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Publication Date

1979-11-01

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LBL-10087

CONF-791102--143

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Accelerator & Fusion Research Division

Presented at IEEE 8th Symposium on Engineering Problems of Fusion Research, San Francisco, CA, November 13-16, 1979; also to be published in the Proceedings of the IEEE 8th Symposium

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MASTER

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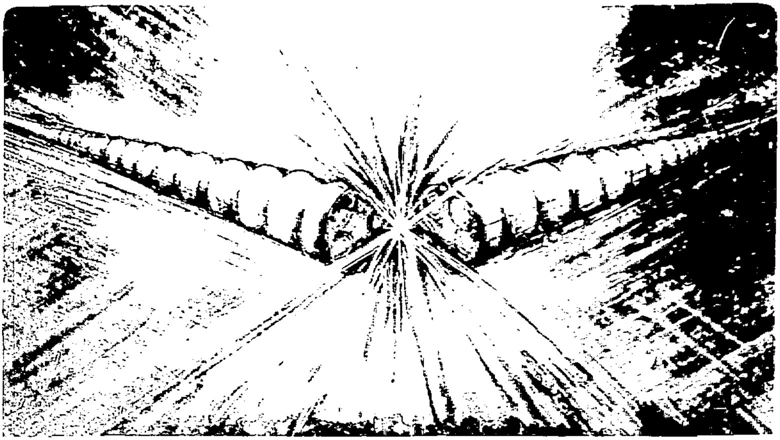
November 1979



Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

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NEUTRON PRODUCTION BY NEUTRAL BEAM SOURCES

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Summary

Neutron yields, from interactions of multiampere 40- to 120-keV deuterium beams with deuterium atoms implanted in copper targets, have been measured in order to provide input data for shielding of neutral-deuterium beam facilities for magnetic fusion experiments.

Introduction

Most of the multi-megawatt neutral-beam injectors to be used in the MFE program will operate with deuterium. Unavoidably, these injectors will generate large numbers of d-d neutrons in the beam lines, and suitable shielding must be designed and built for the development and test facilities.

Prototype neutral-beam-injector components and systems for the MFTF mirror, and TFTR and DIII tokamak experiments are being designed, built and tested at the Lawrence Berkeley and Livermore Laboratories.[1] The deuterium ion currents are 65A at 120 keV and 80A at 80 keV. In our test facilities the ion beams are partially neutralized in deuterium gas, and the emerging charged and neutral beams are stopped in copper calorimeters. The deuterons in the gaseous neutralizer, and beam-implanted deuterons in the calorimeters, collimators, etc., become neutron-producing targets for the intense ion and neutral beams.

In 1977, we reported[2] preliminary data on neutron yields in the neutralizer and the calorimeter of a 120-kV, 10-A, 0.5 second source; additional measurements with beams from the 120-kV, 65-A TFTR source, with power-supply-limited pulse lengths of 20 msec at full-power, were made. Here, the yield versus beam energy from a beam-saturated calorimeter is shown to be in general agreement with theoretical calculations.

Experimental Arrangement

The experiment was carried out on the LBL Test Stand III, shown in Fig. 1. The ion source is followed by a neutralization region 2 meters long. The calorimeter (beam dump) is ~8 meters from the source.

In order to avoid any problems with lost counts from active counters during the high instantaneous periods of neutron production (beam pulse duration times ranged from 18 to 500 msec), neutron yields from the calorimeter and from the neutralizer column were measured with moderated thermal neutron activation foils. Moderated BF_3 counters were used in locations much further removed from the calorimeter and neutralizer in order to monitor the uniformity of the neutron emission as a function of time.

Three moderated indium detectors were spaced 43.5 cm apart on a line parallel to and 150 cm from the beam line and opposite the calorimeter. Another moderated indium detector was placed opposite the neutralizer column at a distance of 133 cm from the beam line.

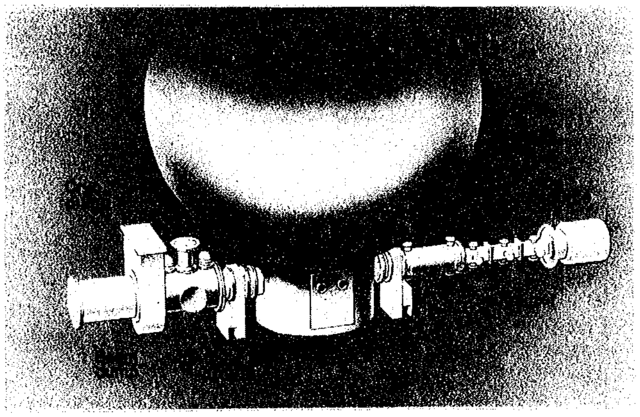

Fig. 1. Schematic of test facility.

These detectors exhibit a reasonably flat response[3] for d-d neutrons for deuterium beam energies up to several MeV. (See Fig. 2). Neutron energy as a function of incident D_1^+ energy is shown in Fig. 3.

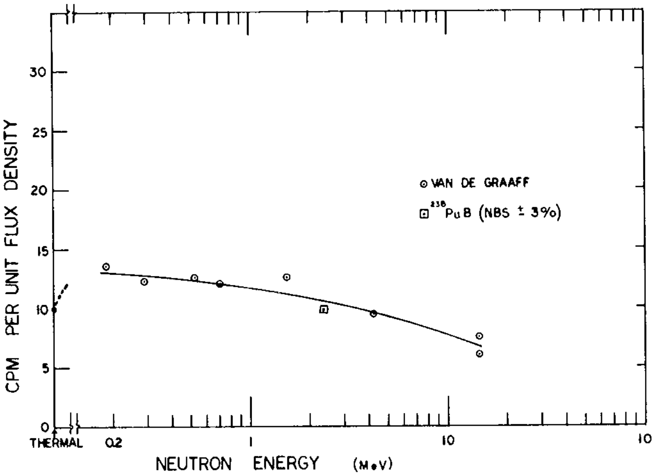

Fig. 2. Detection sensitivity of moderated indium detectors.

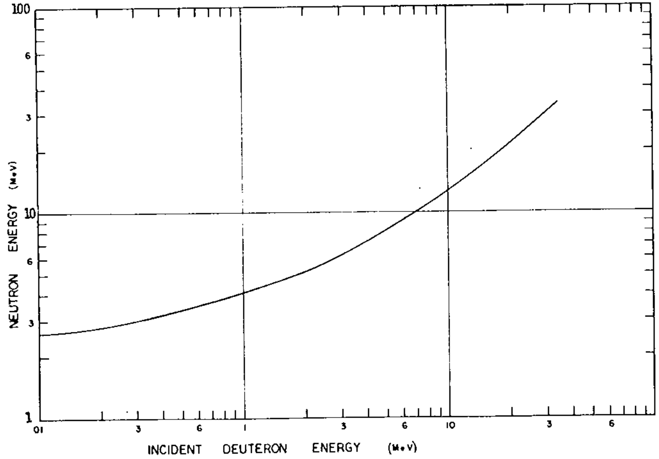

Fig. 3. Neutron energy vs. D^+ energy for d-d reactions.

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*Work supported by U. S. Department of Energy, Office of Fusion Energy, under Contract W-7405-ENG-48.

Directional collimation was not used to prevent one detector from responding to the source associated with the other detectors. However, corrections as high as 11% have been made to the neutralizer neutron data to remove the contribution from the calorimeter.

Experimental Results

Starting with materials that have not been exposed to deuterium beams, we see a build-up in neutron production as the bombardment continues. Eventually a plateau is approached as the diffusion of deuterons out of the interactive layer comes into equilibrium with the implantation rate. An example is given in Fig. 4 for 120-keV, 8-A, and 42-keV, 2-A beams stopping in the copper calorimeter. The BF_3 detectors were used to determine when equilibrium neutron production was attained. The moderated indium detectors were then used to determine the neutron production from a saturated target.

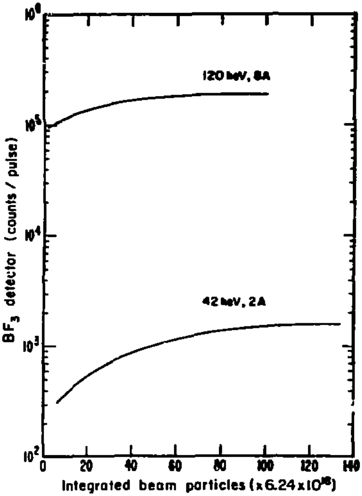

Fig. 4. Neutron-production buildup in a copper target as a function of beam fluence.

Neutron yields given in Table I are normalized to 1-A on the calorimeter for continuous (non-pulsed) beams. A point source is assumed for the calorimeter. Attenuation of neutrons by the vacuum wall and copper calorimeter is assumed to be offset by a 20% contribution by scattering into the detector from the floor, walls and equipment. The neutralizer column is considered to be a 2m uniform line source.

Analysis

Three ion species are produced in the plasma source, D^+, D_2^+ and D_3^+, which, after acceleration, result in full-, half-, and one-third energy components. Table II. An estimate of the fractional neutron yields of atomic (full energy) and molecular (1/2 and 1/3 energy) components have been made (see Table II) which are based on prior experimental knowledge of the fractional power yields of the beam species, and the integrated reaction cross sections as given by Kim.[4]

Table I. Measured instantaneous neutral yield per ampere of deuterons ($D^+ + D^0$)

BEAM ENERGY keV	NEUTRON YIELD (n/sec-A) calorimeter	neutralizer
40	1.4×10^9	7.7×10^8
60	6.0×10^9	2.6×10^9
80	1.3×10^{10}	4.1×10^9
100	2.6×10^{10}	8.4×10^9
120	4.7×10^{10}	1.2×10^{10}

The calculational method used is shown below.

Neutron yield, Q, for an atomic beam is given by:

$$A = CN_d \int_0^R \sigma[E(x)]dx, \text{ neutrons/second}$$

where

C = saturated deuterium density (assumed uniform throughout R)

N_d = number of deuterium beam particles/sec

R = deuteron range

σ = d-d reaction cross section at energy E at depth x.

It is assumed that the implanted saturated deuterium density in the calorimeter is essentially constant over the range of the incident deuterium beam. Justification for this assumption stems from the work of Bartle et al.[5] and by Hilton et al.[6]

The integrated reaction cross sections of Kim[4], shown in Fig. 5, are used because of the strong dependence of cross section on the energy of the incident beam particles which are continuously degraded in energy until they are completely stopped within the target.

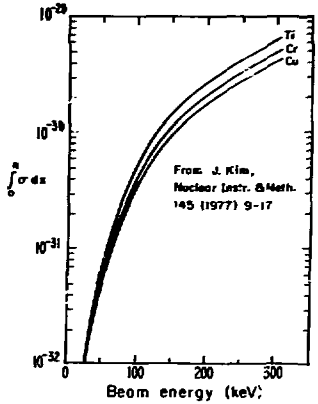

Fig. 5. Integrated reaction cross sections from Ref. 4.

Table 2. Percent Beam Species Distributions

Beam Particle	Beam Energy (keV) 40	60	80	100	120
D_1^+	38	51	60	68	75
D_2^+	10	20	20	19	16
D_3^+	52	29	29	13	9

Table 3. Fractional Neutron Yield Due to D_1, D_2, D_3 Species

Beam Particle	beam Energy (keV) 40	60	80	100	120
D_1	0.92	0.91	0.86	0.89	0.93
D_2	0.08	0.09	0.09	0.08	0.05
D_3			0.05	0.03	0.02

Fig. 6 shows the neutron yield from the calorimeter plotted with Kim's[7] calculations for 80% D_1^+, 20% D_2^+ and 40%, D_1^+, 60% D_2^+. Although the beam species mixture varies with the acceleration potential (Table II) it can be seen that the calculations are in good agreement with experimental measurements. The contribution to neutron emission by the D_2^+ and D_3^+ species is small as can be seen in Table III. A saturated deuterium concentration, uniform along the particle range in the target, of 1.7 x $10^{22}/cm^3$ is assumed in the calculations.

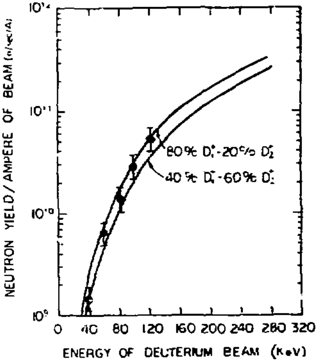

Fig. 6. D-D neutron yield per ampere of deuterium beam from a copper target as a function of beam energy (C = 1.7 x 10^{22} assumed). The lines are calculations by Kim.[7] The points are results of this paper.

Fig. 7 compares Kim's calculations of neutron emission from the neutralizer column with the LBL measurements. For this comparison, the neutralizer neutron yield is normalized to acceleration current as measured at the upstream entrance to the column.

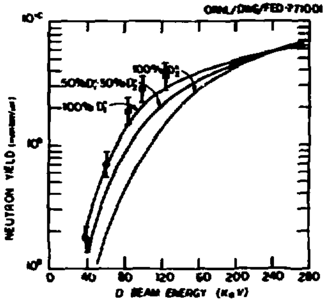

Fig. 7. Neutron yield from neutralizer per ampere of beam current per thickness of 10^{16} molecules/cm^2 as a function of beam energy. The curves are calculations by Kim.[7] The points are results of this paper normalized to 10^{16} molecules/cm^2.

Application to Shielding Design

These experimentally verified neutron yields have been used to design local shielding around the vacuum tank which houses the calorimeter, so as to keep personnel exposure in an otherwise largely unshielded area below the design goal of 0.5 mrem/h average. Six inches of polyethylene reduced the neutron flux by a factor of 16.6. This allows larger deuterium beams to be run or smaller beams to be run for a longer time, but it is still necessary to continuously monitor the neutron flux in the control room and control the amount of time that testing can be done with deuterium beams. Normal hydrogen (protium) is used whenever possible so that neutrons cannot be generated.

Neutron yield data was incorporated in the source term for the Monte Carlo program MORSE[8] to study the shielding requirements for the Neutral Beam Source Test Facility. This facility has been built to test the 120 keV, 0.5 sec sources intended for the TFTR tokamak at Princeton. The main use of the computer code was, of course, to calculate neutron scattering through access ways. The required thickness of the main shield was determined to be [illegible] feet of ordinary (2.4g/cm^3) concrete. The operation of the code was checked against the NCRP-38 dose attenuation data[9] and the results are shown in Fig. 8 for the sum of collided and uncollided neutrons outside various thicknesses of shielding.

Safety and Monitoring

NTA (neutron) and gamma film packets are issued to all employees who work at the facility. Pencil dosimeters are also available for those whose work might entail x-ray exposures.

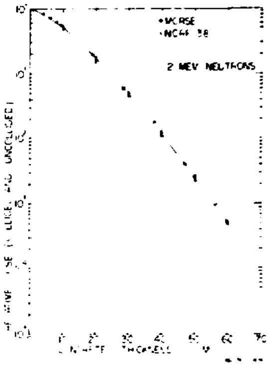

Fig. 8. Calculated attenuation of 2 MeV neutrons in concrete. The dashed portion is a simple graphical extrapolation.

While deuterium beams are being used, the experimental area is cordoned off. The control room, adjacent to the experimental area, is continually monitored for neutrons by a moderated BF_3 counter. The dose is integrated and stored in the facilities' computer following each shot. Fig. 9 shows the integrated neutron dose in the control room, as determined from the moderated BF_3 counter, data for the period 23 May to 16 Aug. 1979. The dose is calculated from measurements of neutron flux by applying the flux-to-dose conversion factor for 2.5 MeV neutrons. Reported dose is therefore an overestimate because it assumes that the neutrons are unscattered and have their maximum energy. Measurements are being planned to determine the energy spectrum, and average neutron energy so that accurate dose assessments can be made.

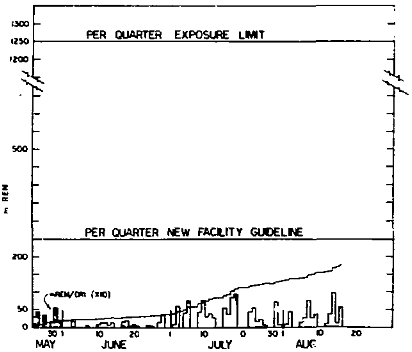

Fig. 9 Neutron dose during 3 months of typical TSIII operation.

Paraffin-moderated tantalum activation foils[10] are also placed in the control room to integrate the neutron flux over 1 month periods as a backup monitor and check on the performance of the active BF_3 counter.

Conclusions

Calculations and experiments of D-D neutron yields are shown to be in substantial agreement over the range of incident deuterium beam energies from 40 keV to 120 keV. Some degree of confidence can be placed in dose rate predictions and shielding calculations for conditions that will exist in the large fusion experiments.

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