IEEE Transactions on Nuclear Science, Vol.NS-22, No.3, June 1975

USE OF Li(d,n) NEUTRONS FOR SIMULATION OF RADIATION EFFECTS IN FUSION REACTORS.*

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Summary

In this paper we show that the neutron spectrum from high-energy deuteron bombardment of a thick Li target is suitable for simulation of radiation effects in a fusion reactor. Neutron spectra from 15, 20, 25, 30 and 35-MeV deuterons incident, respectively, on a 2-cm thick Li target are reported. For these spectra, a recently-developed computer code was used to evaluate damage-energy cross sections, primary recoil energy distributions, and spectrum-averaged reaction cross sections in several metals. The results indicate that a (d,n) source can simulate the energy dependence of the recoil spectra, and the rate of helium production anticipated in a real fusion reactor

Introduction

Intense neutron sources are required for in situ measurements of physical property changes, transient radiation effects, and neutron dose-rate dependences and for blanket studies associated with fusion reactors.[1] Large-volume experiments must be conducted with samples at high or low temperatures over long periods of time at fluxes exceeding 10^{14}n $cm^{-2}sec^{-1}$. In many cases it will be desirable to alter the neutron spectrum to simulate that anticipated at different positions in a hypothetical fusion reactor. All of these considerations lead us to the conclusion that an accelerator-based source is the most versatile one attainable in the next decade.

From the viewpoint of CTR radiation-effects studies the usefulness of this source depends upon positive answers to two questions. First, can a neutron source of high flux in an adequate volume be produced? Second, with respect to radiation damage, can the neutron spectrum of the source be used to simulate effects that are anticipated in a typical fusion reactor? These two aspects of the Brookhaven intense neutron source based on a high-current deuteron LINAC are under investigation. To explore the first question, we have measured the thick-target neutron spectra and yields from the Li(d,n) reactions as a function of incident deuteron energy. In order to investigate the second question, we are using a program developed at Brookhaven to compare the radiation-damage effectiveness of diverse neutron sources.

Li(d,n) Spectrum Measurements

Using the neutron time-of-flight spectrometer at the Naval Research Laboratory Cyclotron,[2] we have obtained neutron spectra from the (d,n) reactions in a thick lithium target. Data were obtained for five deutron energies, nominally 14.5, 20, 25, 30 and 35 MeV. The energy of the deuterons incident on the Li target was approximately 0.5-1 MeV lower in each case because the deuteron beam passed through 0.005 cm of aluminum and 7.5 cm of air before entering the target.

At 13.42 and 34.06 MeV, angular-distribution data were taken for angles of 0°, 5°, 10°, 15° and 20°. In addition, Be(d,n) data were obtained for comparison with earlier NRL results taken when the Be target was inside the cyclotron vacuum chamber. These data established that the effect of using the target in air rather than in vacuum was negligible.

The data were collected in a multiparameter mode and were reduced to absolute yields in units of neutrons/sr-C-MeV as a function of neutron energy. The neutron spectra then served as input to the BNL code[3] which generates those radiation-damage parameters necessary for the evaluation of neutron sources as simulators of CTR neutron damage.

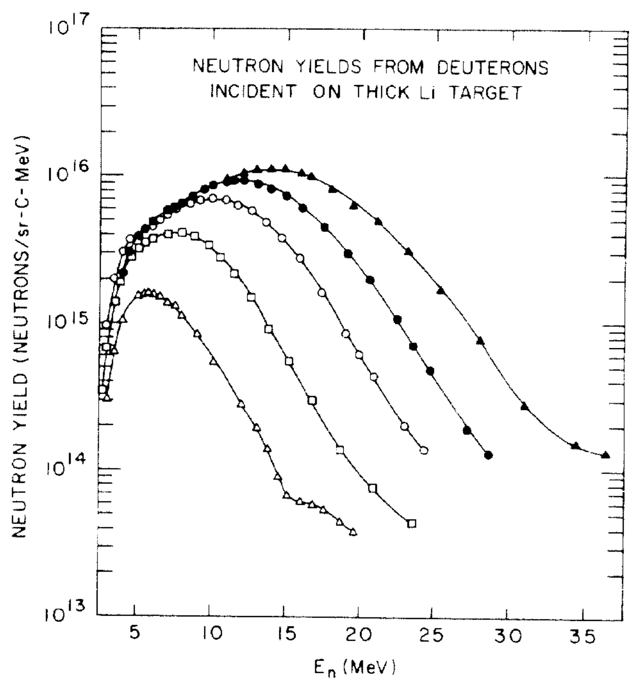

Fig. 1 Neutron Spectra from 13.42-, 18.95-, 24.84-, 28.94-, and 34.06-MeV Deuterons Incident on a Thick Li Target.

*Research supported by the Energy Research and Development Administration.

Figure 1 shows the neutron spectra for the five energies mentioned earlier. The mean energy increases with deuteron energy and is approximately equal to 0.5E(deut). The yield also increases with increasing energy.

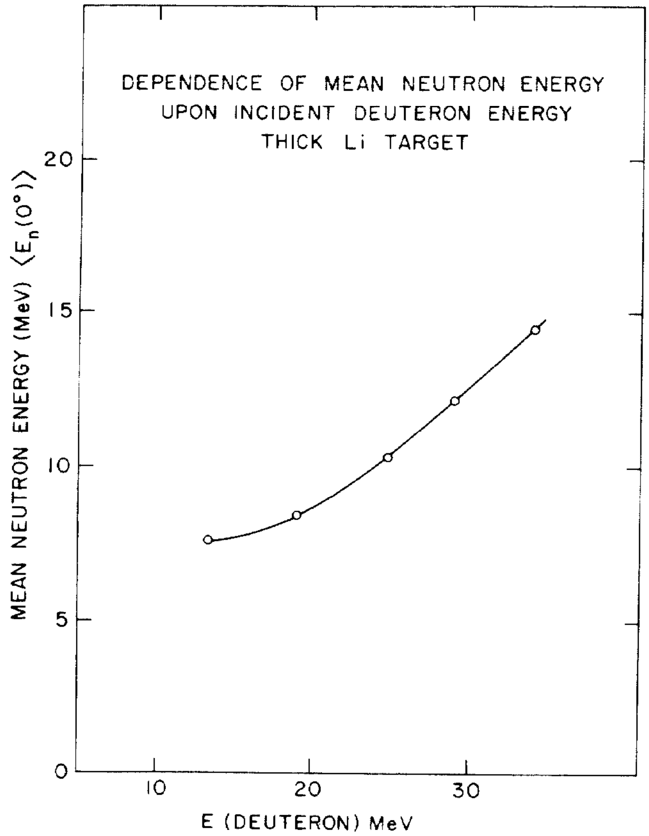

Fig. 2 Dependence of Mean Neutron Energy Upon Incident Deuteron Energy.

Figure 2 exhibits graphically the dependence of the mean neutron energy at 0°, $\langle E_n(0^\circ)\rangle$, upon the incident deuteron energy. The figure shows that $\langle E_n \rangle$ lies between 0.4 and 0.55 times the incident deuteron energy, approaching the lower value as the deuteron energy increases. For a given energy $\langle E_n \rangle$ varies only slightly as the scattering angle increases, whereas the yield decreases with increasing scattering angle. The results confirm the fact that the forward direction is strongly favored in the (d,n) reactions. The yield at 10°, for example, is slightly more than one-half that at 0° for 34.06-MeV incident deuterons.

Table I contains values of the measured yield at 0° in neutrons/sr-C for all measurements made. More precise values could be obtained by extrapolating the measured neutron spectra to zero deuteron energy. In general, this would increase the yields by less than 5 percent. We have omitted this uncertain extrapolation and, therefore, our subsequent flux estimates may be regarded as being conservative. Our measured yields are uniformly lower than those published by Weaver, et al.[4] for deuteron energies up to 19 MeV or those based upon a linear extrapolation of their data to 35 MeV. At present we do not fully understand why the discrepancy exists, but it is most likely attributable to an error in beam-current measurement during one or both of the experiments, a difference in collimation, and differences in the extrapolation to zero of the neutron energy.

Table I. Neutron Yields From Li(d,n) Reaction in Neutrons/sr-C

E (deut) (MeV)	$\langle E_n(0^\circ)\rangle$ (MeV)	Y(0°)	Y(5°)	Y(10°)	Y(15°)	Y(20°)
13.42	7.63	9.685×10^{15}	9.419×10^{15}	7.810×10^{15}	6.338×10^{15}	4.992×10^{15}
18.95	8.46	3.247×10^{16}	-	-	-	-
24.84	10.32	7.129×10^{16}	-	-	-	-
28.94	12.21	1.057×10^{17}	-	-	-	-
34.06	14.46	1.469×10^{17}	1.313×10^{17}	0.8687×10^{17}	0.5904×10^{17}	0.4160×10^{17}

Comparison with Other Calculations

Several years ago we began to develop a code for evaluating radiation-damage parameters associated with various neutron sources. The code is a combination of existing work by Jenkins[5] and by Doran,[6] extended to include calculations of spectrum-averaged cross sections and recoil-energy distributions. Details are given in a recent Brookhaven report.[3] The philosophy which we have adopted is that we wish to calculate radiation-damage parameters which are model independent. These may be used with a variety of models to make comparisons with experimental results. It is possible that a different model will be needed for each kind of experiment.

Kulcinski, Doran, and Abdou[7] have generally included a simple model of displacement production in their calculations so that they can quote displacements per atom (dpa) per unit time. They also quote transmutation product production rates whereas we list spectrum-averaged cross sections. A comparison between their approach and ours illustrates the connection:

Kulcinski, et al. calculate the total displacement cross section at energy E:

$$F(E) = \int_{E_0}^{T_{max}} \sigma(E)p(E,T)\nu(T)dT$$

where $\sigma(E)$ is the appropriate interaction cross section, $p(E,T)$ is the probability that a neutron of energy E transfers energy T to a recoil atom, $\nu(T)$ is the number of displacements produced by a recoil atom of energy T (a model-dependent quantity), and E_0 is the minimum energy required to displace an atom.

Parkin and Goland calculate the equivalent expression:

$$G(E) = \int \sigma(E)K(E,T)g(T)dT$$

where $\sigma(E)$ has the same meaning as above, $K(E,T)$ corresponds to $p(E,T)$, and $g(T)$ is a more general form of $\nu(T)$.

In order to calculate the displacement cross section Kulcinski, et al. set $\nu(T) = (\beta/2E_o)[L(\varepsilon)/\varepsilon]T$, where $\beta\sim 0.8$, and $L(\varepsilon)/\varepsilon$ is the fraction of recoil energy which is available to cause displacements. The factor $\beta/2E_o$ is based upon a simple displacement model introduced by Kinchin and Pease[8] and recently improved by Robinson and Torrens.[9] It cannot take into account the spatial distribution of the displacements or their cluster size distribution.

Parkin and Goland use the corresponding quantity: $g(T) = TL(T) = T[L(\varepsilon)/\varepsilon]$ to calculate the damage-energy cross section, E_D. Thus in this case the correspondence is:

$$\nu(T) = (\beta/2E_o)g(T)\ , \text{ and } F(E) = (\beta/2E_o)E_D(E)\ .$$

Finally, the Brookhaven calculations are averaged over flux distributions which have been normalized to one neutron $cm^{-2}sec^{-1}$. Therefore,

$$\text{dpa/sec} = \underbrace{\langle F(E)\phi(E)\rangle = \left[(\beta/2E_o)\ \phi_{total}\right]}_{\text{Kulcinski et al.}} \underbrace{\langle E_D\rangle}_{\text{Parkin and Goland}}\ ,$$

where the symbol < > denotes a spectral average.

Results

The neutron spectra obtained in the (d,n) experiments were put on a common 47-point energy grid by means of linear interpolation between the original data points. Values of the spectrum for low-energy neutrons were obtained by linear extrapolation to E=0 from the lowest energy measured. This last approximation is not very good, but the low-energy neutrons contribute so little to the important radiation-damage parameters that a better approximation was not sought.

Examples of the Brookhaven results for Nb given relative to unit flux are listed in Table II-a for the Li(d,n) measurements, and in Table II-b for other sources. It is difficult to find acceptable values for total fluxes in other sources, but for the fluxes listed in Table III, the number of dpa/sec and the rate of induced gas production in Nb are given in absolute units.

The results of the calculations for niobium include the normalized primary recoil energy spectrum, various spectrum-averaged cross sections such as $\langle\sigma_{n,\alpha}\rangle$, and the damage energy cross section, $\langle E_D\rangle$. As anticipated, the recoil spectrum shifts to higher energy as the deuteron energy increases. The spectrum-averaged damage energy cross section and the spectrum-averaged (n,α) cross section also increase with increasing deuteron energy. However, while $\langle\sigma_{n,\alpha}\rangle$ increases by a factor of three between 13.42 and 34.06 MeV, $\langle E_D\rangle$ only increases by about 46 percent. Table II-a contains values of these quantities for the various (d,n) neutron spectra. Also listed are the ratio of averaged damage energy cross section to (n,α) cross section, $\langle E_D\rangle/\langle\sigma_{n,\alpha}\rangle$, and the damage energy per primary recoil, $\langle E_D\rangle/\langle\sigma_{Total}\rangle$. These two quantities are especially useful for comparison with other existing or proposed simulation or 14-MeV neutron sources. In fact, Table II-b gives values of the same parameters as Table II-a for several other neutron sources. Spectrum-averaged quantities were calculated for unit neutron flux.

Table II. Radiation Damage Parameters Calculated for:
a) Li(d,n) Neutrons Incident on Nb, and
b) Neutrons From Other Sources Incident on Nb

	$E_d^{incident}$ (MeV)	$\langle\sigma_{n,\alpha}\rangle$ barn	$\langle\sigma_{Total}\rangle$ barn	$\langle E_D\rangle$ barn-eV	$\langle E_D\rangle/\langle\sigma_{n,\alpha}\rangle$ (eV)	$\langle E_D\rangle/\langle\sigma_{Total}\rangle$ (eV)
(a)	13.42	2.269×10^{-3}	3.972	1.730×10^{5}	7.624×10^{7}	4.555×10^{4}
	18.95	3.245	3.987	1.899	5.852	4.763
	24.84	4.834	3.803	2.126	4.398	5.590
	28.94	6.001	3.549	2.315	3.858	6.523
	34.06	6.949	3.221	2.531	3.642	7.858
(b)	Source					
	HFIR	1×10^{-5}	6.006	2.24×10^{4}	2.24×10^{9}	3.730×10^{3}
	EBRII-7	6×10^{-6}	6.354	2.8×10^{4}	4.67×10^{9}	4.407×10^{3}
	LAMPF	4×10^{-4}	6.614	5.6×10^{4}	1.40×10^{8}	8.467×10^{3}
	BENCH	2×10^{-3}	5.718	9.52×10^{4}	4.76×10^{7}	1.665×10^{4}
	"14 MeV"	9×10^{-3}	3.965	2.74×10^{5}	3.044×10^{7}	6.910×10^{4}

A comparison of Table II-a and II-b is very revealing. The entry labeled BENCH in Table II-b represents the first-wall neutron spectrum calculated on the basis of a standard blanket design.[10] If we adopt this spectrum as our reference, then we can draw the following conclusions concerning (d,n) neutrons for the deuteron energy range under consideration.

1. The value of $\langle\sigma_{n,\alpha}\rangle$ exceeds the BENCH value by at most a factor of 3 when Nb is exposed to (d,n) neutrons. Other sources fail to produce an equivalent amount of helium by orders of magnitude except in the case of a 14-MeV source for which $\langle\sigma_{n,\alpha}\rangle$ is larger by a factor of 4.5.

2. The (d,n) source leads to a damage-energy cross section that is very similar to that from 14-MeV neutrons. Both sources exceed the BENCH value by about a factor of two, the 14-MeV value differing somewhat more than the (d,n) values.

3. The ratio of damage-energy cross section to (n,α) cross section can be regarded as a measure of the ability of a source to simulate the simultaneous generation of defects and helium. For the (d,n) source, this ratio always differs by less than a factor of two from the BENCH value. For the appropriate deuteron energy, $\sim$ 23 MeV, the ratio can be made to agree almost exactly with the BENCH value.

Table III Production Rates in Nb at Various Nuclear Facilities

Facility	Flux n cm^{-2} sec^{-1}	dpa/sec $\times 10^7$	He app m/sec $\times 10^7$	dpa/He
HFIR	6×10^{14}	1.49	0.06	24.8
EBRII-7	4×10^{14}	1.24	0.024	51.7
LAMPF	2×10^{13}	0.124	0.08	1.55
BENCH (CTR)	2×10^{14}	2.11	4.0	0.53
"14 MeV" (RTNS)	2×10^{12}	0.061	0.18	0.34
Li(d,n) (34.06 MeV)	1×10^{14}	2.81	6.95	0.40
Li(d,n) (28.94 MeV)	1×10^{14}	2.57	6.00	0.43

4. The total damage energy per primary recoil is between a factor of 3 and 5 times larger than that for BENCH. The 14-MeV source value is about four times larger than the BENCH value, while values for other sources are lower by factors of two or more.

5. It is evident that by varying the energy of the incident deuterons, the values of relevant damage parameters can be varied according to the required simulation demands.

Table III illustrates in an absolute sense the value of a Li(d,n) source on the basis of displacement and gas production rates. There are some special cases such as Ni, for which HFIR is an excellent source because the helium production rate is very high. Generally, however, the Li(d,n) source comes closest to reproducing the simultaneous displacement rates and gas production rates expected in the first wall of a fusion reactor.

Conclusions

On the basis of this analysis, it appears that a 15-30-MeV deuteron LINAC would satisfy the requirements of a CTR neutron simulation source. The mean energy of the neutrons could approximate that of a BENCHMARK spectrum or could be altered to more closely match that of other sources. As the yield increases with increasing energy the best choice of energy for a long-term experiment will depend upon the ultimate deuteron current available. This in turn will be determined by source and target developments in the next few years. If very high current sources can be wedded to the LINAC, and if the beam power can be handled in the Li target, then the lower deuteron energies may be selected without sacrificing too much neutron flux. At present this approach seems to yield the best agreement with the maximum number of radiation-damage parameters.

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