam, by studying the γ-radiation accompanying this process. However, the information is incomplete, since the γ-radiation is the product of a secondary reaction and its characteristics can utterly not reflect the character of the main reaction.

In addition, inelastic scattering of neutrons is not always accompanied by γ-radiation; lithium isotopes are an example of this.

The use of a "white" beam for measurements of differential cross sections of elastic and inelastic scattering of neutrons in the energy range of 0.2-16 MeV is discussed in Ref. 39. Use of time-of-flight technology in conjunction with an amplitude analysis of radiation from scattered neutrons permitted the authors to measure the transverse cross sections and angular distributions of neutrons scattered from the ground and first excited states of ^{56}Fe in the energy range of 2.70-6.62 MeV with an energy resolution of about 5%. A high amplitude resolution and a need to conduct a complex analysis of the spectra are inherent requirements of the method.

4. Conclusion.

The development of thermonuclear studies creates a need to carry out a sufficiently large program of neutron studies over a wider energy range than is required for fission reactors. A characteristic feature of the measurements here is the almost total absence of monoenergetic neutron sources. The interaction of protons with tritium is the least "contaminated" source of monoenergetic neutrons, especially in the acceleration of tritons. However, acceleration of tritium nuclei makes use of this source difficult. In certain cases, other neutron sources can be used, the choice of which depends on the problem posed.

An important part of measurements of nuclear data of interest for fusion reactors is presently conducted with continuous spectrum neutron sources. The optimal source in the energy region considered is the process of break-up of a deuteron at energies up to 30-35 MeV.

Systematic measurements with a "white" beam in conjunction with measurements at separate points with monoenergetic neutrons makes it possible to obtain nuclear data in the needed energy range. The existing difficulties in the measurements require a careful choice of the nuclear constants to be determined, a physics basis for the errors of the parameters studied, permissible energy resolutions, etc., analogous to the nuclear data requirements for fast reactors.

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* Translator's Note.

The authors were unaware of the recent work of:

D. K. McDaniels, M. Drosg, J. C. Hopkins and J. D. Seagrave, "Angular Distributions and Absolute Cross Sections for the T(p,n)^{3}He Neutron-Source Reaction" Phys. Rev. C. 6 1593 (1972).

D. K. McDaniels, M. Drosg, J. C. Hopkins and J. D. Seagrave, "Angular Distributions and Absolute Cross Sections for the T(d,n)^{4}He Neutron-Source Reaction" Phys. Rev. C. 7 882 (1973).

N. Jarmie and J. H. Jett, T(p,n)^{3}He, T(d,n)^{4}He, D(d,n)^{3}He, LASL, Unpublished.

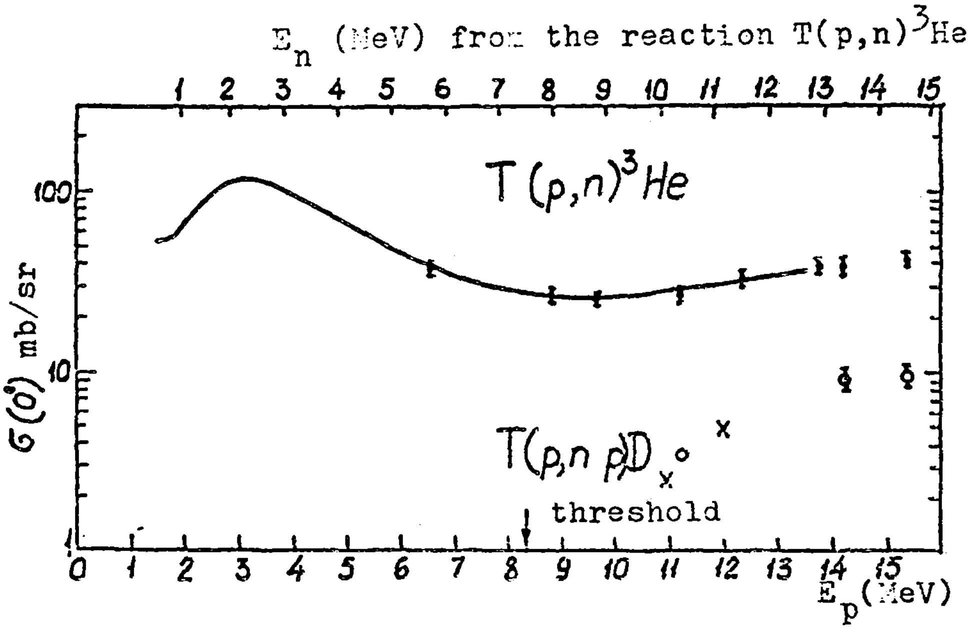

Fig. 1. Cross sections of formation of neutrons at 0° in the interaction of protons with tritium.

Solid line -- cross section of the $T(p,n)^3He$ reaction from Ref. 5 (Hopkins)

● -- cross section of the $T(p,n)^3He$ reaction (IAE data)

x -- upper limit of the cross section of break-up of tritium from Ref. 10 (Holbrow)

o -- cross section of the break-up of tritium (IAE data)

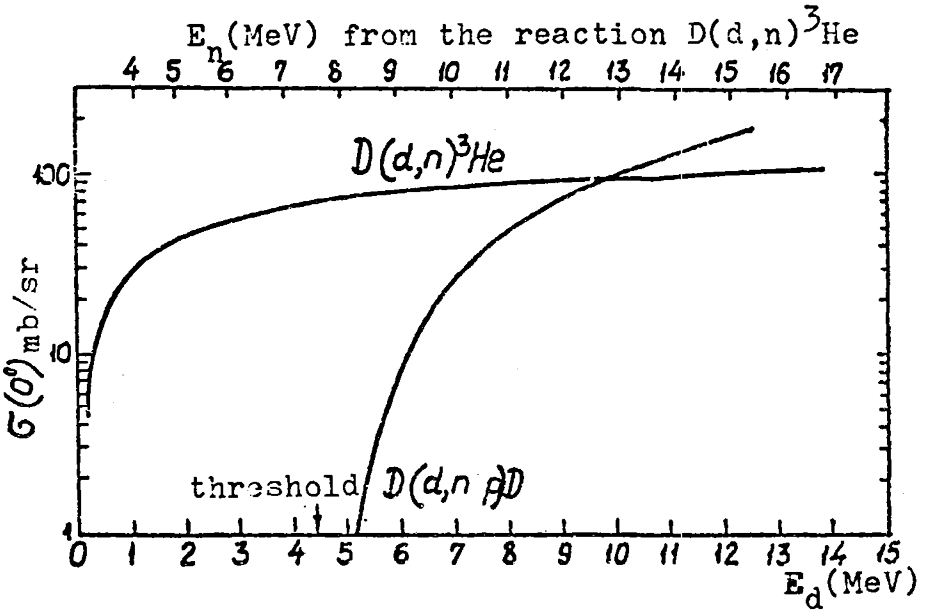

Fig. 2. Cross sections of formation of neutrons at 0° in the interaction of deuterons with deuterium.[5]

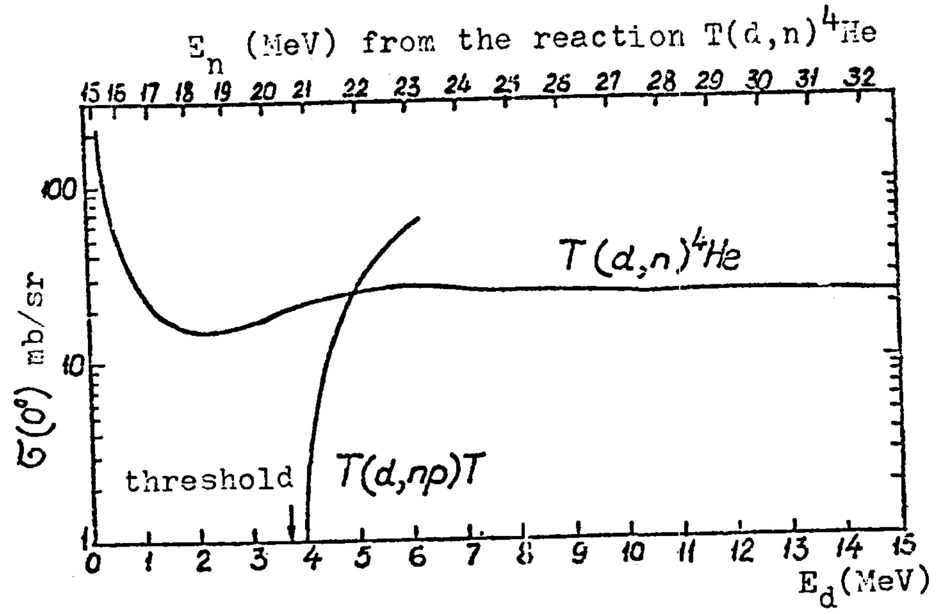

Fig. 3. Cross sections of formation of neutrons at 0° in the interaction of deuterons with tritium.[5]

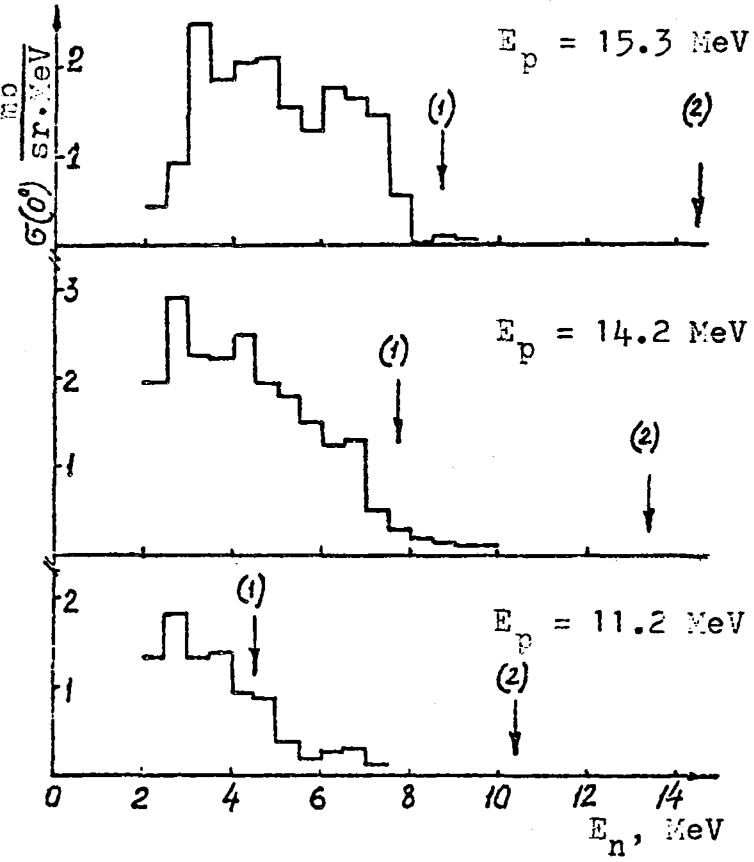

Fig. 4. Energy spectra of neutrons from the break-up of tritium in the interaction of tritium with protons with energies of 11.2, 14.2, and 15.3 MeV. Arrows (1) and (2) denote the calculated E_{max} of neutrons from the break-up of tritium and E_n of neutrons from the $T(p,n)^3He$ reaction, respectively. The presence of neutrons to the right of arrow (2)* is caused by errors in the calculation of the background.

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*Translator's note: arrow (1).

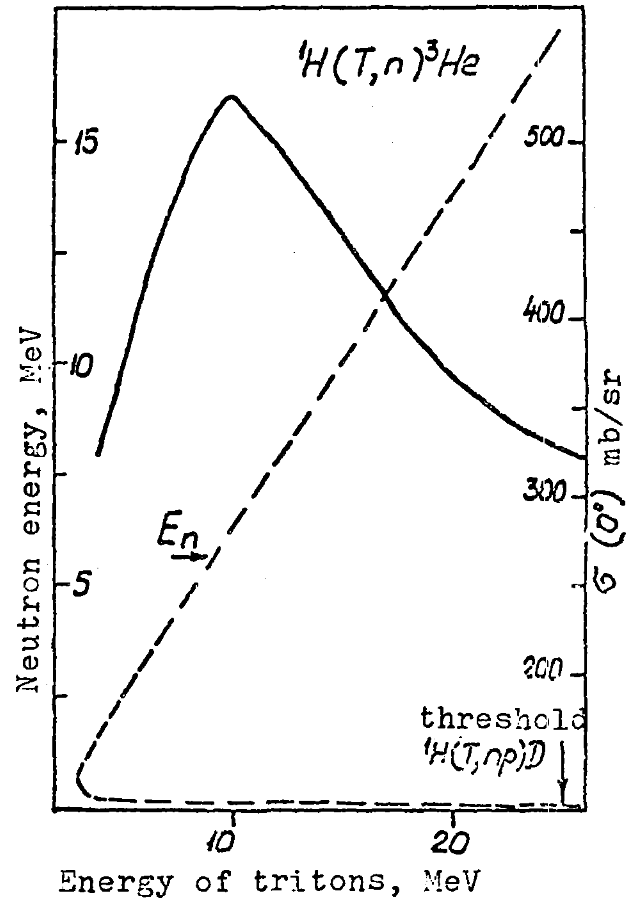

Fig. 5. Energy of groups of neutrons from the reaction H(t,n)^{3}He at 0° (dotted line). Cross section of formation of the high-energy group of neutrons from the reaction H(t,n)^{3}He at 0° (solid line).

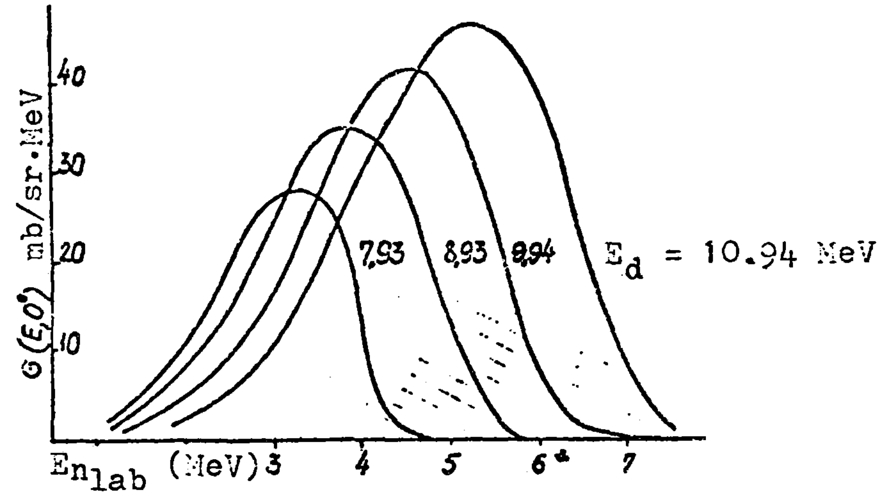

Fig. 6. Neutron spectra at 0° from the reaction D(d,np)D.[15]

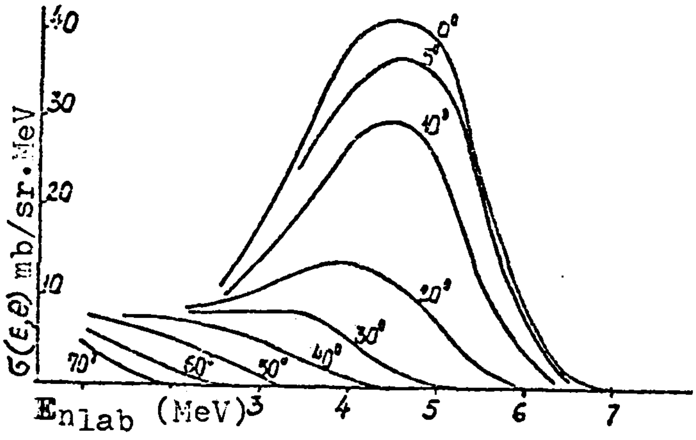

Fig. 7. Neutron spectra at various angles from the reaction D(d,np)D. For $\theta \leq 30^\circ$, $E_d = 9.94$ MeV. For $\theta > 30^\circ$, $E_d = 9.75$ MeV.[15]

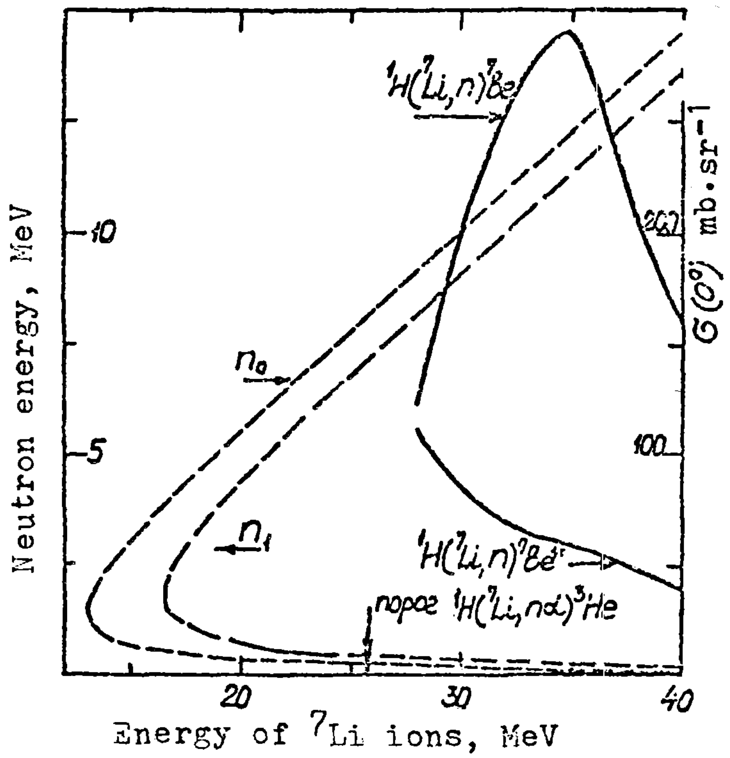

Fig. 8. Energy of neutron groups from the reactions $^{1}H(^{7}Li,n)^{7}Be$ and $^{1}H(^{7}Li,n)^{7}Be^{*}$ at 0° (dotted lines). Cross section of the reactions $^{1}H(^{7}Li,n)^{7}Be$ and $^{1}H(^{7}Li,n)^{7}Be^{*}$ at 0° (solid lines).

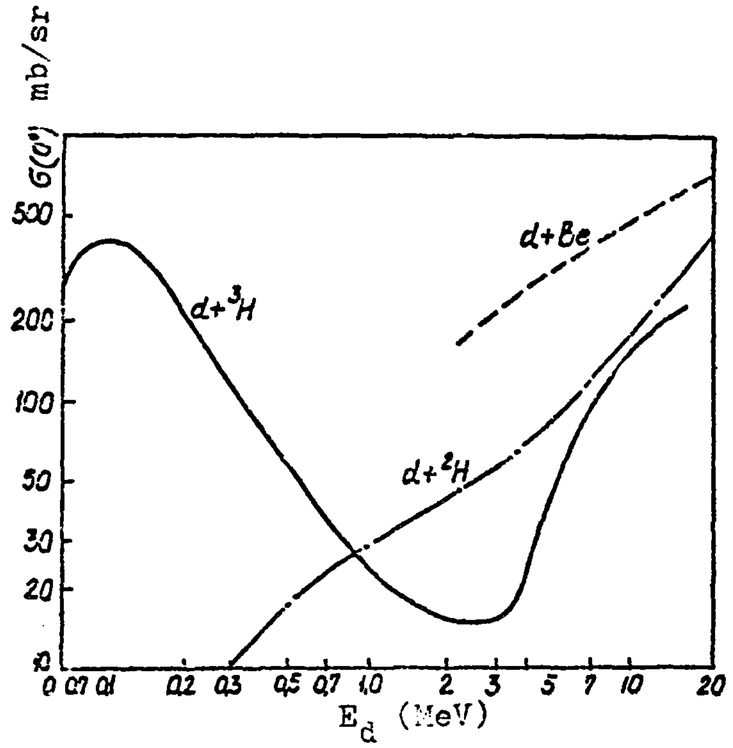

Fig. 9. Cross sections of process of formation of neutrons at 0° from the reactions d + ^{3}H, d + ^{2}H, and d + Be.[18]

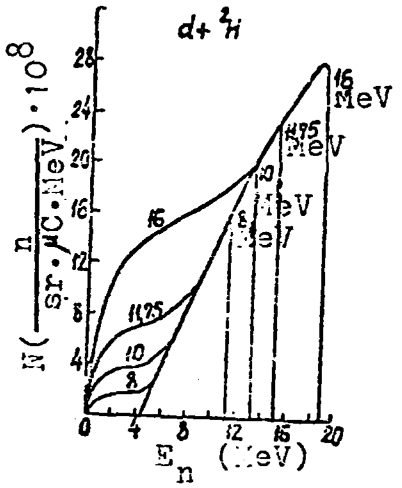

Fig. 10. Calculated neutron spectra at 0° for incidence of monoenergetic deuterons with energies of 8, 10, 11.75, and 16 MeV on a thick deuterium target.[25]

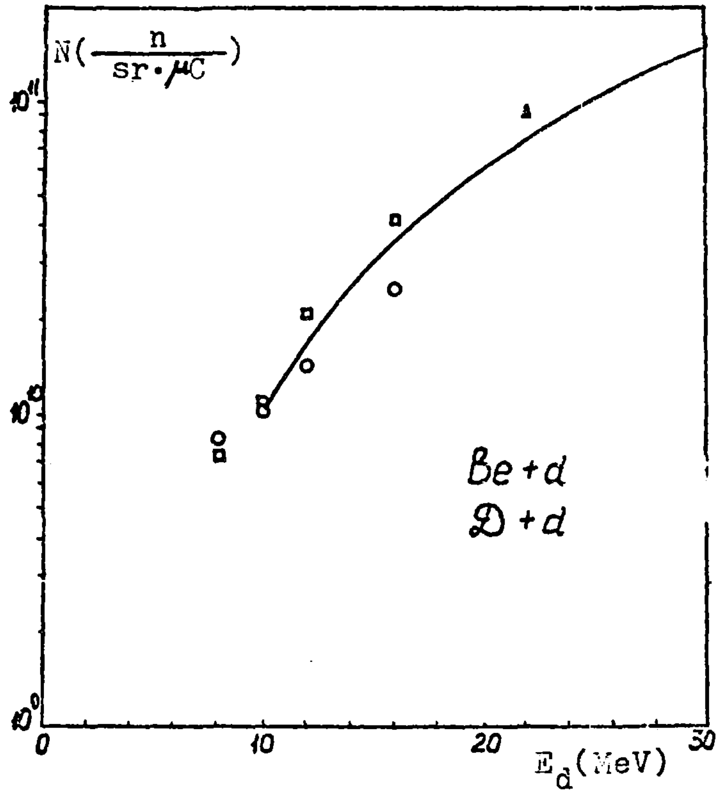

Fig. 11. Neutron yield from thick Be and D targets at 0° as a function of the deuteron energy.

Solid line -- Ref. 18

○ -- Ref. 25

△ -- Ref. 26, Be target

◻ -- Ref. 25, D target

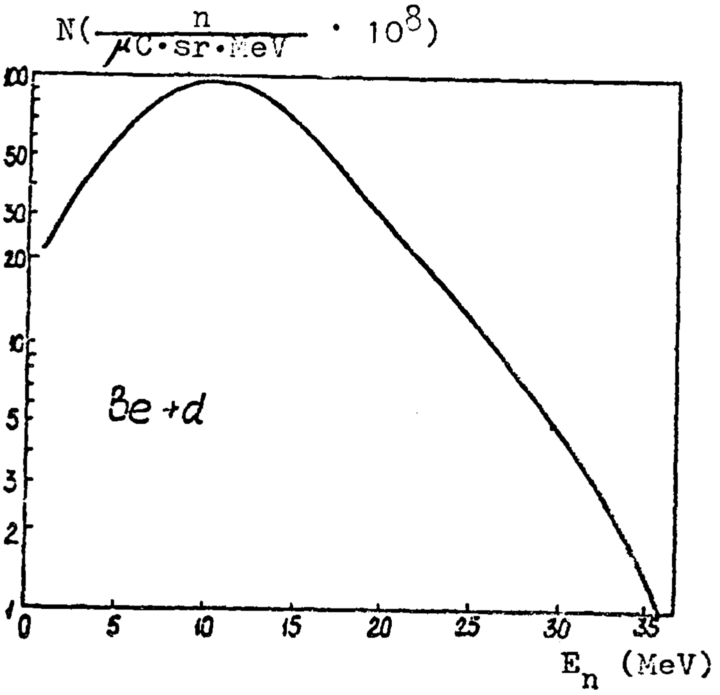

Fig. 12. Calculated neutron spectrum from thick Be target for a deuteron energy of 28.4 MeV.[27]

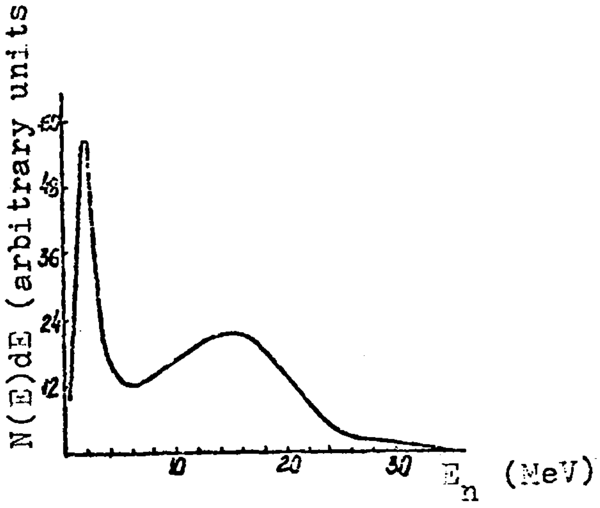

Fig. 13. Neutron spectrum from a thick uranium target bombarded with deuterons with an energy of 40-50 MeV.[28]