Intense Sources of Fast Neutrons

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INTENSE SOURCES OF FAST NEUTRONS

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In recent years there has been a growing interest in intense sources of neutrons of energy higher than that of fission neutrons. Such sources are needed for testing of materials under consideration for fusion reactors, and for medical applications.

The present review is limited to accelerator-based neutron sources and does not include plasma devices, such as fusion test reactors and dense plasma focus sources.

REQUIREMENTS FOR INTENSE SOURCES OF FAST NEUTRONS

Radiation Damage Studies

Present designs of fusion reactors are based on the interaction of deuterons and tritons. Each interaction produces a 14-MeV neutron. In designs in which the reactions occur in a magnetically confined plasma, the plasma is contained in a large vacuum vessel. The inner wall of this vessel will be subjected to bombardment by 14-MeV neutrons with a flux density of about 10^{14} cm^{-2} s^{-1}, or a fluence of 3×10^{21} cm^{-2} in a year (1).

Neutron bombardment will damage the walls in two distinct ways, it will produce bulk radiation damage, i.e., deterioration of the mechanical properties of the wall material, and secondly surface effects, such as the emission of recoiling atoms and the release of surface atoms caused by radiation damage near the surface.

Bulk radiation damage has again two distinct causes, displacement of atoms caused by charged particles produced in neutron interactions, and the presence of atoms generated in transmutations induced by neutrons.

The cross sections for transmutations induced by 14-MeV neutrons are higher than for less energetic neutrons, such as fission neutrons. 14-MeV neutrons are likely to produce hydrogen and helium inside materials through (n,p) and (n,α) reactions. In addition most transmutations produce either directly or after radioactive decay atoms of heavy elements not originally present in the material. For example, neutron reactions with Fe produce Mn and Cr. The dominating effect of transmutations caused by 14-MeV neutrons is expected to be the effect of helium production, especially embrittlement of metals at the high temperatures at which the material will be in an operating reactor.

Although radiation damage caused by fast neutrons has been investigated extensively for the development of fast breeder reactors, results obtained for fission neutrons cannot be directly applied to fusion reactors because of the much larger effect of transmutations for fusion neutrons. If one takes the helium production as a measure of the effect of transmutations and the displacements per atom (dpa) as a measure of recoil effects, the ratio of helium production to dpa in stainless steel is estimated to be about 0.1 ppm He/dpa for a fast breeder, and 20 ppm He/dpa for a Tokamak type fusion reactor (2).

The importance of radiation damage studies to fusion technology is due to the difficulty of replacing the vacuum vessel in Tokamak reactors as presently conceived. Not only is the vacuum vessel surrounded by a thick blanket and magnets, but it will be highly radioactive. In some current designs the surface area of the vacuum vessel is of the order of 3000 m^2 and the mass of the order of 100 tons. Replacement of the vacuum vessel is time consuming and costly, and the problem of the disposal of the material which may have activities of the order of 10^9 Ci is difficult. The feasibility and economics of fusion reactors is influenced by the lifetime of the vacuum vessel, presently estimated to be about two years. Hence development of materials that would extend the lifetime of the vacuum vessel is of greatest importance.

Studies of radiation damage for the design of fusion reactors require a neutron source which produces a similar recoil spectrum and a similar helium production to dpa ratio as fusion neutrons. The test source should produce a higher flux density than is present in the fusion reactor so that the effect of the neutrons produced over the reactor lifetime can be studied within a reasonable time. Hence a flux density several times that expected on the wall of the fusion reactor, i.e., several times 10^{14} cm^{-2} s^{-1} would be desirable.

Accelerator-based sources produce neutrons in a small volume, and the flux falls off according to the inverse square law. The source strength required to attain a certain flux density depends therefore both on the size of the source and of the sample to be irradiated, and on the uniformity of flux density required over the test sample. For example, if the average distance between source and sample is 3 mm an isotropic source producing 10^{14} neutrons/s would produce a flux density of the order of 10^{14} cm^{-2} s^{-1}. On the other hand, if either the neutron source or the sample have to be larger so that the average source-to-sample distance is, say, 3 cm, the source strength to achieve a flux density of 10^{14} cm^{-2} s^{-1} would have to be 10^{16} s^{-1}.

The difficulty of the neutron source problem may be appreciated by recalling that typical laboratory 14-MeV neutron sources have source strengths of 10^{10} s^{-1} and that in 1977 the most intense steady state 14-MeV neutron source had a strength of a few times 10^{12} s^{-1}.

Because of the difficulty of obtaining the desired source strength with the reaction of deuterons with tritons other source reactions which produce a broad neutron spectrum are promising for obtaining adequate intensities even though the effects of these neutrons differ somewhat from that of fusion neutrons.

The first 14-MeV neutron source specifically designed for radiation damage studies for fusion reactors is expected to become operational in 1978. It can produce, however, a flux density of only about 10^{13} cm^{-2} s^{-1} in a very small volume. A much more intense 14-MeV neutron source has been designed, but at this writing the question of its actual construction is still under discussion. The design of a very intense broad-spectrum neutron source for radiation damage studies is underway, but when construction will begin has not been determined.

There is evidence that radiation damage induced by neutrons depends not only on fluence but also on the flux density, i.e., that the effect differs depending on whether a given fluence is obtained from a steady source or a pulsed source. Some proposed neutron sources produce a steady flux, others, such as linear accelerators, produce short bursts of neutrons. The same applies to fusion reactors. Some proposed reactors have long burn cycles, such as Tokamak reactors, while others, especially inertially confined plasmas, produce very short bursts of neutrons. Neutron sources designed for radiation damage studies should preferably have a duty cycle similar to that of the reactor for which the study is made.

Radiotherapy

The use of neutrons for cancer therapy was proposed by Lawrence (3) in 1936, soon after he had developed the cyclotron. Between 1938 and 1943 over 200 cancer patients were treated with neutrons from the Berkeley cyclotron. Although there appeared to be some benefits from this treatment, many patients suffered severe side effects, and the physicians who had directed the neutron treatments concluded that these complications made neutron treatment an undesirable procedure (4). A more recent evaluation (5) of the early Berkeley treatments has shown, however, that, on the basis of present knowledge of the biological effects of neutrons, the patients received too large doses of radiation.

The more recent interest in the use of neutrons in therapy arose from radiobiological studies which showed the importance of the so-called oxygen effect. This term describes the greater resistance to radiation of cells deprived of oxygen (hypoxic cells) than of well-oxygenated cells. Cells at the center of a tumor are often hypoxic, hence radiation resistant. This oxygen effect is much smaller for neutrons than for X-rays. This observation led to the hope that neutrons might cure some malignant diseases which do not respond to conventional X-ray treatment.

The clinical use of neutrons resumed in 1966 at the Hammersmith Hospital in London. The reports from Hammersmith by Catterall (6) and her associates have been so encouraging that radiotherapists in other European countries, in Japan, and in the U.S.A. have started to use neutrons for treating cancer patients.

Neutron sources for radiotherapy must satisfy minimum requirements of both neutron energy and source strength (7). The energy requirement is based on the need for the neutrons to penetrate to the depth at which the tumor is located without too much absorption in the healthy tissue through which they pass. If the neutron energy is too low, the radiation dose to the healthy tissue is so high that the healthy tissue may not recover. Radiotherapists, who have much experience with the γ rays from ^{60}Co sources and find their penetration satisfactory, would like a neutron source that gives comparable or better penetration in tissue. The attenuation of the neutrons is determined largely by the hydrogen scattering cross section which decreases with neutron energy and becomes sufficiently small around 10 MeV neutron energy.

The decrease of neutron intensity as the neutrons penetrate into tissue depends not only on the nuclear interactions, but also on the distance from the source because of the effect of the inverse square law. In order to provide adequate depth dose the source-to-skin distance should be at least 100 cm, preferably 125 cm. This requirement combined with the limitation of a practical treatment time to about 5 minutes determines the needed source strength for an isotropic neutron source as about 10^{13} s^{-1}. If the source is anisotropic, the total source strength may be lower; only the number of neutrons emitted per unit solid angle is important, and this should be at least 10^{12} sr^{-1} s^{-1}.

In the application in radiotherapy there is also a limitation on acceptable source diameter. In order to limit the treatment volume, a collimator has to be used. If the source is too large, an undesirable penumbra is introduced. The diameter of the neutron source should therefore be less than 2 cm. The collimator will increase the flux density at a given distance from the source over that observed without the collimator because the collimator scatters neutrons into the collimated beam. How much increase occurs depends on the field size and the design of the collimator. If the neutron source has a large diameter, the collimator could reduce the flux density rather than increase it. For most practical sources and collimators the collimator increases the flux density by 10-20%.

Sources that produce neutrons with an average energy above 10 MeV and an intensity of 10^{12} sr^{-1} s^{-1} are relatively easy to construct. There are, however, some requirements for the clinical use which are more difficult to satisfy. If neutron therapy is to be used in many hospitals, the cost of neutron sources should be not much more than that of presently used X-ray sources, such as electron linear accelerators. Furthermore, it is important that the neutron source can be rotated around the patient as is the practice with electron accelerators and radioactive sources. Such a facility is called isocentric.

Several approaches to the neutron source problem are being pursued. The most widely used sources use the reaction of deuterons on beryllium, the reaction that was used in the early Berkeley work and at Hammersmith. At the Fermi National Accelerator Laboratory 60 MeV protons from a linear accelerator bombard a beryllium target. A third reaction which produces relatively energetic neutrons with deuterons from a small cyclotron, is the D-D reaction.

The difficulty with cyclotrons and proton or deuteron linear accelerators is that an isocentric treatment facility requires elaborate and expensive beam transport systems. Such a system has been developed for a small cyclotron, but these cyclotrons produce neutrons of an energy below what most radiotherapists want.

An easier way to generate energetic neutrons with a small accelerator is to use the D-T reaction. In this case the development of an accelerator which can be isocentrically mounted is easy, but the development of a target which withstands the large deuteron beams required for the needed intensity has been a difficult problem. Depending on target design, the power dissipation in the target is 10-100 kW.

Development of neutron sources for radiotherapy has reached the point where suitable sources are commercially available. These sources are either cyclotrons that produce a broad spectrum of neutrons or D-T sources. The D-T sources are more compact and lighter, but produce a lower neutron dose rate. A substantial increase in the intensity of compact D-T sources appears difficult. There is the possibility that linear accelerators could replace cyclotrons for broad-spectrum neutron sources. Linear accelerators would eliminate the heavy magnet that makes cyclotrons difficult to move around the patient.

Previous Reviews

The needs of the fusion program and possible source designs for this program were the subject of an International Conference on Radiation Test Facilities for the CTR Surface and Materials Program in 1975 (8). The needs and sources for radiation therapy were discussed at an International Workshop on Particle Radiation Therapy in 1975 (9) and at an International Conference on Particles and Radiation Therapy in 1976 (10). Cross sections and yields of high energy neutron source reactions were summarized in 1977 at an International Specialists Symposium (11) and at a Symposium on Neutron Cross Sections (12). The review of "Intense Fast Neutron Source Reactions" by Lone (13) at the Neutron Cross Section Symposium contains a very complete summary and list of references that will not be repeated in the present review. A review of neutron sources for biomedical applications may be found in ICRU Report 26 (14). A special issue of Nuclear Instruments and Methods published in August 1977 was devoted to High-Energy, High-Intensity Neutron Sources (15). The present review is based to a large extent on information contained in these publications; it is limited to reports published before and during 1977.

SOURCE REACTIONS

The requirement that the neutrons have an average energy of 10 MeV or more limits the source reactions to the interaction between light nuclei, because the interaction of even very energetic projectiles with heavy nuclei produces an energy spectrum with a median energy well below that desired for the applications in this review. Although the energy distribution of neutrons produced in the bombardment of heavy nuclei with energetic projectiles usually has a component that extends up to the bombarding energy, most of the neutrons have an energy distribution similar to a Maxwellian distribution with a temperature of 1-2 MeV. Fission neutrons likewise have too low an energy for the applications under consideration. Only the reactions of the hydrogen isotopes with targets lighter than carbon have been found to yield sufficiently high average energies.

Some of the useful reactions yield monoenergetic neutrons in a given direction for thin targets. The intensity requirements for the present applications make it necessary, however, to use thick targets, usually targets in which the bombarding particles stop.

This section summarizes information on neutron yields from various source reactions; a later section describes targets that can be used for producing high intensities of neutrons from these reactions. The monograph "Fast Neutron Physics" edited by Marion and Fowler and published in 1960 (16) gives an excellent summary of the kinematics of neutron-producing reactions, and of their neutron yields. The emphasis in this monograph is on monoenergetic sources, i.e., thin-target sources, rather than high-intensity thick-target sources. Another useful summary of the same source reactions was published in 1963 by Goldberg (17). Although more recent measurements have provided new information on thick target yields and have extended the older measurements to higher bombarding energies, there have been no very significant changes in our knowledge of the properties of these reactions in the last twenty years.

^{2}H(d,n)

The reaction ^{2}H+d → ^{3}He+n+3.3 MeV (the D-D reaction) was historically the first reaction that served as a source of monoenergetic fast neutrons. Its usefulness as a source of monoenergetic neutrons is limited to neutron energies below about 8 MeV, since at bombarding energies above 4.5 MeV the deuterons break up and produce a continuum of much lower energy. In the forward direction the intensity of this continuum exceeds that of the monoenergetic neutrons, when the energy of the monoenergetic neutrons is above 12 MeV.

An evaluation of the measured cross sections of the reaction ^{2}H(d,n)^{3}He up to deuteron energies of 10 MeV was prepared by Liskien and Paulsen (18). There are additional measurements at higher bombarding energies (19, 20). For deuteron bombarding energies up to 600 keV the kinematics and cross sections for thin targets, and the spectra and yields for thick targets have been calculated and plotted by Seagrave (21).

Several measurements of the cross section for deuteron breakup for bombarding energies up to 20 MeV have been reported. Reference (22) contains a comparison of the 0° cross sections with earlier measurements (23-25). Additional studies of the deuteron breakup have been reported for deuteron energies up to 12 MeV (26).

Figure 1 shows the differential cross section for the production of neutrons in the forward direction as a function of deuteron energy for the reaction of deuterons with deuterium (27).

The neutron spectra from the bombardment of deuterium targets of various thicknesses have been measured for 10.6 MeV deuterons (28), and for 17.3 MeV deuterons (29). These measurements address particularly the use of these neutrons in radiotherapy and include measurements of dose rate and depth dose. There is also a measurement of dose rate and depth dose for 7.5 MeV deuterons on a thick target (30).

For the application of the D-D reaction to the design of high-intensity-high-energy neutron sources two problems have to be considered. The increase in the probability of deuteron breakup with increasing bombarding energy results in a slow increase of average neutron energy with bombarding energy above deuteron energies of about 5 MeV as shown in Figure 2. The second problem relates to the difficulty in designing a thick deuterium target needed to obtain sufficient intensity. Nevertheless this reaction offers the possibility of producing a fairly intense source of energetic neutrons with a small cyclotron.

$^{3}H(d,n)$

The reaction $^{3}H+d \rightarrow {}^{4}He+n+17.6$ MeV (the D-T reaction) is of interest as an accelerator-based source for the same reason that it is the most promising reaction for a fusion reactor, i.e., it has a very large cross section at low bombarding energies, as shown in Figure 1.

For the radiation damage application its obvious advantage is that it is the same reaction as that proposed for fusion reactors. Nevertheless in accelerator-based sources the energy of the neutrons produced may differ significantly from the energy of thermonuclear neutrons. For example, even at as low a deuteron bombarding energy as 0.4 MeV the average neutron energy from a thick tritium target in the forward direction is above 15 MeV, while the thermonuclear neutrons have an average energy of 14.1 MeV. Some important transmutation cross sections, especially those that have a threshold above 10 MeV, vary strongly between 14 and 15 MeV.

For the radiotherapy application the possibility of using a low voltage accelerator is the principal reason for considering the $^{3}H(d,n)$ reaction as a neutron source.

The principal disadvantage of the reaction is the need for using radioactive tritium. This introduces problems in the radiation damage application because of the difficulty in designing tritium targets for the large required source strengths, and in the radiotherapy application because of the difficulty of handling large amounts of tritium in a hospital.

An evaluation of the measured cross sections of the reaction $^{3}H(d,n)^{4}He$ up to deuteron energies of 10 MeV is contained in reference 18. Actually for intense neutron sources the energy region of interest is below 600 keV and in this energy region reference 21 is particularly useful, since it contains graphs of thick-target neutron yields and spectra.

Figure 2 shows the average energy of neutrons produced in the interaction of deuterons with a tritium target. The decrease in average energy above 4 MeV bombarding energy is due to neutrons from deuteron breakup (31).

Although in existing intense neutron sources based on the D-T reaction the tritium serves as target, a proposed source uses a tritium beam on a deuterium target. While the published data on the reaction are for deuteron projectiles and tritium targets, the conversion to the reverse arrangement is straightforward.

d+Li

Interest in the reaction of deuterons with Li for intense sources was stimulated by a proposal from Brookhaven (32) which pointed out the advantages of a liquid lithium jet target for dissipating the high power generated in the target of an intense neutron source for radiation damage studies. At the time of that proposal relatively little was known about the yield and spectra of neutrons produced in the bombardment of thick Li targets by deuterons, but several good measurements are now available which appear to resolve the discrepancies both in yield and spectra of earlier measurements. Such measurements are difficult because of the need of observing low-energy neutrons in the presence of much more energetic neutrons.

The measurements most directly applicable to the use of the reaction as a neutron source for radiation damage studies were performed by Saltmarsh et al. (33) for 40 MeV deuterons on thick Li targets. Figure 3 shows the measured neutron energy distributions for various emission angles. There are several measurements at lower deuteron energies, particularly the results obtained by Lone et al. (34). These more recent data are consistent with earlier measurements by Weaver et al (22), which had found a large intensity of neutrons of energy below 5 MeV, while other authors had found spectra which showed a rapid decrease of intensity at energies below 10 MeV.

Measured neutron spectra yield a value for the average energy of the neutrons emitted in the forward direction of 0.4 times the deuteron bombarding energy for deuterons above 10 MeV, but this includes only neutrons of energy above 2 MeV.

The angular distribution of the emitted neutrons is strongly forward peaked; the intensity drops to half value at about 15° at a bombarding energy of 23 MeV (34) and more rapidly at higher bombarding energies. The average energy of the emitted neutrons also drops off rapidly from the 0° value as the emission angle increases. This anisotropy of the reaction causes problems in its use as a neutron source for radiation damage studies because samples irradiated close to the source are exposed to neutrons that vary in both intensity and energy over the sample.

<u>p + Be and p + Li</u>

Interest in the reaction of protons on Be developed on the basis of a proposal by the Fermi National Accelerator Laboratory to use the protons from the injector of the National Accelerator for producing neutrons for radiotherapy. This injector is a linear accelerator which permits extraction of protons in the energy range 37-66 MeV. There was little known about the yield and energy of neutrons from protons in this energy range on thick targets, and the information necessary to design a neutron source was obtained from measurements performed at the University of California at Davis. The results were published in three papers (35-37). Unfortunately the spectra published in references 35 and 36 differ from each other; the data reference in (36) are considered more reliable by the author (private communication). Measured neutron energy distributions at several bombarding energies are shown in Figure 4. There are also data available at lower proton energies, especially references 34 and 38, and at higher energy (39, 40). Figure 5 shows the energy dependence of the neutron yield as a function of proton energy.

The neutron spectra from the proton bombardment of thick Li and Be targets are similar and show a large peak at energies below 5 MeV. This peak is interpreted as caused by evaporation neutrons; its intensity is fairly independent of emission angle and varies slowly with bombarding energy. At neutron energies above 5 MeV there is a broad maximum for neutrons emitted in the forward direction; this broad distribution extends up to the proton bombarding energy. The intensity of the energetic neutrons decreases rapidly with emission angle. Although the average energy of the neutrons is relatively low, at high bombarding energies the number of high energy neutrons is high enough to make the reaction useful for radiotherapy.

The average energy of the emitted neutrons for both Li and Be targets is shown as a function of proton energy in Figure 6. Because of the presence of many low energy neutrons the observed average energy depends strongly on the lower limit of neutron energy observed in the measurements. In some applications the low energy neutrons may be filtered out. The yields plotted in Figure 5 do not include these low energy neutrons.

d+Be

Traditionally neutron sources based on cyclotrons have used deuterons on beryllium targets. Beryllium metal is a convenient target material. Since the last neutron in the Be nucleus is loosely bound, this neutron should be easily knocked out, so that bombardment of Be was expected to give a high neutron yield. In the first application of neutrons to radiotherapy at Berkeley (3) the neutrons were produced by this reaction, and it is still used at Hammersmith. Many of the more recent clinical trials of neutron radiotherapy also use this reaction. for example at the University of Washington, the Naval Research Laboratory, and Texas A&M University.

Neutron spectra from the bombardment of thick beryllium targets by deuterons have been measured by many investigators. For neutrons emitted in the forward direction measurements performed before 1972 agreed that the spectrum was similar to a Maxwellian distribution with a peak not far below half the deuteron bombarding energy. The more recent measurements (22, 33, 34, 41) show little or no decrease in intensity at low neutron energies. In fact, the most recent data (33, 34) agree that the energy distribution increases towards low neutron energies. For example, Lone et al. (34) find a neutron distribution which is about four times higher at 0.5 MeV than at 2.5 MeV for a deuteron bombarding energy of 18 MeV.

Recent measurements of yields and spectra extend to bombarding energies around 80 MeV (22, 33-35, 37, 39-42). Generally the angular distributions are peaked in the forward direction; the peak becomes more pronounced at higher bombarding energies. The average energy of the neutrons emitted in the forward direction is about 0.4 times the deuteron bombarding energy, if one excludes neutrons below about 2 MeV. As the emission angle increases, the average energy of the emitted neutrons decreases. Generally spectra and yields of neutrons from the bombardment of Be targets with deuterons are similar to those from the bombardment of Li targets (Figure 3).

The thick target yield of the neutrons emitted in the forward direction from a thick Be target is shown in Figure 5 and the average energy of the neutrons is shown in Figure 2. The neutron yield from deuteron bombardment of Be is about an order of magnitude higher than for proton bombardment for the same bombarding energy. Since cyclotrons of a given size can accelerate protons to twice the energy of deuterons, the difference in yield between the two reactions for a given cyclotron is not very large.

Because of the wide use of the d+Be reaction in biomedical applications the dose rate of the neutrons emitted in the forward direction has been measured by several groups (43-46). The dose rate increases somewhat more slowly than the third power of the deuteron bombarding energy. For the application in radiotherapy a knowledge of the decrease of dose with penetration in tissue is of importance. The depth at which the dose drops to 50% has been measured at various neutron radiotherapy centers. In order to increase the average neutron energy and to increase the penetration of the neutrons some of the centers use Be targets in which the deuterons do not stop. At Hammersmith where 16 MeV deuterons bombard a 0.8 mm thick Be target the depth at which the dose is 50% was found to be 8.8 g cm^{-2} of tissue equivalent material, while at Texas A&M University where 50 MeV deuterons bombard a thick target the corresponding value was 13.8 g cm^{-2} (47).

Other Reactions

A convenient target for a neutron source is carbon. Neutron yields and spectra from deuterons on thick carbon targets have been measured for deuteron energies from 12 MeV to 50 MeV (22, 42). Although the shape of the neutron spectrum is similar for thick C and thick Be targets bombarded by deuterons, the yield from C is about 40% lower so that there is no advantage in using C over Be.

Another reaction which has been considered as a source of energetic neutrons for radiotherapy is ^{3}He on Be. A cyclotron produces $^{3}He^{++}$ ions of 2.5 times the energy of deuterons. This led to the hope that relatively high neutron energies could be obtained with a small cyclotron. Studies of the ^{3}He+Be reaction (48, 49) show, however, that the yield of the reaction is rather low, and that the reaction has no real advantage over d+Be.

Although the reaction of protons with tritons is useful as a source of monoenergetic neutrons, this reaction is not useful for producing high intensities of energetic neutrons.

At a fixed deuteron energy the neutron yield generally decreases with atomic weight (41, 42), so that targets heavier than Be offer no advantages for high intensity sources.

ACCELERATORS

For the neutron sources in present use the development of suitable accelerators has been much easier than the development of suitable targets. Cyclotrons that produce 50 μA of external beam at 40 MeV are available for neutron sources based on the d+Be reaction. For $d+{}^3H$ sources an accelerator that produces 25 mA at 400 keV (50) and a single-gap accelerator that produces 200 mA at 160 keV (51) are in operation with external beams, and another system operates at 200 kV with a current of 500 mA in a closed tube (52).

For the radiotherapy application available accelerators are adequate, and the problem has been primarily in the development of targets. For the much higher source strengths desired for radiation damage studies higher current accelerators have to be developed. Desired currents for two accelerators presently under consideration are 1.1 A at 0.3 MeV and 0.2 A at 35 MeV. In both cases well-focused external d.c. beams are needed, and at this writing there are no accelerators in operation that approach these specifications.

Low Voltage Accelerators

At present several high-current low-voltage accelerators are being designed or constructed for neutron sources. The accelerator that has been completed (53) is designed to provide a 1-cm diameter external beam of 0.15 A, 400-keV atomic deuterium ions. An ion source (54) with 17 apertures allows extraction of up to 0.4 A d.c. total beam at 15 kV. A 90° double focusing magnet separates out the D^+ ions which pass through a solenoid lens into a uniform gradient acceleration tube with reentrant electrodes. The acceleration tube has three intermediate electrodes between ground and the high voltage terminal and produces a gradient of 17 kV/cm for accelerating the ions. Space charge effects are avoided by maintaining a high enough pressure for complete space charge neutralization.

High Voltage Accelerators

At present most neutron sources that require deuterons of energies above 5 MeV use cyclotrons to accelerate the deuterons. For the high currents needed for neutron sources planned for radiation damage studies cyclotrons are not expected to be able to provide high enough currents, and linear accelerators are preferred (55).

Although the linear accelerator planned for the acceleration of 200 mA has not yet been designed in detail, it will undoubtedly consist of an injector similar to the low-voltage accelerators described in the preceding section. The output of the injector has to be chopped and/or bunched to match the times during which the accelerator accepts ions for acceleration. If a d.c. beam is desired on target, the accelerated beam has to be debunched probably by allowing the ions to drift through a long distance.

The design of the accelerator is complicated by the need to minimize beam losses. Even a small fraction of the 7 MW of beam power would melt any components it might strike and/or would induce a high level of radioactivity.

TARGETS

Deuterium

SOLID TARGETS. Thick deuterium targets for generating neutrons with a low-voltage accelerator are most easily prepared by freezing heavy water on a liquid-nitrogen cooled metal plate (56). Because of the low thermal conductivity of ice, such targets evaporate rapidly at high beam currents.

Heavy-ice targets have been used for beam currents up to 0.2 mA. Currents up to 0.5 mA can be used if the target rotates (57).

Deuterium absorbed in metals, such as Ti and Zr, has been used for producing neutrons. Such hydride targets will be discussed further for tritium. The neutron yield is lower than for a heavy-ice target by a factor of the order of three, partly because of the higher stopping power of the metals compared to O, partly because the targets contain fewer than two deuterium atoms per metal atom.

Deuterium may be imbedded in the target by the deuteron beam. This method of loading the target usually produces a lower deuterium concentration than if the deuterium is loaded from gas at elevated temperature. Neutron yields have been reported to be of the order of a tenth of those from heavy ice targets.

None of the solid targets have been found to be useful for neutron sources for the applications discussed in this review.

LIQUID TARGETS. Although heavy water may be a useful target material for neutron sources, it does not appear to have been used. Heavy water could either be separated from the accelerator vacuum system by a foil, or it might be used in the form of a free-standing jet in the vacuum system (58). Experiments with a jet of ordinary water injected at velocities up to 300 m/s indicate that the jet is quite stable in vacuum. The temperature rise of the water caused by 20 mA of 35-MeV deuterons is estimated to be only 1°C.

GAS TARGETS WITH ENTRANCE FOIL. Deuterium gas targets have been used extensively in accelerators for nuclear physics experiments (56). The gas target is separated from the accelerator by a thin window through which the beam passes. Foils of Al, Ni, Mo, and Havar, a Co-Ni-Cr alloy of high tensile strength, have served as window materials. Often the foils rupture when the beam strikes them. Such failures are most likely at high beam currents and high gas pressures, i.e., under the conditions for which the neutron output is highest.

At the Cancer Research Center in Heidelberg a deuterium gas target has been in use for biomedical research (59). 70 μA of 11 MeV deuterons from a cyclotron pass through a 10 mg/cm^2 Havar foil into a 30-cm long chamber filled with deuterium gas to a pressure of 11 atmos. Typically a foil lasts 8 hours. The beam power dissipated in the target is removed by circulating the gas and cooling it with water. With this arrangement dose rates of 0.35 Gy/min have been obtained 1 m from the target in the forward direction, and the dose in water decreased to 40% in 10 cm.

Kuchnir et al (60) have pointed out the advantages of cooling the target gas to liquid nitrogen temperatures. The increased density permits the use of a shorter target, and the lower temperature increases the tensile strength of the Havar foil. A cryogenic target system has been developed for use with 200 μA of 8.3-MeV deuterons from the 30" cyclotron at the University of Chicago. A 10 mg/cm^2 Havar foil separates the accelerator vacuum system from the 7.5 cm long deuterium gas target which is at a pressure of 10 atmos. and a temperature of 80 K.

DIFFERENTIALLY PUMPED GAS TARGETS. One of the earliest suggestions to use a differentially pumped high pressure gas target was made in

1957 (61). A decade later Colombant and Lidsky (62, 63) proposed a high pressure differentially pumped deuterium gas target for an intense neutron source. This was to be accomplished by bombarding the deuterium with 1 A of tritium. A neutron source based on this proposal has been designed at Los Alamos (64). A group in Canada (65) has been studying various types of deuterium gas target systems using subsonic, transonic, and hypersonic flow.

The deuterium gas target designed by the Los Alamos group (64) uses a supersonic (3300 m/s) jet that enters the target region at a temperature of 30-40 K and experiences a 1400 K temperature rise because of the 300 kW power dissipation by the beam. 80 g/s of deuterium pass through the 1-cm diameter target region and produce a density of 2×10^{19} deuterium molecules/cm^3. The target system designed at Los Alamos is shown in Figure 7.

Tritium

Although the same types of targets could be used for tritium as have been described for deuterium, the radiation hazards associated with tritium and the higher cost of tritium compared with deuterium impose restrictions in its use. For example, tritiated water or ice have never been employed for targets.

Another difference is the much higher neutron yield of the DT-reaction relative to the DD reaction at low bombarding energies. The cross section for the D-T reaction peaks at about 100 keV deuteron energy. For a thick target the neutron yield rises rapidly up to a deuteron energy of 200 keV; it increases by about 40% from 200 keV to 400 keV, but only about 10% from 400 keV to 600 keV. Hence neutron generators using this reaction operate at voltages between 150 and 400 keV, while high intensity neutron sources using the DD-reaction employ energies above 5 MeV. This difference affects the target design.

The radioactivity of tritium favors closed rather than pumped acceleration systems, especially in hospitals so that much effort has gone into the development of closed systems using mixed d-t beams.

SOLID TARGETS. Tritiated solid targets were first used in 1949 (66). Originally tritium was absorbed in Zr, but other elements, such as Sc, Ti, and Er form useful hydrides. Ti is presently most widely used. The first Zr targets were backed by W, but other materials such as Cu, Ag, Ta, and Pt have also served as backings. For high-current applications the cooling requirements determine the choice of the target backing, and Cu or copper alloys are most useful. In particular, a Cu-Zr alloy, Amzirc, combines good thermal conductivity and high mechanical strength. There are several suppliers of metal tritide targets, such as Oak Ridge National Laboratory in the USA and Nukem in Germany.

The neutron yield from tritide targets decreases with use because tritium may be released when the target is heated by the incident beam, but also because the incident deuterons displace tritium in the target. The combination of these effects results in a decrease of the neutron yield by a factor of two when about 6 C of deuterons have bombarded a target in a typical, commercially available, 14-MeV neutron generator, as is often used for neutron activation analysis.

Tritium loss by heating can be greatly reduced by adequate cooling. The rotating target developed by Booth (67) at Livermore, has provided particularly effective cooling. In this design the outside of the target is in contact with a 1 mm thick layer of water. In order to provide adequate cooling the target rotates at 1100 rpm. This rapid rotation is made possible by a specially designed vacuum seal (68, 69). The first use of the rotating targets was with 8 mA of 400 keV deuterons, and these targets had a diameter of 15 cm. When the beam current was increased to 25 mA, a target diameter of 22 cm was chosen (50). For the more intense source now under construction at Livermore 50 cm diameter targets will be used, and the rotation speed will be increased to 5000 rpm (53). With these larger targets and the higher rotation speed the power requirement to overcome the viscous drag caused by the external cooling would be excessive. Hence the cooling is placed inside a sandwich target backing containing convoluted channels to produce turbulent flow.

For long target life an analyzed deuteron beam is essential, because the displacement of tritium in the target occurs most rapidly where the deuterons come to rest. If both atomic and molecular ions are used, the molecular ions displace tritium at a depth where the atomic ions have the highest probability of producing neutrons (70). The fact that the loss of tritium occurs most rapidly at the depth at which the deuterons stop has been corroborated by measuring the tritium distribution in a used target (71).

For an extension of the target life time the rotating target can be mounted in such a way that the beam strikes different concentric rings at different times (70). This arrangement is shown in Figure 8.

The life time of the target depends strongly on how sharply the beam is focused. While a sharply focused beam increases the flux density near the source, it drastically reduces target life. In the Livermore rotating target source, when a 1.6 cm diameter beam of 15 mA produces an initial source strength of 4×10^{12} s^{-1}, the source strength decreases about 15% in 100 h of operation (72). With a more sharply focused beam a high flux density (1.5×10^{12} cm^{-2} s^{-1}) can be achieved on small samples placed very near the source, but the targets deteriorate more rapidly (73).

There are several other neutron sources that use rotating targets similar to Booth's design. The first of these was built by Broerse et al (74) at the Radiobiological Institute in Rijswijk. It uses 6 mA of 270 keV deuterons and produces a source strength of 6×10^{11} s^{-1} with a 15 hour half life. Another rotating target source is in operation at the Eppendorf Hospital in Hamburg. This unit was manufactured by Radiation Dynamics and uses 12 mA of 500 keV deuterium ions (75). It produces 2.5×10^{12} neutrons/s, with a half life of less than 10 hours. A very large rotating target source is in operation at Valduc, France. A 25-cm diameter target which rotates at 3000 rpm is cooled with a NaK alloy. When the target is bombarded with 110 mA of 160 keV deuterons, a source strength of 6×10^{12} s^{-1} can be obtained, but the intensity drops to half its initial value in only 3 hours (51).

The much longer life times of the rotating targets at Livermore are undoubtedly due to the use of an analyzed beam, while an unanalyzed beam which contains both atomic and molecular ions is used at the other installations.

Cranberg (76) has suggested that the target life could be extended in installations where both atomic and molecular ions are accelerated, by applying a weak magnetic field near the target so that the different species of ions impinge on separate adjoining portions of the target.

DRIVE-IN TARGETS. The decrease of neutron source strength from a metal hydride target may be avoided by replenishing the tritium by the charged-particle beam. For this purpose the beam should consist of approximately equal numbers of deuterium and tritium ions. Such a self-replenishing system can be sealed off. For the same concentration of hydrogen in the target a mixed deuterium-tritium beam on a mixed target gives only half the source strength of a monoisotopic beam and target, since only half the collisions are between deuterons and tritons, while collisions between deuterons and deuterons or tritons and tritons produce a relatively very small number of neutrons.

The performance and general aspects of drive-in targets have been discussed by Hillier et al. (77) and more recently by Kim (78). An experimental study of solid targets for intense neutron sources is underway at the Sandia Laboratories where a special target test facility has been constructed (79).

As self-replenishing targets either metal tritide or pure metal has been used. Metal tritide targets give initially a much higher neutron yield, but they tend to blister and, in addition, to lose the originally present tritium by diffusion (77).

The neutron generators that use drive-in targets and have been reported to produce the highest neutron yields have quite different targets. One uses chromium-plated copper tubing (80, 81). These tubes are arranged in such a way that 280 mA of mixed deuterium-tritium ions from two ion sources can bombard the target from opposite directions. With this arrangement a source strength of 5.6×10^{12} s^{-1} has been achieved within a target spot 6 cm in diameter. The other system (52) shown in Figure 9 employs a conical scandium deuteride-tritide target. This cone is concentrically surrounded by a ring shaped ion source which produces about 150 mA of mixed deuterium-tritium ions. A neutron source strength of 5×10^{12} s^{-1} has been reported. When one looks along this axis of the cone, the neutron source appears as a ring with 3.2 cm inner diameter and 4.2 cm outer diameter.

Two types of sealed-tube neutron generators that produce 1×10^{12} neutrons/s are commercially available; one is manufactured by Elliott in England, and two such units are in operation (at Manchester and Glasgow) (82); the other generator is manufactured by Philips in The Netherlands and is used at a hospital in Amsterdam. Both types of generators have 250 kV power supplies, the Elliott unit has an ion current of 30 mA incident on an Er target, while the Philips unit has 18 mA incident on a Ti target. In both generators the tube life times have been more than 100 hours (83).

GAS TARGETS. A target of tritium gas produces three to five times more neutrons per incident deuteron than a metal tritide target, since all the collisions are between the hydrogen isotopes. Gas targets have the problem that the gas must be prevented from getting into the acceleration tube which must be under vacuum. The currents needed for high intensity sources preclude the use of foils so that differential pumping has to be applied between the target cell and the acceleration tube. Because of the cost and hazards of tritium the gas has to be recirculated. Chenevert et al (84) have designed a system, shown in Figure 10,to accomplish this. 15 mA of 250 keV deuterons pass through a 0.4 cm diameter aperture into a 50 cm long target chamber which contains tritium at a pressure of 10 Torr. So far only 4 mA of deuterons have been used, and the highest observed source strength has been $2 \times 10^{12}\ s^{-1}$. The principal problem has been isotopic mixing not only between the deuterium in the beam and the target gas, but also exchange with ordinary hydrogen present in components of the target and gas handling system. This has resulted in a decrease of neutron yield to half its initial value in two hours.

Lithium

Evaporated lithium metal has been the usual target material for neutron production in low-current accelerators. Because of the low melting temperature of Li, metal targets are not stable at high beam currents. A liquid Li target has therefore been selected for the intense source presently being designed for construction at Hanford. This design is expected to be based on a Brookhaven proposal (55), but the details have not yet been decided. The design aim is for a beam power dissipation of 3-10 MW in the target.

According to the Brookhaven proposal liquid lithium at 200°C will flow at a rate of 18 ℓ/s to form a 1.5 cm thick, 12 cm wide layer.

Beryllium

Beryllium targets for cyclotron-based neutron sources usually consist of a sheet of beryllium metal thick enough to stop the incident particles. The range of 30-MeV deuterons in Be metal is about 3.5 mm. The target is usually cooled by attaching it to a water-cooled copper backing. Such targets can be used with a beam power of 1-2 kW without melting provided the beam is not too sharply focussed.

For radiation damage studies a sharply focussed beam is desirable for achieving high neutron flux densities near the target. In a target system designed for this application (85) the beryllium is brazed into the copper backing. The cooling water flows through convoluted channels in the backing, close to the back surface of the Be target. This target has been used with 20 μA of 30 MeV deuterons focussed on a 5 mm spot, but is designed for 100 μA.

Just as for tritium targets much higher currents can be accomodated on a rotating Be target. Calculations (58) indicate that an internally cooled Be wheel, 32 cm in diameter, rotating at 6000 rpm could be used with a beam power of 3 MW and a beam diameter of 1 cm. This corresponds to 85 mA of 35-MeV deuterons. In such a wheel the stresses caused by centrifugal forces would be very small compared with the tensile strength of Be.

The neutron yield of an internally cooled Be target could be increased by using D_2O as the coolant because the deuterium in D_2O would contribute to the neutron production.

STATUS OF NEUTRON SOURCES

Radiation Damage Studies

DT SOURCES. At present most studies of radiation damage induced by DT neutrons employ the rotating target neutron source at Lawrence Livermore Laboratory (RTNS I). The characteristics of this source and typical experiments are described in reference (73). The experiments have included both surface and bulk radiation damage measurements, at temperatures ranging from that of liquid helium to 800°C. The highest observed neutron flux density is 1.7×10^{12} cm^{-2} s^{-1} on a small sample; a more typical value is 1×10^{12} cm^{-2} s^{-1} for an extended run or a fluence of 3×10^{17} cm^{-2} in an 80-hour run.

Two larger sources of similar design (RTNS II) are nearing the completion at Livermore (53). These sources are expected to produce 4×10^{13} DT neutrons per second and to provide a maximum neutron flux density of 1.2×10^{13} cm^{-2} s^{-1}. The design should permit a future upgrading to a source strength of 10^{14} s^{-1} and a flux density of 2-3 $\times 10^{13}$ cm^{-2} s^{-1}.

While the older (RTNS I) source was originally built for nuclear physics experiments and is in a building without adequate shielding for high intensity operation, the new sources (RTNS II) are designed for radiation damage studies and are located in a well-shielded building. The facility has provisions for remote handling for target replacements and sample positioning.

Two larger DT neutron sources (INS) for radiation damage studies have been designed at the Los Alamos Scientific Laboratory (64, 86). These sources use a tritium beam on a deuterium jet target and are designed to produce 10^{15} DT neutrons per second. At this source strength the neutron flux density would be more than 10^{14} cm^{-2} s^{-1} within a 3 cm^3 volume and more than 10^{13} cm^{-2} s^{-1} within about 100 cm^3. One of the sources will be surrounded by concentric spheres of lithium, ^{235}U, and beryllium. The uranium multiplies the number of neutrons, and the combination of shells is designed to produce, together with the primary neutrons, a neutron spectrum similar to that at the first wall of a fusion reactor. While the flux density of primary neutrons decreases with distance from the source according to the inverse square law, the flux density of secondary neutrons is fairly uniform within the spherical shell so that the total flux density is high over a much larger volume than for a bare source, but the ratio of the numbers of primary and secondary neutrons varies rapidly within the shell.

BROAD SPECTRUM SOURCES. Many of the radiation damage studies with broad-spectrum sources have been performed with neutrons from the d+Be reaction at the University of California at Davis. In these experiments about 25 μA of 30-MeV deuterons bombard a 3.5-mm thick Be target. This source produces about 5×10^{12} neutrons s^{-1} sr^{-1}, or a flux density of the order of 10^{12} cm^{-2} s^{-1} at a distance of 2 cm from the target in the forward direction. For a sample that subtends an appreciable angle at the source both the flux density and the average neutron energy decrease rapidly with angle.

A large broad-spectrum neutron source is being designed for construction at the Hanford Engineering Development Laboratory (55). The plan is to bombard a liquid lithium target with 0.1-0.2A of 35 MeV deuterons. Such a source would produce about 3×10^{16} neutrons s^{-1} sr^{-1} in the forward direction, and the flux density would be above 10^{14} cm^{-2} s^{-1} within 15-20 cm from the source. This would permit the irradiation of fairly large samples at a flux density comparable to that at the first wall of a fusion reactor. The characteristics of operating and planned neutron sources for radiation damage studies for fusion reactors are listed in Table 1.

Radiotherapy

DT SOURCES. While neutron sources for radiation damage studies have been designed and built at the institutions where they are used, DT neutron sources for medical uses have been supplied by commercial manufacturers. Three of these manufacturers produce mixed-beam sealed-tube sources, one produces a pumped tube with mixed beam, and one uses a deuteron beam on a rotating target. All DT neutron generators are isocentrically mounted which is a great advantage in the clinical use, compared with most broad-spectrum sources.

Since these generators are commercially produced, less information about the construction of the systems has been published than for systems manufactured at research laboratories. Specifications are not necessarily indicative of actual hospital experience. Table 2 summarized published information. Quoted neutron source strengths are usually not the number of neutrons produced at the target, but are deduced from the flux density at the exit of a collimator. This number includes scattered neutrons.

Although two of the DT generators listed in Table 1 promise to provide much higher intensities than those listed in Table 2, these high-intensity sources are not suitable for clinical use. The development of DT sources for clinical applications with intensities much higher than those listed in Table 2 appears very difficult.

BROAD-SPECTRUM SOURCES. Most of the broad-spectrum sources used in radiotherapy use accelerators which were not constructed for this application and are located in nuclear physics research laboratories. All of them have horizontal charged particle beams and have a fixed horizontal neutron beam. The only exception are two cyclotrons that were installed in Essen and in Edinburgh in 1976; these cyclotrons produce 15 MeV deuterons, and have a magnetic beam transport system that permits isocentric treatment.

Table 3 summarizes information about broad-spectrum sources for radiotherapy. In all of them the accelerator is a cyclotron except at the Fermi National Accelerator Laboratory where a linear accelerator is employed. This listing does not include all the cyclotrons used for radiotherapy but gives typical parameters. For example, a 30-MeV cyclotron has been in use for neutron radiotherapy in Japan, and a cyclotron similar to that at Hammersmith has been used for neutron therapy at Dresden (GDR).

A cyclotron of a given size accelerates protons to twice the energy of deuterons. For isocentric treatment, magnetic beam transport systems of a given size can also handle protons of twice the energy of deuterons. For these reasons the reaction p+Be has advantages over d+Be for use in small cyclotrons. The last two lines of Table 3 give the expected performance of commercially available cyclotrons if the neutrons are generated by the reaction p+Be. These cyclotrons are available with a magnetic beam transport system for isocentric treatment.

Table 1. High-Energy Neutron Sources for Radiation Damage Studies.

Location	Name	Reaction	Beam Energy (MeV)	Target Current (mA)	Target Spot Size (cm)	Source Intensity neutrons sr^{-1} s^{-1}	Status
Livermore	RTNS I	$d+^{3}H$	0.4	22	0.6 diameter	5×10^{11}	Operating
Livermore	RTNS II	$d+^{3}H$	0.4	150	1 diameter	3×10^{12}	Scheduled for 1978
Valduc	Lancelot	$d+^{3}H$	0.16	110	5 diameter	5×10^{11}	Operating
Los Alamos	INS	$t+^{2}H$	0.3	1000	1×1 cylinder	8×10^{13}	Planned
UC Davis		d+Be	30	0.025	0.5 diameter	5×10^{12}	Operating
Hanford	FMIT	d+Li	35	100	1-10 diameter	3×10^{16}	Planned

Table 2. DT Generators for Radiotherapy

Manufacturer	Voltage (kV)	Current (mA)	Target Material	Source Strength 10^{12} s^{-1}	Effective Lifetime (hours)	Status
Elliot	250	30	Er	1	170	Operating at Glasgow and Manchester
Philips	250	18	Ti	1	130-150	Operating at Amsterdam
Haefely	250	500	Sc	5*	700*	Operating at Heidelberg; To be installed at Zürich
Cyclotron Corp.	200	300	?	8*	500*	To be installed at Riyadh
Radiation Dynamics	500	15	Ti-T	2.5	10	Operating at Hamburg

* Manufacturer's specifications

Table 3. Broad-Spectrum Neutron Generators for Radiotherapy

Location	Reaction	Beam Energy (MeV)	Beam Current (μA)	Dose rate in air at 125 cm (Gy/min)	Depth of 50% dose in tissue (cm)
Hammersmith	d+Be	16	80	0.35	8.8
U. Washington	d+Be	21.5	30	0.45	10.2
Naval Research Lab.	d+Be	35	10	0.66	12.8
Texas A&M	d+Be	50	7	0.75	13.8
Fermilab	p+Be	66	30	1.1	16
Heidelberg	$d+{}^2H$	10.6	70	0.20	10
Chicago	$d+{}^2H$	8.3	200	0.20	10
	p+Be	30	66	0.46	10.6
	p+Be	42	47	0.84	12.6

LITERATURE CITED

1. Kulcinski, G.L., Conn, R.W. 1974. Nucl. Fusion Supp., pp. 51-77

2. Kulcinski, G.L., Doran, D.G., Abdou, M.A. 1976. Spec. Tech. Publ. 570, Am. Soc. Test. Mater., pp. 329-51

3. Lawrence, E.O. 1937. Radiology 29:313-22

4. Stone, R.S. 1947. Am. J. Roentgenol. 59:771-85

5. Sheline, G.E., Phillips, T.L., Field, S.B., Brennan, J.T., Raventos, A. 1971. Am. J. Roentgenol. 111:31-41

6. Catterall, M., Sutherland, I., Bewley, D.K. 1975. Br. Med. J. 2:653-56

7. Catterall, M. 1976. Br. J. Radiol. 49:203-5

8. Proc. Int. Conf. on Radiation Test Facilities for the CTR Surface and Materials Program 1975. Report ANL/CTR-75-4, 873 pp.

9. Particle Radiation Therapy, Proc. of Int. Workshop, American College of Radiology. 1976. 572 pp.

10. Particles and Radiation Therapy II Conf., Berkeley, 1976, in press

LITERATURE CITED (Cont'd)

11. Lone, M.A. 1977. ed. Report NBSIR 77-1279, 34 pp.

12. Bhat, M.R., Pearlstein S.1977. Ed. Symp. on Neutron Cross Sections from 10-40 MeV. Report BNL-NCS-50681, 555 pp.

13. Lone, M.A. 1977, See Ref. 12, pp. 79-116

14. Int. Comm. on Radiation Units and Measurements, Washington, D.C. 1977, ICRU Report, 132 pp.

15. Ullmaier, H., Ed. 1977. Nucl. Instrum. Meth. 145:1-218

16. Marion, J.B., Fowler, J.L. eds. 1960. Fast Neutron Physics, Part I. Interscience Publishers pp. 1-176

17. Goldberg, M.D., 1963, Progress in Fast Neutron Physics, University of Chicago Press, pp. 3-21

18. Liskien, H., Paulsen, A. 1973. Nucl. Data Tables 11:569-619

19. Van Oers, W.T.H., Brockman, K.W. 1963. Nucl. Phys. 48:625-46

20. Roy, M., Bachelier, D., Bernas, M., Boyard, J.L., Brissaud, I., Detraz, C., Radvanyi, P., Sowinski, M. 1969. Phys. Lett. 29B:95-96

21. Seagrave, J.D. 1958. Los Alamos Report LAMS 2162. 38 pp.

LITERATURE CITED (Cont'd)

22. Weaver, K.A., Anderson, J.D., Barschall, H.H., Davis, J.C. 1973. Nucl. Sci. Eng. 52:35-45

23. Cranberg, L., Armstrong, A.H., Henkel, R.L. 1956. Phys. Rev. 104:1639-42

24. Lefevre, H.W., Borchers, R.R., Poppe, C.H. 1962. Phys. Rev. 128:1328-35

25. Rybakov, B.V., Sidorov, V.A., Vlasov, N.A. 1961. Nucl. Phys. 23:491-98

26. Coçu, F., Ambrosino, G., Guerreau, D. 1977. Saclay Report CEA-R-4838

27. Barschall, H.H., 1974. Nuclear Structure Study with Neutrons, Plenum Press, New York, pp. 289-297

28. Schraube, H., Morhart, A., Grünauer, F. 1975. Second Symposium on Neutron Dosimetry in Biology and Medicine, EUR 5273 d-e-f, pp. 979-1003

29. Edwards, F.M., Fielding, H.W., Kraushaar, J.J., Weaver, K.A. 1974. Med. Phys. 1:317-22

30. McDonald, J.C., Kuo, T.Y.T., Freed, B.R., Laughlin, J.S. 1977. Med. Phys. 4:319-21

LITERATURE CITED (Cont'd)

31. Poppe, C.H., Holbrow, C.H., Borchers, R.R. 1963. Phys. Rev. 129:733-39

32. Goland, A.N., Snead, C.L., Parkin, D.M., Theus, R.B. 1975. IEEE Trans. Nucl. Sci. NS-22:1776-79

33. Saltmarsh, M.J., Ludemann, C.A., Fulmer, C.B., Styles, R.C. 1977. Nucl. Instrum. Meth. 145:81-90

34. Lone, M.A., Bigham, C.B., Fraser, J.S., Schneider, H.R., Alexander, T.K., Ferguson, A.J., McDonald, A.B. 1977. Nucl. Instrum. Meth. 143:331-44

35. Heintz, P.H., Johnsen, S.W., Peek, N.F. 1977. Med. Phys. 4:250-54

36. Johnsen, S.W. 1977. Med. Phys. 4:255-58

37. Amols, H.I., Dicello, J.F., Awschalom, M., Coulson, L., Johnsen, S.W., Theus, R.B. 1977. Med. Phys. 4:486-93

38. Nelson, C.E., Purser, F.O., Von Behren, P., Newson, H.W. 1977. See Ref. 12, pp. 125-33

LITERATURE CITED (Cont'd)

39. Harrison, G.H., Cox, C.R., Kubiczek, E.B., Robinson, J.E. 1977. See Ref. 11, pp. 19-23

40. Madey, R., Waterman, F.M., Baldwin, A.R. 1977. Med. Phys. 4:322-23

41. Daruga, V.K., Matusevich, E.S., Narziev, Kh. 1972. At. Energ. 33:934-36

42. Meulders, J.P., Leleux, P., Macq, P.C., Pirart, C. 1975. Phys. Med. Biol. 20:235-43

43. Parnell, C.J., Page, B.C., Chaudhri, M.A. 1971. Br. J. Radiol. 44:63-66

44. August, L.S., Theus, R.B., Attix, F.H., Bondelid, R.O., Shapiro, P., Surratt, R.E., Rogers, C.C. 1973. Phys. Med. Biol. 18:641-47

45. Weaver, K.A., Anderson, J.D., Barschall, H.H., Davis, J.C. 1973. Phys. Med. Biol. 18:64-70

46. Howell, R.H., Barschall, H.H. 1976. Phys. Med. Biol. 21:643-45

LITERATURE CITED (Cont'd)

47. Smith, A.R., Almond, P.R., Smathers, J.B., Otte, V.A., Attix, F.H., Theus, R.B., Wootton, P., Bichsel, H., Eenmaa, J., Williams, D., Bewley, D.K., Parnell, C.J. 1975. Med. Phys. 2:195-200

48. Broerse, J.J., Barendsen, G.W. 1967. Int. J. Radiat. Biol. 13:189-94

49. Parnell, C.J., Page, B.C., Jones, E.J. 1975. Phys. Med. Biol. 20:125-27

50. Booth, R., Barschall, H.H., Goldberg, E. 1973. IEEE Trans. Nucl. Sci. NS 20-3, pp. 472-74

51. Hourst, J.B., Roche, M., Morin, J. 1977. Nucl. Instrum. Meth. 145:19-24

52. Schmidt, K.A., Dohrmann, H. 1976. Atomkernergie 27:159-60

53. Booth, R., Davis, J.C., Hanson, C.L., Held, J.L., Logan, C.M., Osher, J.E., Nickerson, R.A., Pohl, B.A., Schumacher, B.J. 1977. Nucl. Instrum. Meth. 145:25-39

54. Osher, J.E., Hamilton, G.W. 1974. Report UCRL 76020, 8 pp.

LITERATURE CITED (Cont'd)

55. Grand, P., Goland, A.N. 1977. Nucl. Instrum. Meth. 145:49-76

56. Coon, J.H., see Ref. 16, pp. 677-720

57. Van Dorsten, A.C. 1955. Philips Tech. Rev. 17:109-11

58. Logan, C.M., Anderson, J.D., Barschall, H.H., Davis, J.C. 1975. See Ref. 8, pp. 410-15

59. Scheer, K.E., Schmidt, K.A., Höver, K.-H. 1976. Proc. of Int. Conf. on the Interactions of Neutrons with Nuclei, ERDA Report CONF 760715, pp. 1162-85

60. Kuchnir, F.T., Waterman, F.M., Forsthoff, H., Skaggs, L.S., Vander Arend, P.C., Story, S. 1976. Fourth Conf. on the Use of Small Accelerators in Research Teaching and Industrial Applications, pp. 513-16

61. Schumacher, B.W. 1957. Can. J. Phys. 35:239-40

62. Colombant, D. 1969. High Intensity 14 MeV Neutron Source. Ph.D. Thesis. Massachusetts Institute of Technology, Cambridge.

63. Lidsky, L.M., Colombant, D. 1967. IEEE Trans. Nucl. Sci. NS-14:945-49

LITERATURE CITED (Cont'd)

64. Armstrong, D.D., Emigh, C.R., Meier, K.L., Meyer, E.A., Schneider, J.D. 1977. Nucl. Instrum. Meth. 145:127-48

65. Deleeuw, J.H., Haasz, A.A., Stangeby, P.C. 1977. Nucl. Instrum. Meth. 145:119-25

66. Graves, E.R., Rodrigues, A.A., Goldblatt, M., Meyer, D.I. 1949. Rev. Sci. Inst. 20:579-82

67. Booth, R. 1967. IEEE Trans. Nucl. Sci. NS 14 pp. 938-42

68. Booth, R. 1968. Nucl. Instrum. Meth. 49:131-35

69. Booth, R., Logan, C.M. 1977. Nucl. Instrum. Meth. 142:471-73

70. Booth, R., Barschall, H.H. 1972. Nucl. Instrum. Meth. 99:1-4

71. Davis, J.C., Anderson, J.D. 1975. J. Vac. Sci. Technol. 12:358-60

72. Booth, R., Goldberg, E., Barschall, H.H. 1974. Br. Jl. Radiol. 47:737

73. Van Konynenburg, R.A., Barschall, H.H., Booth, R., Wong, C. 1975. See Ref. 8, pp. 171-82

74. Broerse, J.J., Broers-Challiss, J.E., Mijnheer, B.J. 1975. Strahlentherapie 149:585-96

LITERATURE CITED (Cont'd)

75. Cleland, M.R., Offermann, B.P. 1977. Nucl. Instrum. Meth. 145:41-47

76. Cranberg, L. 1976. Proc. of Int'l Conf. on the Interaction of Neutrons with Nuclei. Report CONF-760715 pp. 926-41

77. Hillier, M., Lomer, P.D., Stark, D.S., Wood, J.D., 1967. Third Conference on Accelerator Targets Designed for the Production of Neutrons. Euratom Report EUR 3895, pp. 125-45

78. Kim, J. 1977. Nucl. Instrum. Meth. 145:9-17

79. Bacon, F.M., Riedel, A.A., Cowgill, D.F., Bickes, R.W., Boers, J.E. 1977. Sandia Laboratories Report SAND 77-1326,28 pp.

80. Brennan, J.T., Hendry, G.O., Block, P., Hilton, J.L., Kim, J., Quam, W.M. 1974. Br. J. Radiol. 47:912-13

81. Brennan, J.T., Hendry, G.O., Herring, D.F., Hilton, J.L., Kim, J., Quam, W.M. 1973. Br. J. Radiol. 46:233

82. Hillier, M., Lomer, P.D., Wood, J.D.L.H. 1971. Br. J. Radiol. 44:716-19

83. Broerse, J.J., Greene, D., Lawson, R.C., Mijnheer, B.J. 1977. Int. J. Radiation Oncology Biol. Phys. 2:361-65, Supp. 2

LITERATURE CITED (Cont'd)

84. Chenevert, G.M., De Luca, P.M., Kelsey, C.A., Torti, R.P. 1977. Nucl. Instrum. Meth. 145:149-55

85. Logan, C.M., Booth, R., Nickerson, R.A. 1977. Nucl. Instrum. Meth. 145:77-79

86. Dierckx, R., Emigh, C.R. 1977. Los Alamos Report LA-UR-77-2187, 18 pp.

FIGURE CAPTIONS

Figure 1 Differential cross sections for the production of neutrons in the forward direction as a function of deuteron bombarding energy for the reactions of deuterons with targets of ^{2}H, ^{3}H, and Be.

Figure 2 Average energy of the neutrons emitted in the forward direction in the bombardment of thick targets of ^{2}H, ^{3}H, and Be by deuterons as a function of deuteron energy.

Figure 3 Energy distribution of neutrons emitted at various angles with respect to the incident deuterons when 40-MeV deuterons are incident on thick Li and Be targets. (From reference 33).

Figure 4 Energy distribution of neutrons emitted in the forward direction when protons of various energies are incident on a thick Be target. (From reference 36).

Figure 5 Thick target yields of high energy neutrons emitted in the forward direction for protons and deuterons incident on thick beryllium targets. The plotted yields are based on the observation of neutrons of energy above 5 MeV for p+Be, and above 2 MeV for d+Be. Many neutrons of lower energy are produced in both reactions, but their number is not accurately known. (From reference 13).

FIGURE CAPTIONS (Cont'd)

Figure 6 Average energy of the neutrons emitted in the forward direction in the bombardment of thick targets of Li and Be as a function of proton energy. The large number of low energy neutrons emitted results in a much lower average neutron energy, if neutrons below 5 MeV are included in the average. (From reference 13).

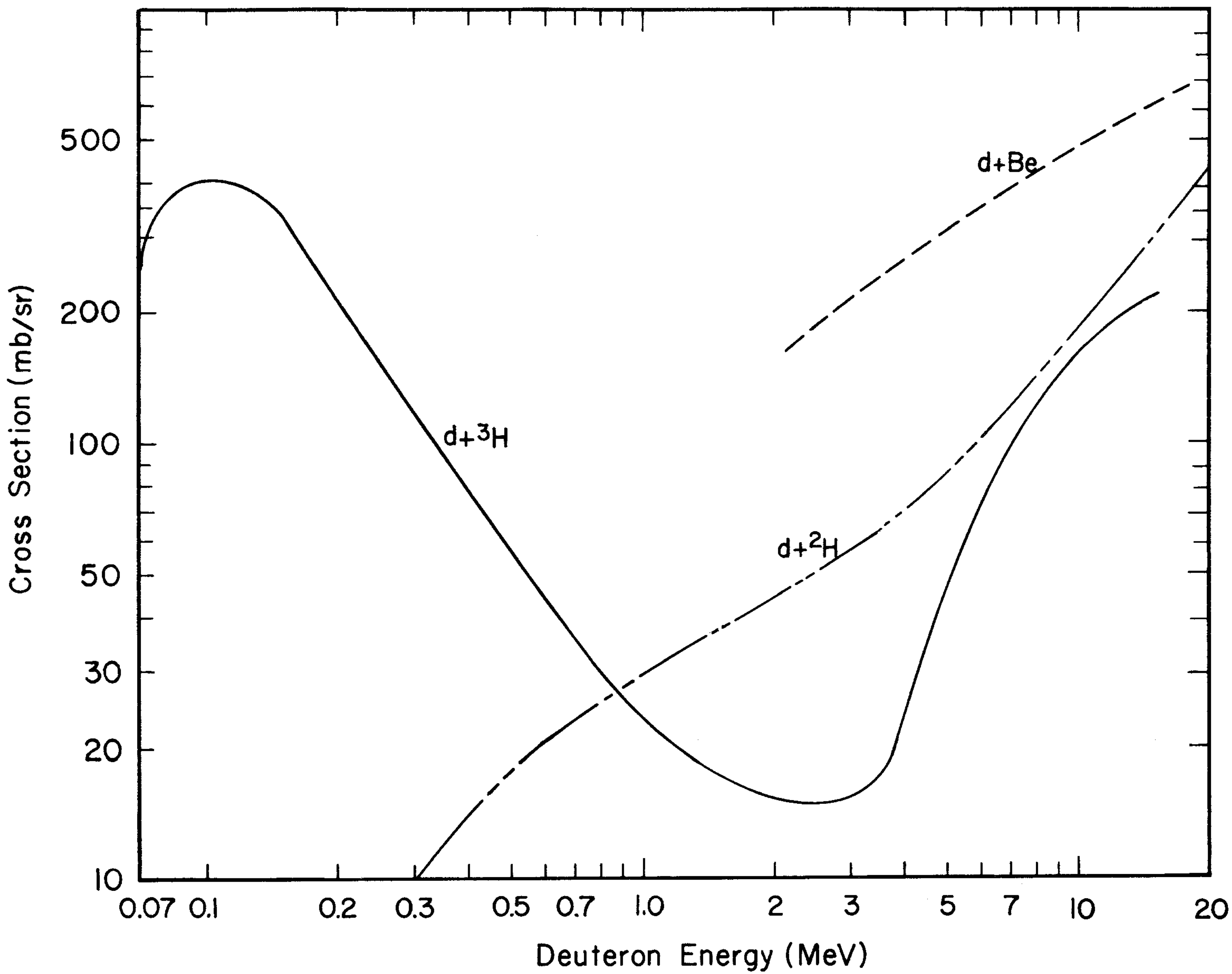
Figure 7 Schematic of the supersonic-jet deuterium target (INS). A beam of tritium ions is incident from the left. (From reference 64).

Figure 8 Schematic of the rotating target neutron source (RTNS I) at Lawrence Livermore Laboratory. The section to the right of the bearing and seal rotates at about 1100 rpm. The tritium loaded target is held with an O-ring seal at the end of the vacuum system. The section to the right of the bellows can be moved up and down so that the entire tritium loaded target area can be used. The neutron source remains fixed in space. Samples may be placed on the beam axis within a few millimeters of the neutron source. (From reference 50).

Figure 9 Sealed neutron generator tube. A mixed beam of deuterons and tritons from a toroidal ion source is focused by magnet coils onto the conical Sc target electrode at the center of the tube. Neutrons emitted downward are used. (From reference 52).

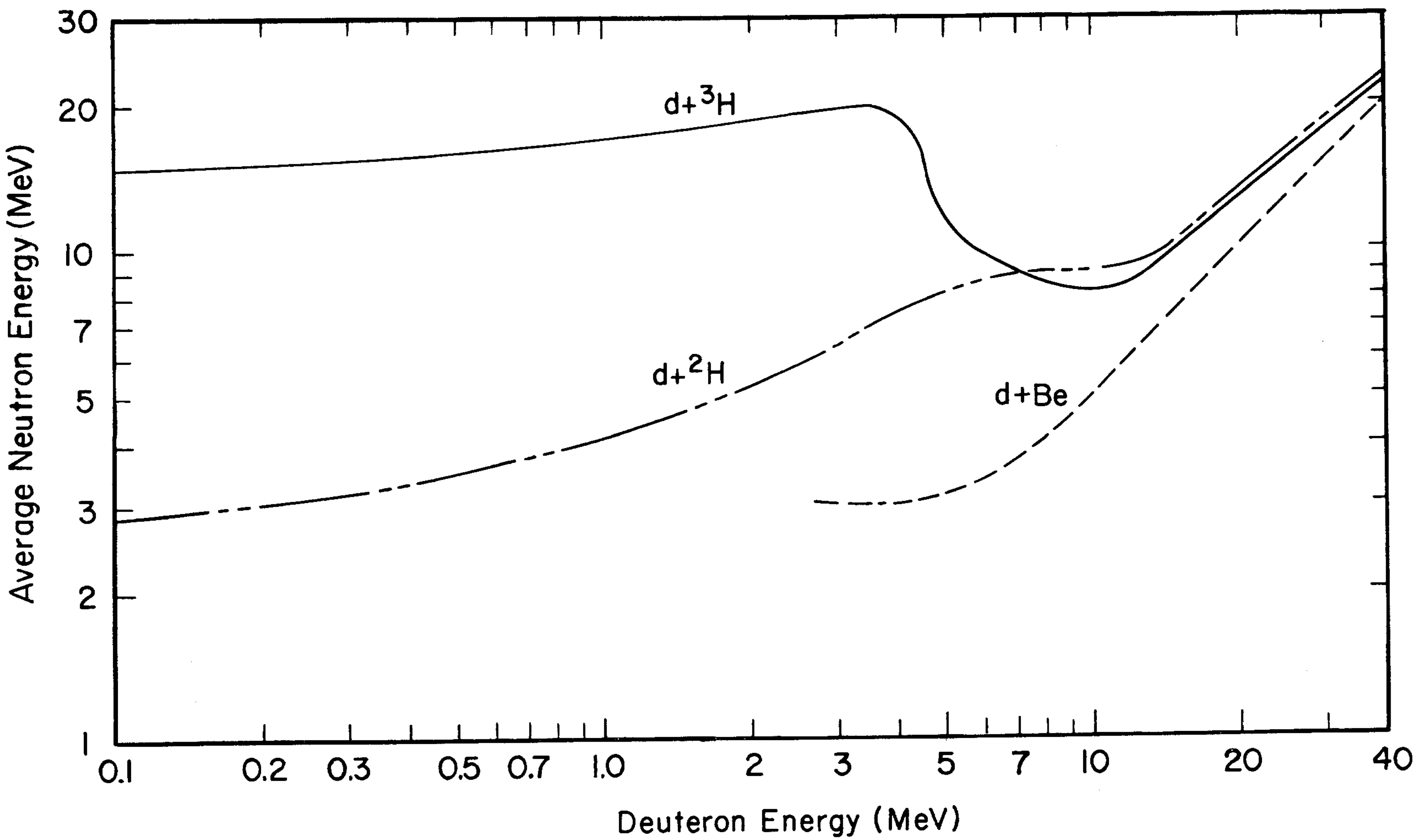
FIGURE CAPTIONS (Cont'd)

Figure 10 Differentially pumped tritium gas target. Deuterons are incident from the left. Neutrons emitted to the right are used. (From reference 84).



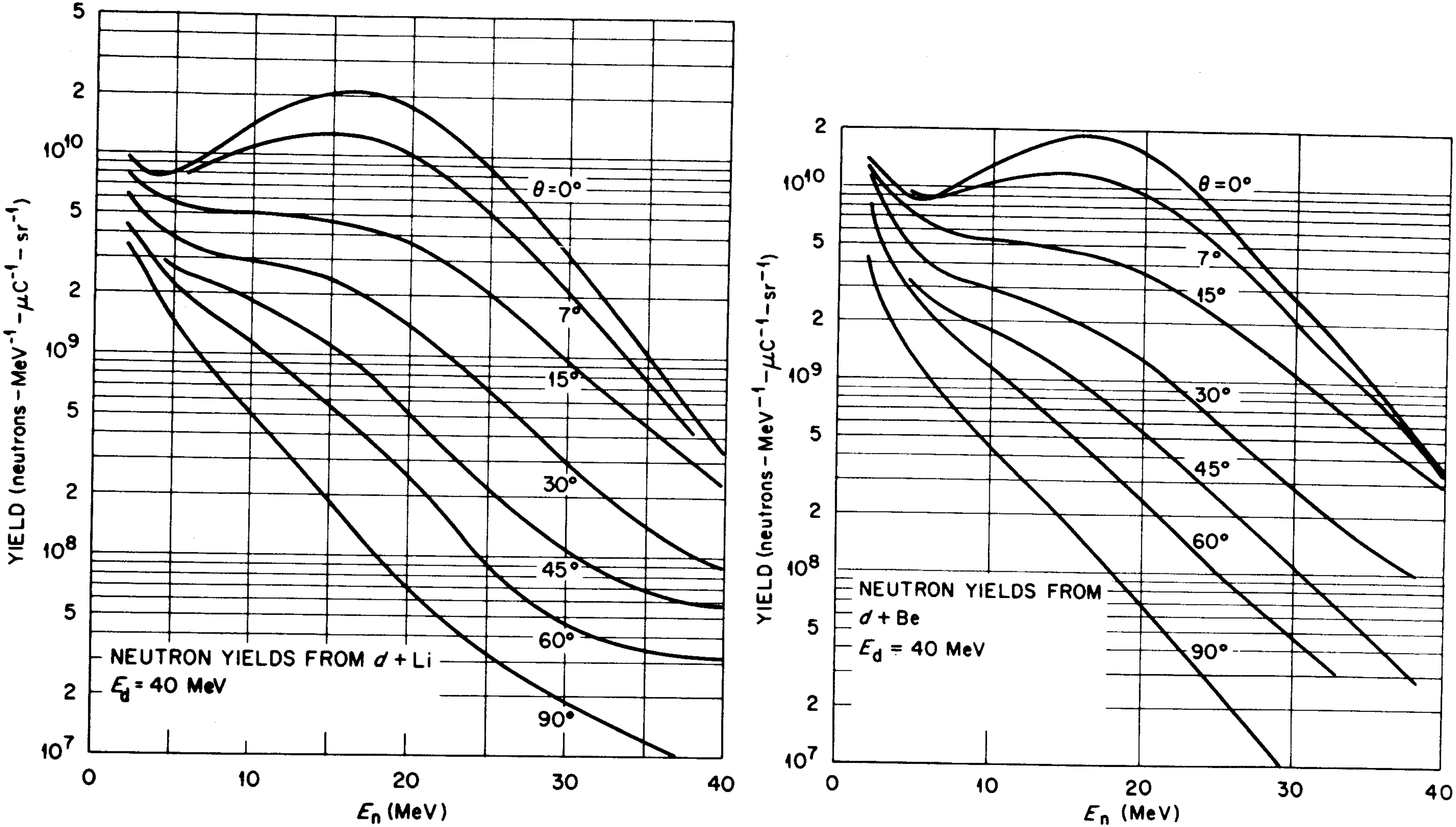
Cross Section (mb/sr)
500
200
100
50
30
20
10
0.07 0.1
0.2
0.3
0.5
0.7
1.0
2
3
5
7
10
20
Deuteron Energy (MeV)
d+Be
d+^{3}H
d+^{2}H

Figure 1



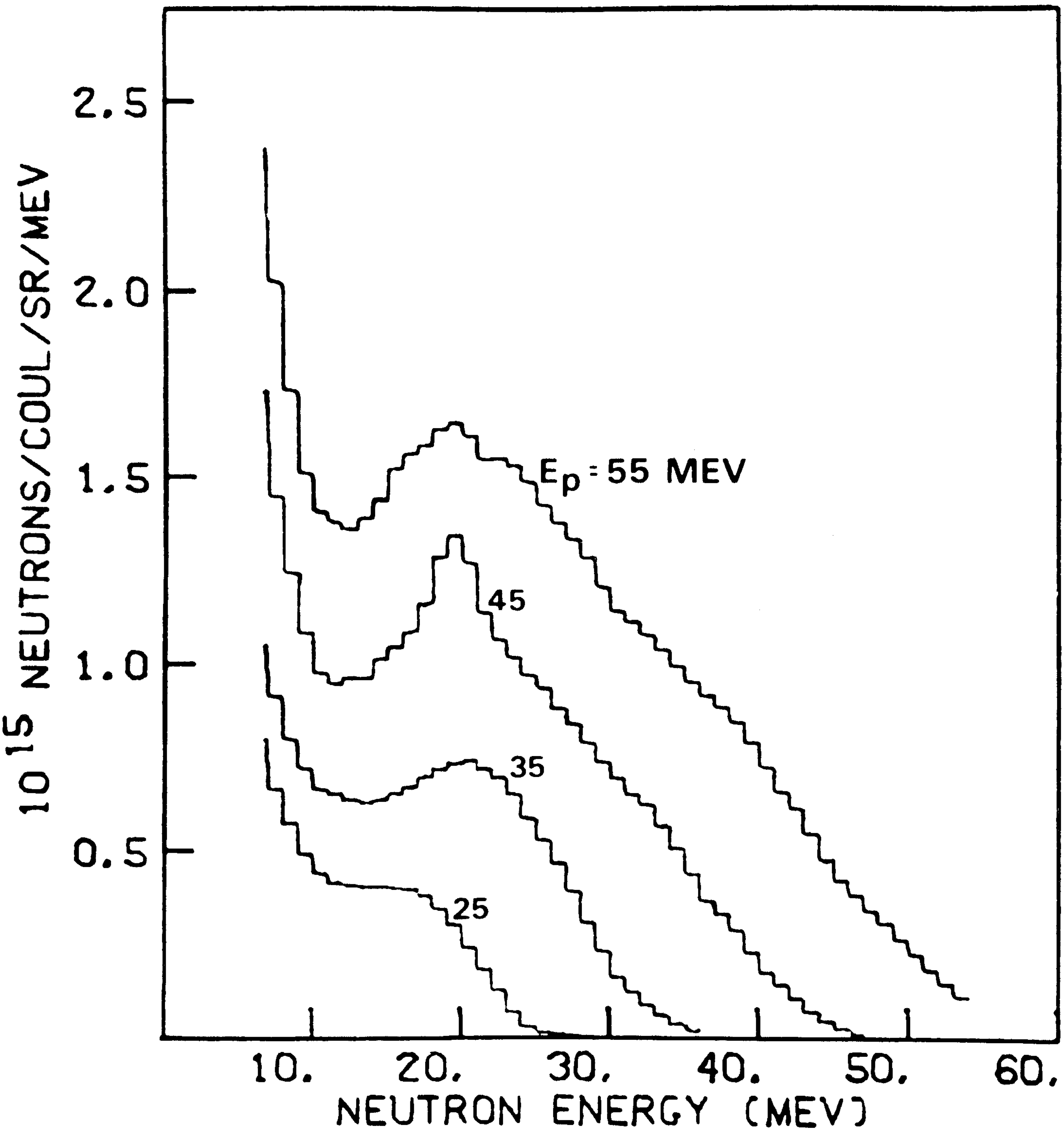
Average Neutron Energy (MeV)
30
20
10
7
5
3
2
1
0.1
0.2
0.3
0.5
0.7
1.0
2
3
5
7
10
20
40
Deuteron Energy (MeV)
d+3H
d+2H
d+Be

Figure 2



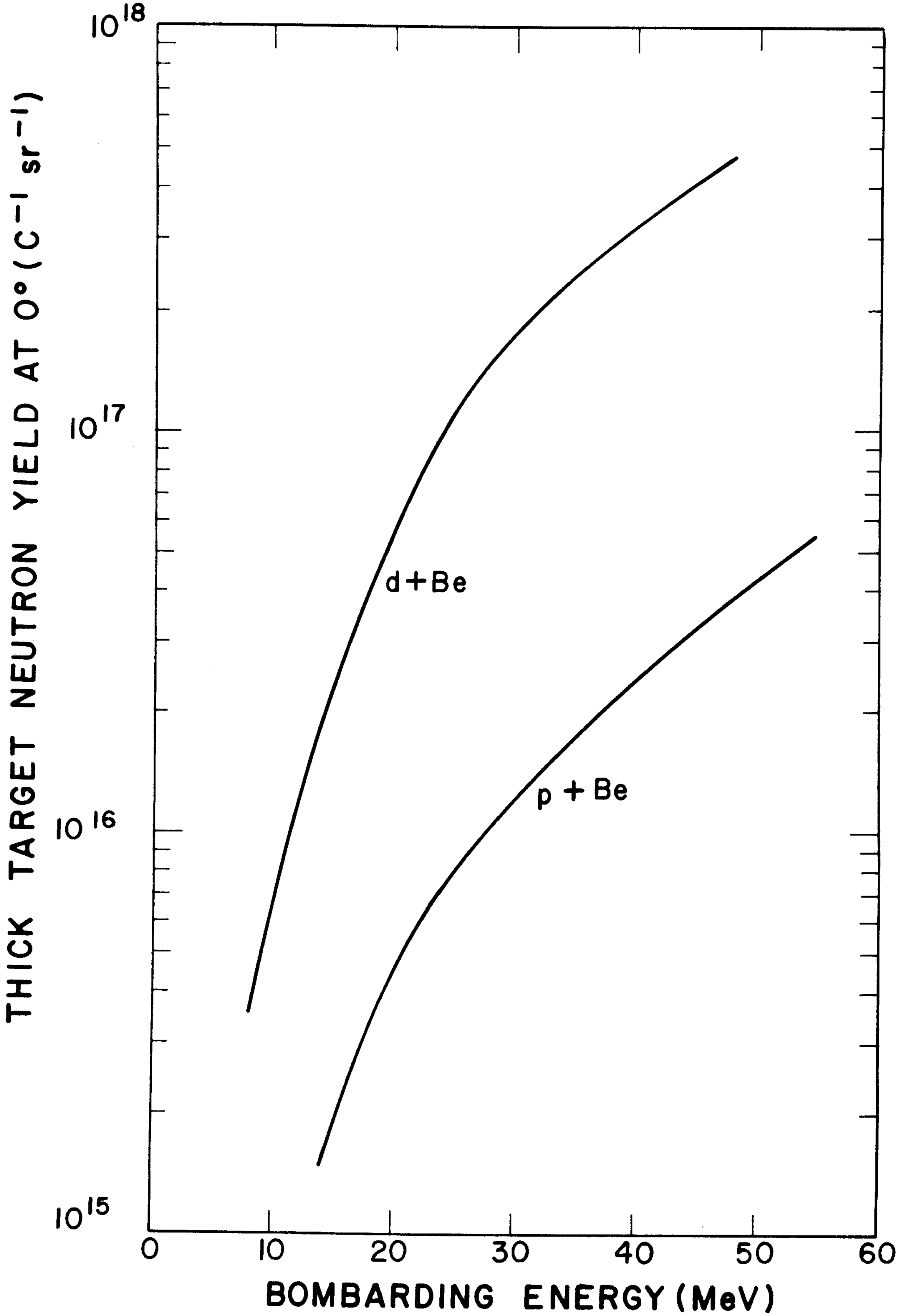
YIELD (neutrons - MeV⁻¹ - μC⁻¹ - sr⁻¹)
θ = 0°
7°
15°
30°
45°
60°
90°
NEUTRON YIELDS FROM d + Li
E_d = 40 MeV
E_n (MeV)
NEUTRON YIELDS FROM
d + Be
E_d = 40 MeV

Figure 3



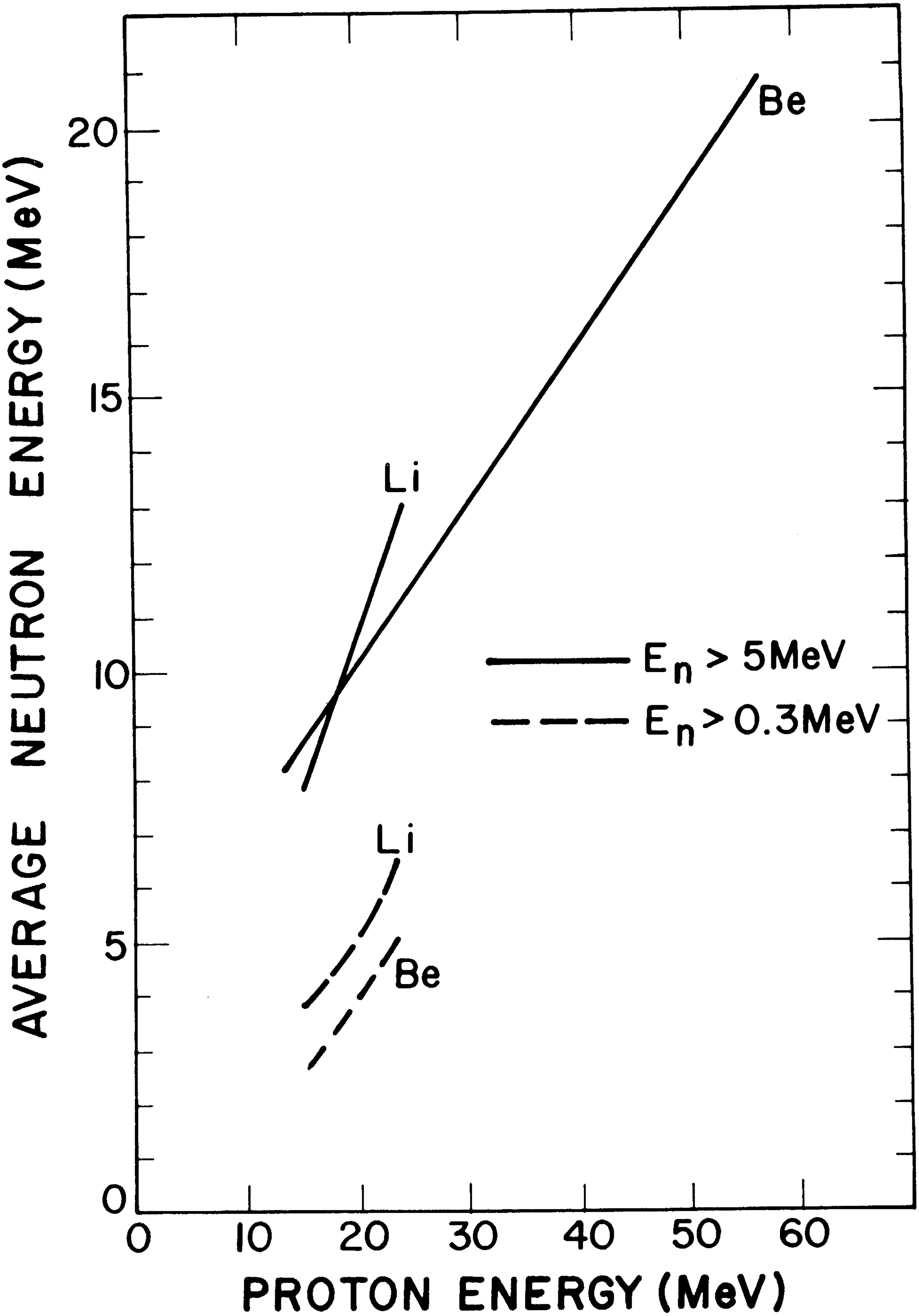
2.5
2.0
1.5
1.0
0.5
10^{15} NEUTRONS/COUL/SR/MEV
E_p = 55 MEV
45
35
25
10.
20.
30.
40.
50.
60.
NEUTRON ENERGY (MEV)

Figure 4



THICK TARGET NEUTRON YIELD AT 0° (C⁻¹ sr⁻¹)
10^18
10^17
10^16
10^15
d + Be
p + Be
0
10
20
30
40
50
60
BOMBARDING ENERGY (MeV)

Figure 5



AVERAGE NEUTRON ENERGY (MeV)
20
15
10
5
0
0
10
20
30
40
50
60
PROTON ENERGY (MeV)
Be
Li
$E_n > 5$MeV
$E_n > 0.3$MeV
Li
Be

Figure 6

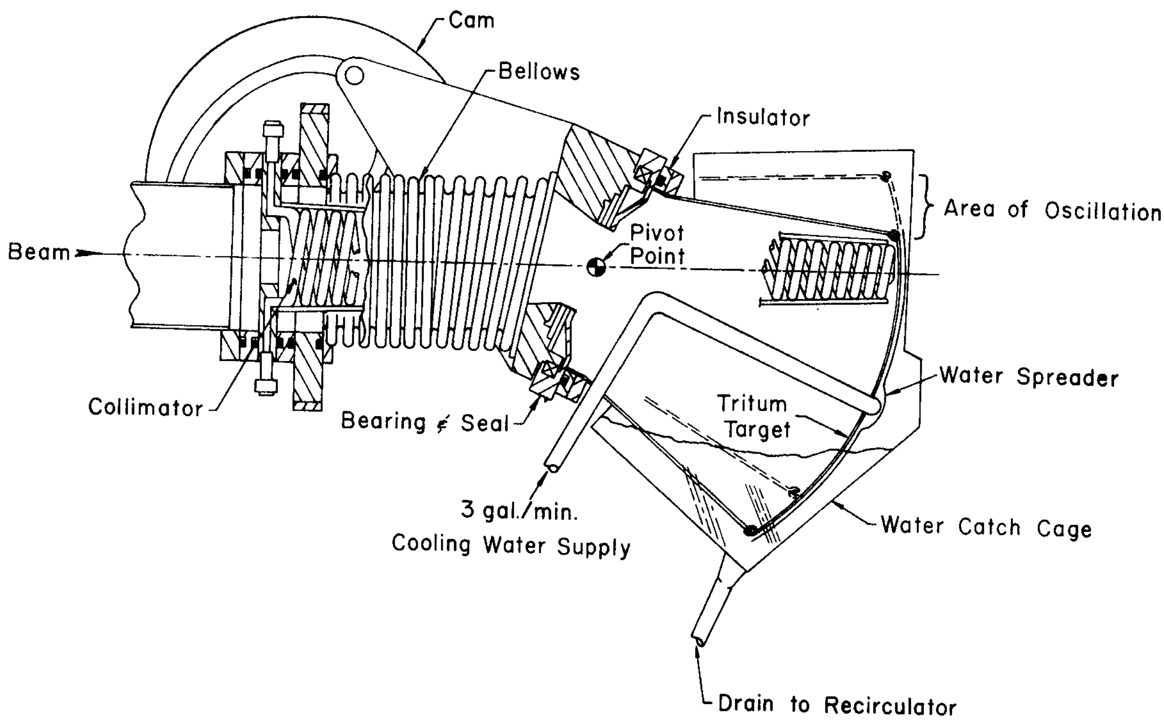

Cam
Bellows
Insulator
Area of Oscillation
Beam
Pivot Point
Collimator
Bearing & Seal
Water Spreader
Tritum Target
3 gal./min.
Cooling Water Supply
Water Catch Cage
Drain to Recirculator

Figure 8

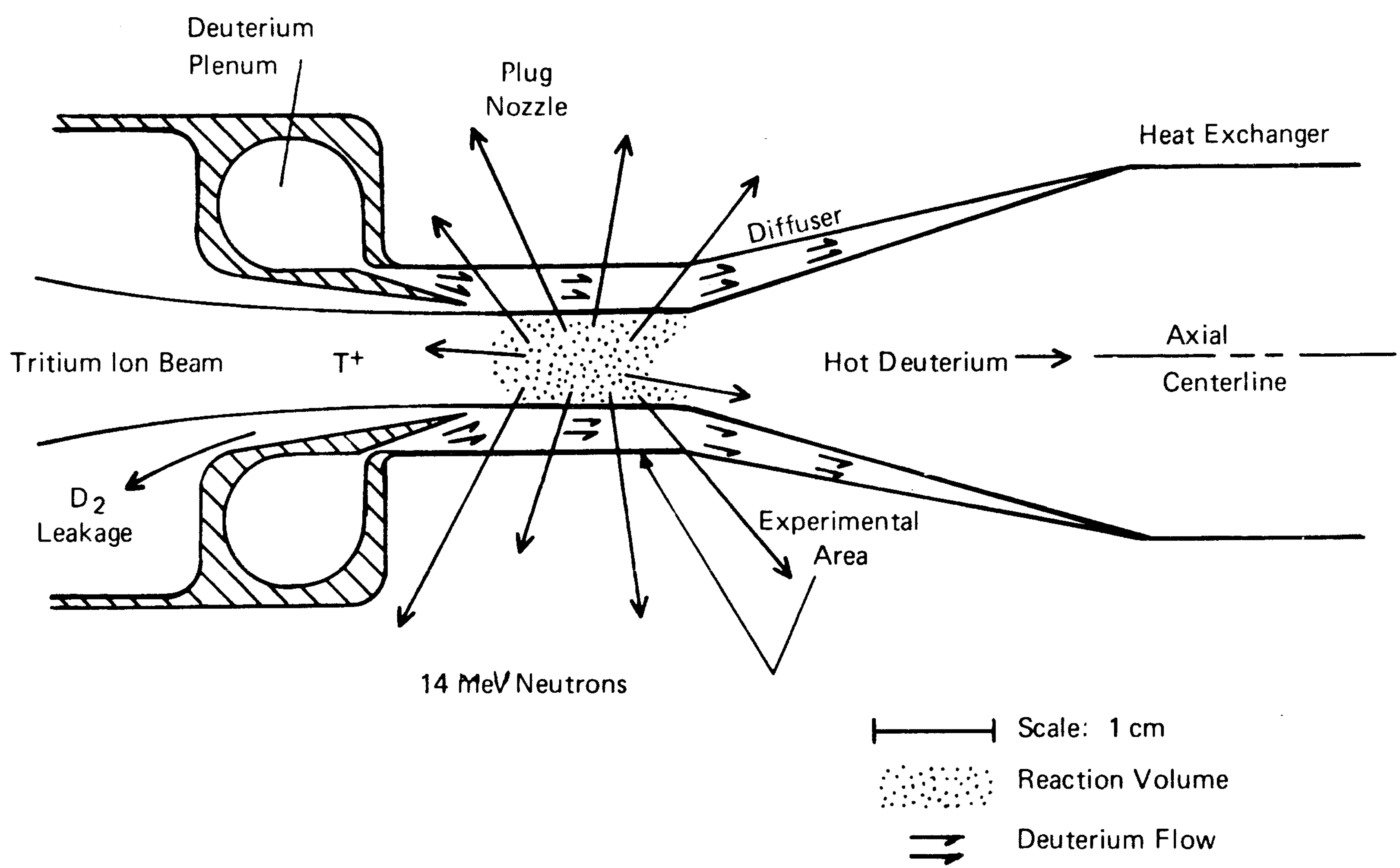

Deuterium
Plenum
Plug
Nozzle
Heat Exchanger
Diffuser
Tritium Ion Beam
T+
Hot Deuterium
Axial
Centerline
D2
Leakage
Experimental
Area
14 MeV Neutrons
Scale: 1 cm
Reaction Volume
Deuterium Flow

Figure 7

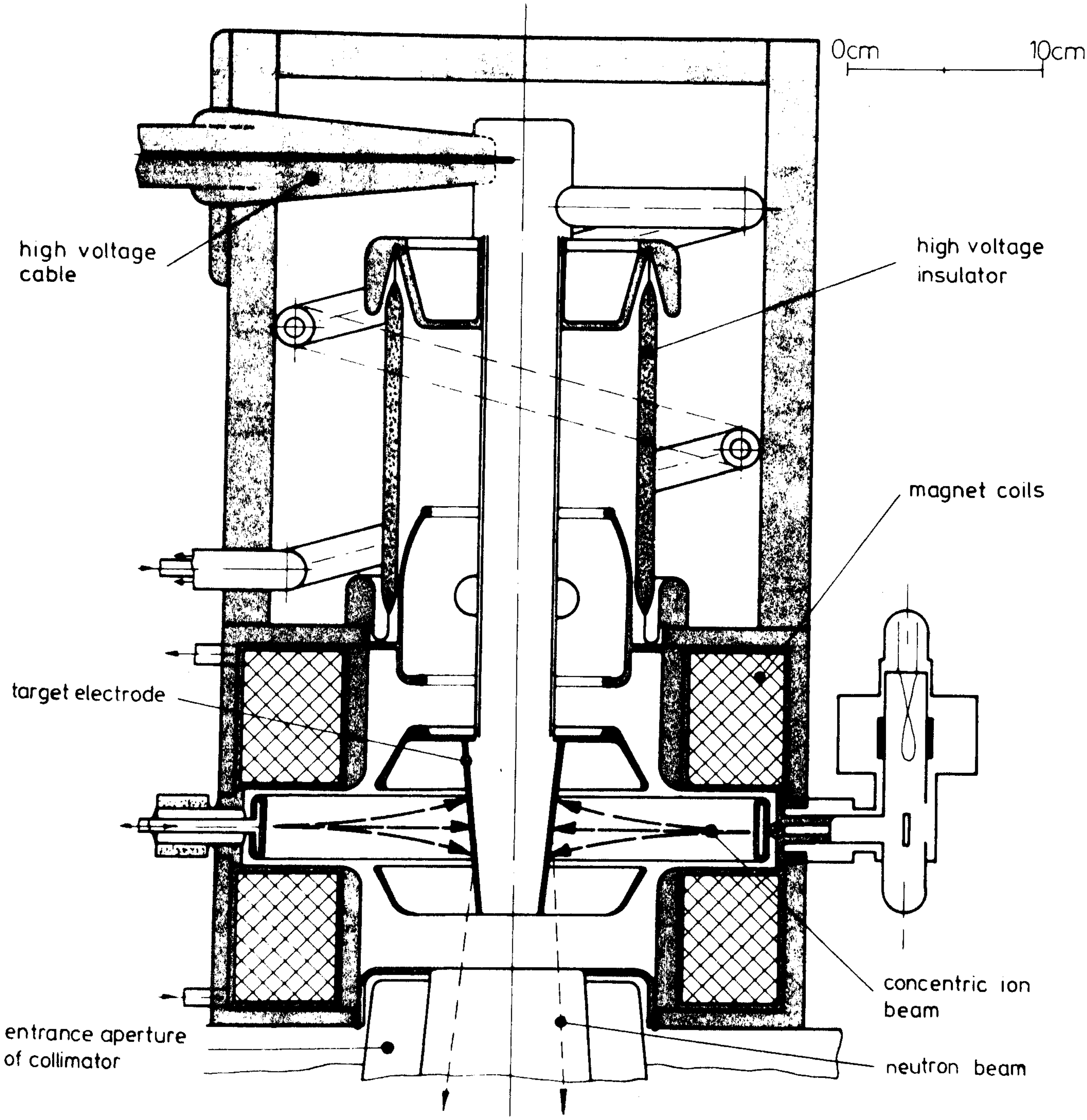

0cm
10cm
high voltage cable
high voltage insulator
magnet coils
target electrode
concentric ion beam
entrance aperture of collimator
neutron beam

Figure 9

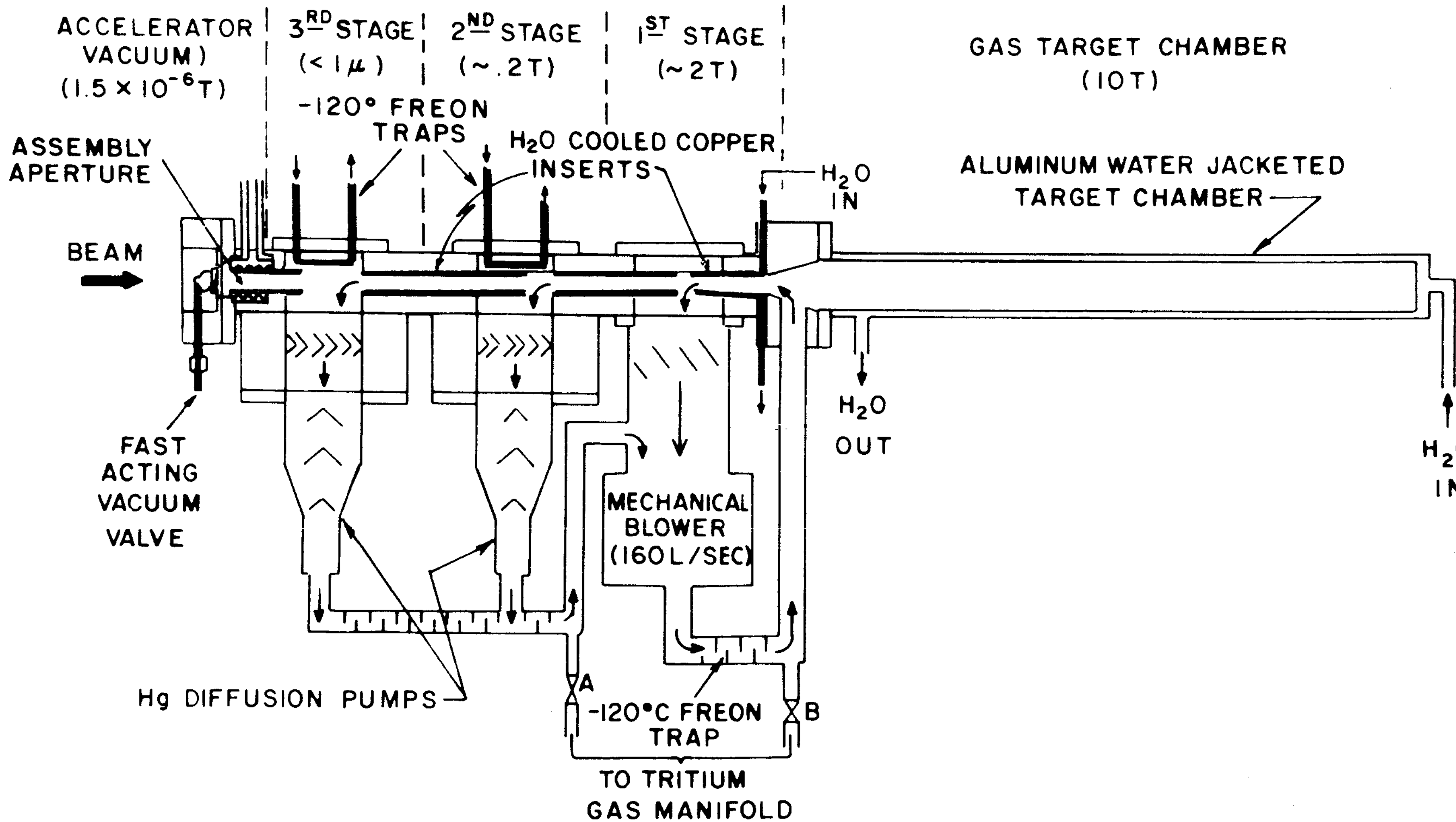

ACCELERATOR VACUUM)
(1.5 x 10⁻⁶T)
3RD STAGE
(< 1 μ)
2ND STAGE
(~ .2T)
1ST STAGE
(~2T)
GAS TARGET CHAMBER
(10T)
-120° FREON TRAPS
H2O COOLED COPPER INSERTS
ASSEMBLY APERTURE
BEAM
H2O IN
ALUMINUM WATER JACKETED TARGET CHAMBER
H2O OUT
H2O IN
FAST ACTING VACUUM VALVE
MECHANICAL BLOWER (160L/SEC)
Hg DIFFUSION PUMPS
A
-120°C FREON TRAP
B
TO TRITIUM GAS MANIFOLD

Figure 10