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University of California/Livermore, California

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H. H. Barschall

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INTENSE SOURCES OF HIGH ENERGY NEUTRONS*

H. H. Barschall

Lawrence Livermore Laboratory
Livermore, California, USA 94550

1. Introduction

In reviewing the status of new intense sources which produce neutrons of energies above 10 MeV I deviate from the principal theme of this conference. For most studies of nuclear structure with neutrons, sources that have been available for some time have had adequate intensity. Although higher intensity is helpful in many measurements, especially if high precision is required or if a very small cross section has to be determined, the great effort presently under way in developing new intense sources of high-energy neutrons is motivated primarily by demands from two quite different disciplines, i.e. medicine and fusion power engineering. On the other hand, as new intense sources become available, they will undoubtedly be used in nuclear structure research also.

The present review will not emphasize the distinction between pulsed and steady (d.c.) sources. The d.c. sources can, of course, also be used in a pulsed mode for time of flight applications.

2. Requirements

Recent interest in the development of intense sources of high energy neutrons has been directed towards applications in material testing for the program in Controlled Thermonuclear Reactions (CTR) and in radiotherapy. Although the requirements for these two applications differ, a source satisfying one need is likely to be useful for the other.

The radiotherapy application has the more clearly defined requirements: The average energy of the neutrons must be above 10 MeV, the source strength must be high enough to produce 10 rad/min at 125 cm from the source,¹⁾ which means a source strength of at least $5 \times 10^{11} \text{ s}^{-1} \text{ sr}^{-1}$ or $6 \times 10^{12} \text{ s}^{-1}$ for an isotropic source. The additional requirement is that the source must be simple and cheap enough that it can be used in hospitals.

The CTR interest is primarily in 14-MeV neutrons although the dependence of various effects on neutron energy is also of interest. Persiani²⁾ has recently summarized the requirements of the CTR program. It would be most desirable to duplicate the neutron flux expected in the walls of a

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thermonuclear reactor, (on the order of $10^{14} \text{ cm}^{-2} \text{ s}^{-1}$) and the fluence in several years of operation (on the order of 10^{22} cm^{-2}). Since this is at present impossible, there is an interest in examining the effect of 14-MeV neutrons on materials beginning with fluences on the order of 10^{17} cm^{-2} . Most of the effects are on a microscopic scale so that samples of mm size can be irradiated. As a consequence, the required source strength depends strongly on the size and accessibility of the source. If the irradiation is to be carried out in a couple of weeks, a flux density of $10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ which is as much as is presently available, would yield 10^{18} cm^{-2} . More intense sources are likely to be of larger size and less accessible. While a flux density of $10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ can be obtained with a source strength of $2 \times 10^{12} \text{ s}^{-1}$, a flux density of $10^{15} \text{ cm}^{-2} \text{ s}^{-1}$ would require a source strength of $3 \times 10^{17} \text{ s}^{-1}$ if the effective distance between source and sample were 5 cm.

3. Source Reactions

The most intense available neutron sources are fission reactors and electron linear accelerators in which neutrons are produced in photonuclear reactions. Neutrons from both these sources have average energies well below 10 MeV.

When high-energy protons bombard targets of heavy materials, the resulting neutrons have a most probable energy of the order of 1 MeV although the spectrum extends to quite high energy. With light targets, such as deuterium or beryllium higher average energies can be obtained, but, since high-energy protons have a long range (500-MeV protons have a range of 1 m in Be metal), the neutron source would have large dimensions.

Deuterons are most effective in producing neutrons. For the purpose of producing intense high-energy neutron sources usually only the following three materials serve as targets for deuteron bombardment: deuterium, tritium, and beryllium. In Fig. 1 the neutron production cross sections^{3,4,5} in the forward direction are sketched for these three reactions in the region up to about 20 MeV, i.e., the region accessible with small accelerators. At low bombarding energies only $d + {}^3\text{H}$ has a large cross section. At higher energies $d + {}^9\text{Be}$ gives the highest yield. For the applications considered in this review the average energy of the neutrons is of importance. In fig. 2 the average energy of the neutrons is shown for deuterons bombarding thin targets. There is considerable uncertainty in both the cross sections and average energies, especially at the higher

Fig. 1

Fig. 2

bombarding energies, because the neutron spectra have not been studied at the low-energy end. The increase with bombarding energy in the cross sections, and the decrease in energy for the reaction $d + {}^3\text{H}$ and, to a lesser extent, for $d + {}^2\text{H}$, is caused by the onset of deuteron breakup which becomes the dominant reaction above 6 MeV for $d + {}^3\text{H}$ and above 10 MeV for $d + {}^2\text{H}$. Fig. 1 and 2 apply to thin targets, but permit the calculation of thick-target yields and average neutron energies for thick targets, as has recently been done for ${}^2\text{H}$ and ${}^3\text{H}$ targets by Batra et al.⁶⁾ The average neutron energy for thick targets is lower than that for thin targets. For example for $d + {}^9\text{Be}$ the average energy for a thick target is about 30% less than that for a thin target for the same bombarding energy. Fig. 3 shows thick target yields for this reaction.

Fig. 3

Deuteron bombardment of other light targets produces lower yields than Be, but there is some evidence⁸⁾ that the average energy of the neutrons from d on Li and C is slightly higher than for d on Be.

4. Accelerators and Targets

Proton Linear Accelerators. High-current, high-energy proton accelerators will soon become operational at Los Alamos (LAMPF) and Brookhaven (BLIP). LAMPF is expected to produce 1 mA of 800-MeV protons, BLIP 0.2 mA of 200-MeV protons. There are plans to use both these accelerators for studies of the effect of neutrons on materials. Although the average energy of the neutrons is expected to be similar to that in the walls of a thermonuclear reactor, the neutron spectra will be very different, with the most probable energy considerably below that desired. The Brookhaven group⁹⁾ has estimated that they can obtain flux densities of the order of $5 \times 10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ with a Be target, while the Los Alamos group estimates about ten times higher flux densities with a Cu target, but the neutrons will have a lower average energy.

Cyclotrons. For producing neutrons from d + Be a cyclotron is usually employed as accelerator. The average energy of the neutrons emitted at 0° from a thick target is somewhat below 0.4 times the energy of the deuterons. In order to produce 10-MeV neutrons one needs a cyclotron that accelerates deuterons to 25 MeV. In order to produce $5 \times 10^{11} \text{ s}^{-1} \text{ sr}^{-1}$ one needs only about 5 μA which is easily obtained from a cyclotron. The needs of the radiotherapist can therefore readily be satisfied with a cyclotron although for hospital use an accelerator would be desirable that is smaller and cheaper than a 25-MeV cyclotron. In addition, average neutron energies higher than 10 MeV would be desirable.

Deuterons from a cyclotron bombarding a thick Be target provide also the most intense source presently available for materials testing with high-energy neutrons. 100 μA of 50-MeV deuterons produce $5 \times 10^{13} \text{ s}^{-1} \text{ sr}^{-1}$. Since these deuterons have a range of less than 1 cm flux densities of $5 \times 10^{13} \text{ cm}^{-2} \text{ s}^{-1}$ at an average energy of 20 MeV could be obtained. While it would be difficult to obtain currents much higher than 100 μA from a cyclotron, 1 mA could be obtained with a linear accelerator. Assuming that one desires an average energy of 15 MeV, a 40-MeV deuteron linac that accelerates 1 mA would produce on the order of $2 \times 10^{14} \text{ s}^{-1} \text{ sr}^{-1}$. With this source strength flux densities of $2 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ could be reached.

Low-Voltage Accelerators. The possibility of producing a high flux of 14-MeV neutrons with a low voltage accelerator has stimulated a large effort on the part of several groups to develop a suitable device. The technology of producing large ion currents has been perfected and currents of amperes can be produced. On the other hand, the difficulties of dissipating hundreds of kW in a target of deuterium or tritium are enormous. The radioactivity of tritium either in the source or in the target or both makes the problem even more formidable. Various approaches to the target problem will be discussed in the remainder of this review.

Tritium in Ti and Zr. D-T neutron sources were originally developed in 1949 at Los Alamos.¹⁰⁾ Deuterium ions from a low-voltage accelerator bombarded tritium absorbed in thin metal layers. This method has been used almost exclusively ever since. The source strength that can be obtained in this way is limited by the release of tritium from the target if the target becomes too hot. In addition, even if tritium is not driven off by heating, there is replacement of tritium by the incident deuterons. The neutron source strength from tritium-in-metal targets decreases with deuteron bombardment. Values of half-life reported vary greatly, ranging from a fraction of a coulomb to many hundreds of coulombs for target spots 0.2 cm^2 in area.¹¹⁾ These uses involved beam currents below 0.1 mA or source strengths of 10^{10} s^{-1} . Larger beam currents would produce excessive heating of the targets.

If larger source strengths are to be attained a larger area has to be bombarded and better cooling has to be provided. Two methods for doing this have been used.

In the "High Energy Neutron Reactions Experiment" a 40 cm diameter target was bombarded by 400 mA of 150-keV deuterons.¹²⁾ The deuteron beam had a diameter of about 30 cm. The target consisted of a layer of Er containing 1800 Ci of tritium backed by 21 kg of Cu. A source strength of up to $4 \times 10^{13} \text{ s}^{-1}$ was obtained but because of the large target size the maximum flux density was only $2.5 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1}$, and the intensity decreased by a factor of eight in 4 hours.

The second method that has been used to obtain high intensity from a tritium in metal target uses about 10 mA of 400-keV deuterons.¹³⁾ The deuteron beam has a diameter of about 1 cm. The target which rotates at high speed has a diameter of 14 cm and consists of a layer of Ti containing about 500 Ci of tritium backed by a 1-mm thick copper sheet and is water-cooled on the outside. The target is shown schematically in Fig. 4.

0 0.1 0.2m

Fig. 4

Source strengths of $2-3 \times 10^{12} \text{ s}^{-1}$ have been obtained, and flux densities of the order of $10^{12} \text{ cm}^{-2} \text{ s}^{-1}$ have been reached next to the target. The source strength falls off to half its original intensity in about 100 hours of operation. The intensity of this source is below that desired by radiotherapists, but it should be possible to increase the intensity by using larger deuteron beam currents and larger rotating targets.

In order to avoid the depletion of the target Haywood et al.¹⁴⁾ have proposed to replenish the Ti target by adding tritium that passes through a permeable membrane behind the Ti. The membrane consists of a foil of Pd-Ag alloy 0.75 mm thick. The deuteron beam heats the membrane, and tritium from a reservoir diffuses through the membrane. When this target was bombarded by 1 mA of 185-keV deuterons, sustained yields of $3 \times 10^{10} \text{ s}^{-1}$ were obtained.¹⁵⁾ How these targets would behave under bombardment with 100 times larger currents has not yet been tested.

Drive-in Targets. Fairly good targets of deuterium have been produced by bombarding a metal with deuterons accelerated to several hundred keV. Such drive-in targets have been used extensively to produce d-d

neutrons. The suggestion to make d-T neutrons by bombarding a metal target with a mixed beam of deuterons and tritons is at least 15 years old,¹¹⁾ but its implementation involved the problems of tritium acceleration and recovery. Current efforts to overcome these problems involve the acceleration of mixed beams either in sealed tubes or a closed loop system in which the deuterium-tritium gas mixture is introduced back into the ion source.

Sealed tubes have actually operated with D-T mixtures and are commercially available. In 1965 Bounden et al.¹⁶⁾ described a sealed tube in which 1 mA of mixed beam was accelerated to 150 keV. This tube produced 10^{10} s^{-1} for over 100 hours. Similar tubes have since then been operated at higher currents and voltages, and have been reported¹⁷⁾ to produce $3 \times 10^{11} \text{ s}^{-1}$. It is claimed that such tubes could produce 10^{12} s^{-1} , but it is not clear how long they would last.

There has recently been considerable effort to develop a closed loop system for higher intensity. Hilton, Kim, and Hendry¹⁸⁾ have designed a system that is intended to produce $5 \times 10^{12} \text{ s}^{-1}$ by accelerating 200 mA of mixed beam to 300 keV. They have obtained a source strength of $3 \times 10^8 \text{ s}^{-1}$ when 10 mA of 130-keV deuterons were incident on a Cu target. They find an even more favorable behavior for Cr targets.

In comparing yields one should keep in mind that a mixed d-T beam on a mixed d-T target gives only half as many d-T reactions as the same current of deuterons on a tritium target.

Gas Targets. Both in the deuteron accelerators with tritium-in-metal targets and in mixed-beam accelerators with drive-in targets most of the energy loss in the target is to the metal. A gain in yield by a factor of about 8 would arise if a gas target could be employed instead of a metal target. The difficulty with this possibility is that the gas has to be at a much higher pressure than the acceleration region. While foils that separate gas targets from accelerators can tolerate beams of microamperes, they cannot withstand milliampere beams. Several methods have been proposed for separating the high and low pressure regions without a foil.

Falsey et al.¹⁹⁾ are attempting to construct a closed loop system in which a gas target is separated from the acceleration tube by a 1-mm diameter aperture. By rapid pumping on the accelerator side of the aper-

ture the pressure in the accelerator is kept low enough to maintain 250 kV across the acceleration tube. In order to obtain the design source strength of 10^{13} s^{-1} 20 mA of mixed beam have to enter the gas target. Preliminary studies with deuterons on deuterium gas are encouraging.

O. B. Morgan of Oak Ridge National Laboratory has suggested a modification of the differentially pumped target. This modification involves the extraction from the ion source of a sharp enough and energetic enough beam that there is no need for either differential pumping or an acceleration tube.

In 1969 Colombant²⁰⁾ proposed an intense 14-MeV source that is designed to produce two orders of magnitude more neutrons than previous sources. The proposal involves the acceleration of 1A of tritons to 400 keV. The deuterium target is at the large density gradient that occurs at the sonic line of a free jet expansion. The power (400 kW) is removed by the flowing deuterium gas. Since more than 50 g/s of deuterium pass through the target, the deuterium has to be recycled. The deuterium will collect 0.1 g of tritium per hour so that it is extremely radioactive. The engineering problems involved in the development of the gas handling system as well as in the development of the target would require great effort and cost. An additional disadvantage of the system is that the neutron source is relatively inaccessible so that the flux density may be lower than corresponds to the gain in source strength.

There is a proposal by Henderson²¹⁾ to build a source similar to that proposed by Colombant which would produce neutron fluxes of $10^{14} - 10^{15} \text{ cm}^{-2} \text{ s}^{-1}$ with a source strength of $8 \times 10^{14} \text{ s}^{-1}$.

A quite different type of d-T neutron source that promises to yield high intensity is the Dense Plasma Focus. This is a pulsed discharge device originally studied around 1960 and developed by Filippov²²⁾ in the USSR and by Mather²³⁾ in the USA. Work on these devices is now in progress in many laboratories and in many countries.²⁴⁾ The devices require large capacitors that can store energies of the order of 1 MJ. They produce neutron pulses lasting on the order of 100 ns. Source strengths of the order of 10^{13} and fluences of the order of 10^{11} cm^{-2} have been obtained per pulse. On the other hand, only slow pulse rates, at the most one every five minutes, can be used so that the average source strength is so far not competitive with that obtained with accelerators, and the cost is high.

5. Conclusions

For radiation therapy adequate intensities can be obtained with available cyclotrons using neutrons from Be(d,n) . With low voltage accelerators the presently available source strength with d-T neutrons is about a factor of three below the desirable intensity, but several approaches for obtaining adequate intensity are being pursued, and one or several of these will undoubtedly be successful.

For the application in materials testing for CTR there is no source available that will duplicate the effects on materials in such a reactor. Only studies from which extrapolations can be made appear feasible with neutron sources available now or in the near future. At present the most intense source available is again a cyclotron that produces Be(d,n) neutrons although d-T sources of somewhat lower intensity are available and may have some advantages.

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