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RELATIVE INTENSITIES OF 2.5 AND 14-MEV SOURCE NEUTRONS FROM COMPARATIVE RESPONSES OF U-238 AND U-235 DETECTORS

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ABSTRACT

The response of polyethylene-moderated U-235 fission counters is only weakly dependent on incident neutron energy, while the response of unmoderated U-238 or Th-232 fission counters increases strongly with energy. A given concentration of D-T neutrons in a mixed DT-DD source results in a unique relative detector response that depends on the parameters R_{14} and $R_{2.5}$, where R_{14} is the ratio of the unmoderated U-238 and moderated U-235 detector efficiencies for a pure 14-MeV neutron source, and $R_{2.5}$ is the corresponding ratio for a pure 2.5 MeV source. We have determined R_{14} and $R_{2.5}$ using D-D and D-T neutron generators inside the TFTR vacuum vessel. The results indicate that, for our detector geometry, the ratio of U-238 to U-235 count rates should increase by a factor of about 3 when the fusion neutron source changes from pure D-D to pure D-T. This calibration is being applied to recent TFTR "supershot" data, where the uncollided neutron flux in the post-beam phase contains a high proportion of D-T neutrons from the burnup of D-D tritons.

INTRODUCTION

The TFTR fusion neutron source consists of two distinct components, the first near 2.5 MeV (D-D neutrons) and the second near 14 MeV (D-T neutrons). In order to measure the relative intensities of the two components, we are pursuing an approach based on the difference in signals from two similar detectors, one of which has a detection efficiency nearly insensitive to neutron energy, while the other has an efficiency increasing with energy.

If S_{14} and $S_{2.5}$ are the intensities of the 14-MeV and 2.5-MeV neutron sources, respectively, then the count rates for the two detectors are given by

$$C_1 = {}^1\epsilon_{DD} S_{2.5} + {}^1\epsilon_{DT} S_{14} \quad , \qquad (1)$$

$$C_2 = {}^2\epsilon_{DD} S_{2.5} + {}^2\epsilon_{DT} S_{14} \quad , \qquad (2)$$

where ${}^i\epsilon_{DD}$ and ${}^i\epsilon_{DT}$ are the detection efficiencies. If ${}^2\epsilon_{DD} \neq {}^2\epsilon_{DT}$, one can find $S_{14}/S_{2.5}$ from Eqs. (1) and (2), even if ${}^1\epsilon_{DD} = {}^1\epsilon_{DT}$. A system of fission counters[1-3] is appropriate for this purpose. The response of a U-235 fission counter shielded by 10 cm of lead and enclosed in a 5-cm thick polyethylene container is nearly independent of incident neutron energy. An unmoderated U-238 fission counter, on the other hand, has a threshold near 1.2 MeV, and the detection efficiency generally increases with energy.

I. SPECTROMETER EQUATION

We define R_{14} as the ratio of the U-238 and U-235 detector efficiencies for a "pure" 14-MeV neutron source, $R_{2.5}$ as the corresponding ratio for a "pure" 2.5 MeV source, and R' as the ratio of the U-235 detector efficiencies for D-T and D-D neutron sources. Then with $C_1 = C_{235}$ and $C_2 = C_{238}$, Eqs. (1) and (2) give the ratio of the source intensities as

$$\frac{S_{14}}{S_{2.5}} = \frac{R'(C_{238}/C_{235} - R_{2.5})}{(R_{14} - C_{238}/C_{235})} . \qquad (3)$$

The objective of the calibration reported herein was to determine $R_{2.5}$ and R_{14} by operating both D-D and D-T neutron generators in TFTR bays containing U-238 and U-235 fission counters. For present purposes it is not necessary to know the absolute calibration of the neutron generator because only ratios of D-D and D-T efficiencies appear in Eq. (3).

II. CALIBRATION APPARATUS

The fission counters[2,3] used in this calibration are listed in Table I. The U-235 detector (NE-2) is shielded by lead and moderated by 5 cm of polyethylene,[3] while both U-238 detectors are unshielded and unmoderated. Figure 1 shows the nominal positions of the detectors at TFTR. NE-2 is located at the center of Bay M; its coordinates measured from the axis of the TFTR vacuum vessel are $R_d = 315$ cm, $\theta = 0°$, and $z = -184$ cm. For this calibration, NE-7 was located off-center in Bay F, with the detector coordinates approximately $R_d = 245$ cm, $\theta = 3.5°$, and $z = -139$ cm.

The neutron generator (Kaman Model A-711) with D-D and D-T heads was inserted in Bay K and positioned at various locations along the toroidal axis, always pointing away from Bay K as indicated in Fig. 1. The angular position of the generator with respect to the center of Bay F or Bay M is denoted θ, with positive values of θ in the clockwise direction relative to the center of the bay.

In the following, all NE-2 and NE-7 detector counts are normalized to the source monitor counts to give relative detector efficiencies, ϵ_{DD} and ϵ_{DT}. Activation foil measurements[4] gave the ratio of the D-T and D-D neutron detection efficiencies for the monitor as 2.1, and this factor is incorporated into the quoted ϵ_{DT}.

III. DETECTION EFFICIENCIES OF THE U-235 DETECTOR (NE-2)

Figure 2 shows the detection efficiencies vs angular source position for the U-235 detector in Bay M. The ratio $R' = \epsilon_{DT}/\epsilon_{DD}$ was found by three different methods:

(1) At $\theta = 0°$, $\epsilon_{DT}/\epsilon_{DD} = 1.45$.

(2) ϵ_{DD} and ϵ_{DT} were each found by dividing the sum of the NE-2 counts for all generator positions by the sum of all the NE-4 (monitor) counts. The ratio $\epsilon_{DT}/\epsilon_{DD}$ is 1.28.

(3) For application to the TFTR volume source, the most appropriate procedure is to use averages over "equivalent points"; i.e., ϵ_{DD} and ϵ_{DT} are determined using the same set of generator positions, with the measured counts at each position normalized to the same number of source neutrons. This method gives $\epsilon_{DT}/\epsilon_{DD} = 1.34$.

Table II lists the various values of R' with their uncertainties.

IV. DETECTION EFFICIENCIES OF THE U-238 DETECTOR (NE-7)

A. EFFICIENCY OF THE U-238 DETECTOR FOR D-T NEUTRONS

Figure 3 shows the NE-7 (U-238) detection efficiency vs angular source position. The output of the neutron generator is markedly anisotropic.[4] Figure 3 also shows the NE-7 efficiencies when corrected for this anisotropy and the source-detector distance, for $\theta \nless 3°$. The corrected profile is practically flat for $\theta < 2°$, which indicates that (i) the U-238 detector views mainly neutrons in the source energy group, (ii) the anisotropy correction is reasonably accurate, and (iii) the neutron "beam" suffers constant attenuation in this region. This attenuation is due mainly to the 15-cm total thickness of the front and back panels of the stainless steel inter-coil structural member in front of the detector.

The discontinuity in the efficiency profile between 2° and 3° is apparently due to the source-detector line of sight intersecting the solid end region of the structural member. There is increasing attenuation by this structure at $\theta > 3°$.

B. EFFICIENCY OF THE U-238 DETECTOR FOR D-D NEUTRONS

The background count rate in the U-238 detector was sufficiently large to be a problem with the D-D source. An extended background run established an average background rate of 0.026 ± 0.003 ct/s, which was of the order of one-half the total count rate for the D-D head. Figure 3 shows the NE-7 (U-238) detection efficiency vs angular source position, after subtracting the background counts appropriate to the source exposure time for each point. The average efficiency ϵ_{DD} over the angular span -12° to

+14°, determined by subtracting background from the total counts at all positions, is indicated by the dashed line in Fig. 3.

There was also an extended 9400-sec exposure with the source at 2°, which permitted ϵ_{DD} to be determined with ±13% uncertainty at that point. This result is 19% above the average ϵ_{DD}.

C. EXPLANATION OF MAGNITUDE OF THE EFFICIENCY RATIOS FOR NE-7

The ratio $\epsilon_{DT}/\epsilon_{DD}$ was determined by each of the three methods used for the U-235 detector (see Sec. III), and gave consistent results: $\epsilon_{DT}/\epsilon_{DD}$ is 5.2 for the long exposure at 2°, 5.05 for the simple average over all generator positions, and 5.49 for the average over "equivalent points." The explanation of this sizeable factor is the following:

1. Cross Sections. The U-238 detector has a 2.1 times larger cross section for 14-MeV neutrons than for 2.5-MeV neutrons.

2. Differential Source Anisotropy. For a given total source intensity, the ratio of D-T to D-D neutron current is 1.5 at θ = 2° (approximately 90° to the generator beam) and 1.3 when averaged over the scan.

3. Differential Attenuation. D-T neutrons have greater attenuation length in stainless steel than do D-D neutrons (viz. 8.3 cm vs 6.5 cm calculated from removal cross sections[5]). The ratio of the attenuation factors increases from 1.64 at θ = 2°, where there is about 15 cm of steel in front of the detector, to about 1.95 averaged over the generator scan.

The product of these factors is 5.2 at 2° and 5.3 when averaged over the generator scan. The anisotropy effect must be removed to use the calibration factors with an isotropic fusion plasma source. Table II shows the efficiency ratios when all the NE-7 data have been corrected for source anisotropy. No correction has been made for the U-235 detector, which detects mainly scattered neutrons,[2,3] although a small correction would be justified near $\theta = 0°$.

V. APPLICATION TO TFTR DATA

Table II also summarizes the measured inter-detector efficiency ratios defined earlier. The quantity $RR = R_{14}/R_{2.5}$ is the factor by which the ratio of the U-238 to U-235 detector count rates is expected to increase when going from a pure D-D source to a pure D-T source [see Eq. (3)]. Both determinations of this parameter gave RR = 3.1, but the method most appropriate for comparison with TFTR data has an uncertainty of 41.7%.

In TFTR operation to date, D-T neutron production has resulted only from the burn-up of D-D tritons. While $S_{14}/S_{2.5}$ is usually $\lesssim 1\%$, it is thought to reach at least several tens of percent during the post-neutral-beam phase of supershots because the slowing-down time of the tritons is many times that of the beam ions.[6-8] As both the D beam ions and the D-D tritons are expected to have isotropic velocity distributions late in the post-beam plasma, the value of RR obtained from the calibration when corrected for source anisotropy should be applicable.

From Eq. (3), we expect C_{238}/C_{235} to increase monotonically from $R_{2.5}$ to R_{14} in the post-beam phase. In actual TFTR practice, the data acquisition computer normalizes the processed signals so that both detectors give the same source strength for an isotropic pure D-D source; i.e., $R_{2.5} = 1$ and $R_{14} = RR$. The maximum

C_{238}/C_{235} found in examining TFTR data to date is in the range 2.0 to 2.3 (see example in Fig. 4). From Eq. (3) with R' = 1.34, and using 20% uncertainty in (C_{238}/C_{235} - 1), the maximum $S_{14}/S_{2.5}$ is 2.2 ± 1.2; i.e., D-T neutrons comprise 50 to 77% of the total source strength.

Aside from statistical uncertainties, the present calibration may possibly yield inaccurate determinations of $S_{14}/S_{2.5}$ for the following reasons:

1. The NE-7 detector was calibrated in a bay different from that used in obtaining the TFTR data (although the relative position of the detector in each bay was the same).
2. There is some uncertainty in obtaining purely isotropic, purely D-D neutron emission from TFTR for normalization of the U-235 and U-238 detector count rates.
3. There may be some differences in the relative properties of the TFTR D-T and D-D sources (such as different major radii) that are not simulated in the calibration.

One way to increase neutron energy discrimination is to replace the U-238 with Th-232, for which the ratio of fission cross sections at 14.2 and 2.5 MeV is 3.0, compared with 2.1 for U-238. A potentially more powerful approach is to enhance the differential attenuation by placing in front of the U-238 detector a slab of material (such as graphite) that has a much larger removal cross section for 2.5-MeV than for 14-MeV neutrons. This method will be most useful when the absolute level of neutron flux is high, so that statistical error is small, and when $S_{14} \ll S_{2.5}$, as when a small amount of tritium is injected into the plasma.

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Table I.	Fission Counters		
DETECTOR	TYPE	MASS	LOCATION
NE-2	U-235	1.3 g	Bay M, at 0
NE-7	U-238	50 g	Bay F, at 3.5 (approx.)
Monitor	U-238	0.26 g	On neutron generator head

Table II. Measured Fission-Detector Relative Efficiencies. The NE-7 Data are Corrected for Source Anisotropy.

	ANGULAR SCAN (deg)	EFFIC. FOR D-D GEN.SCAN	EFFIC. FOR D-T GEN.SCAN	---DT/DD EFFICIENCY RATIOS--- FOR ALL POINTS	at 2°:NE7 or 0°:NE2	EQUIV. POINTS
U-238 (NE-7)	-7.5 to +18	2.77×10^{-4} ±13.7%	1.09×10^{-3} ±1.0%	3.94 ±14.7%	3.44 ±13.0%	4.16 ±35.4%
U-235 (NE-2)	-36 to +36	0.0371 ±0.5%	0.0474 ±2.1%	1.28 ±2.6%	1.45 ±9.2%	1.34 ±6.3%
U-238/U-235 EFFIC. RATIOS		0.0074 ±14.2% ($R_{2.5}$)	0.0229 ±3.1% (R_{14})	3.09 ±17.3% $RR=R_{14}/R_{2.5}$	2.37 ±22.2%	3.10 ±41.7% ($R_{14}/R_{2.5}$)

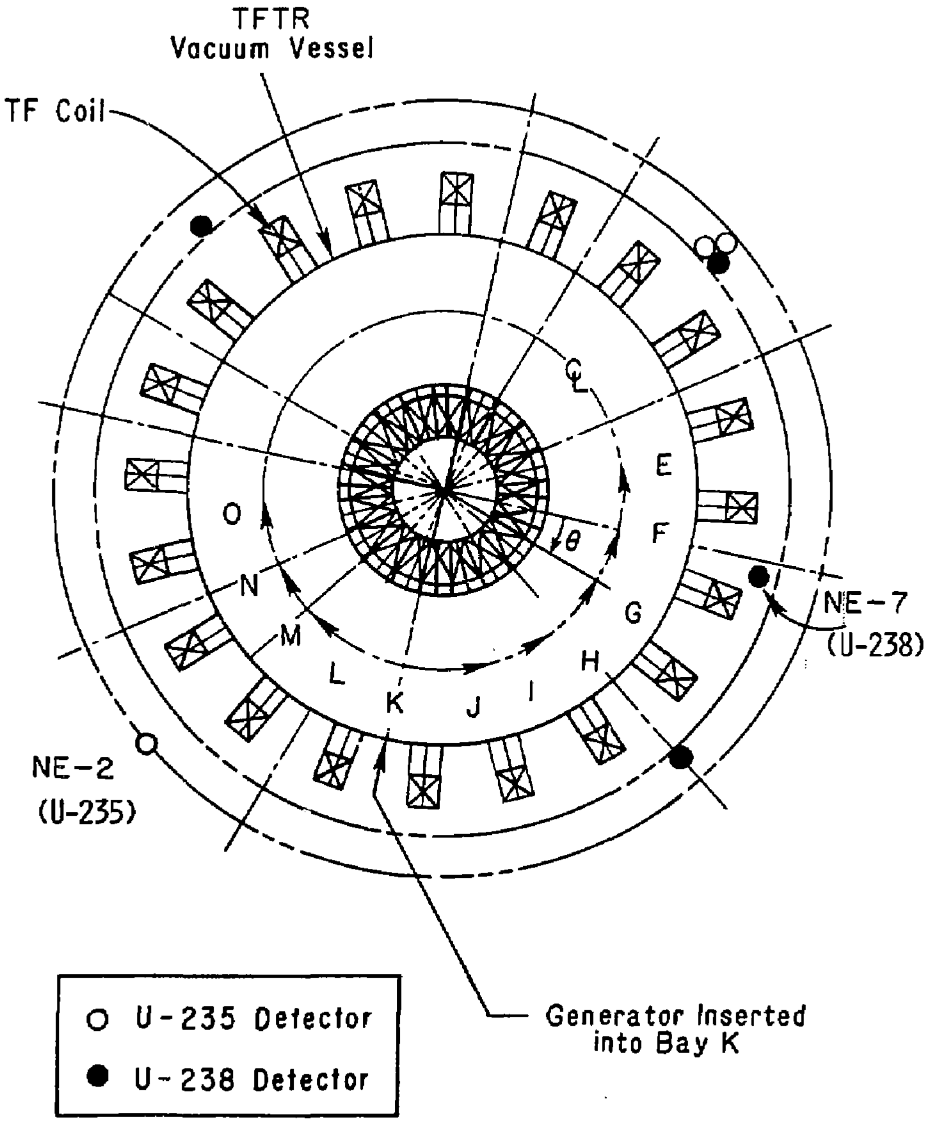

FIG. 1. Schematic plan diagram of TFTR showing locations of fission chambers. Arrows show the direction of the ion beam in the neutron generator. Capital letters identify bays.

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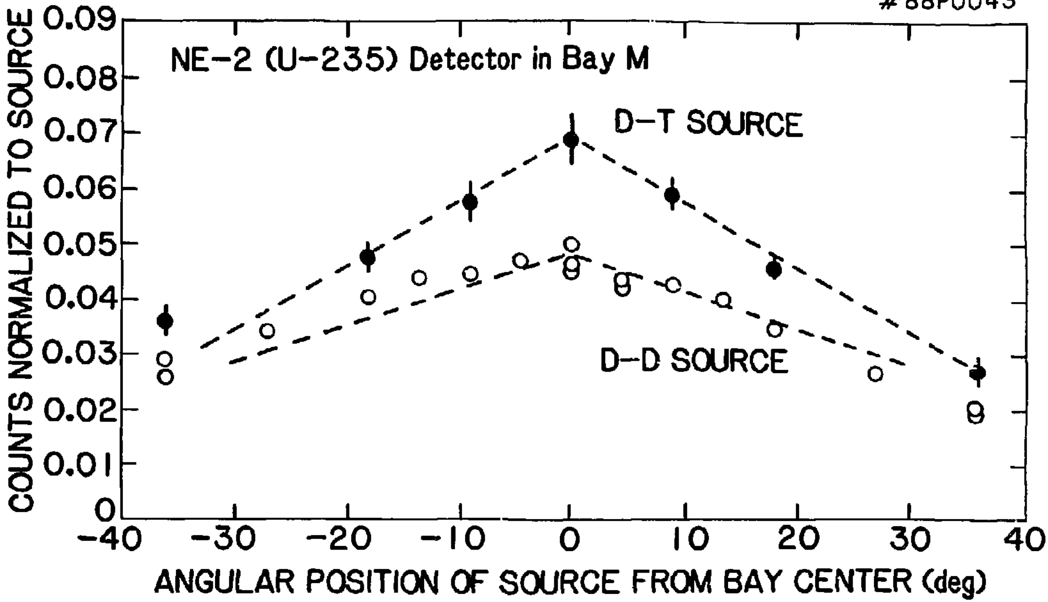

FIG. 2. U-235 (NE-2) detection efficiency versus neutron source position. The detector is located at 0°. Dashed lines are symmetric with respect to 0°.

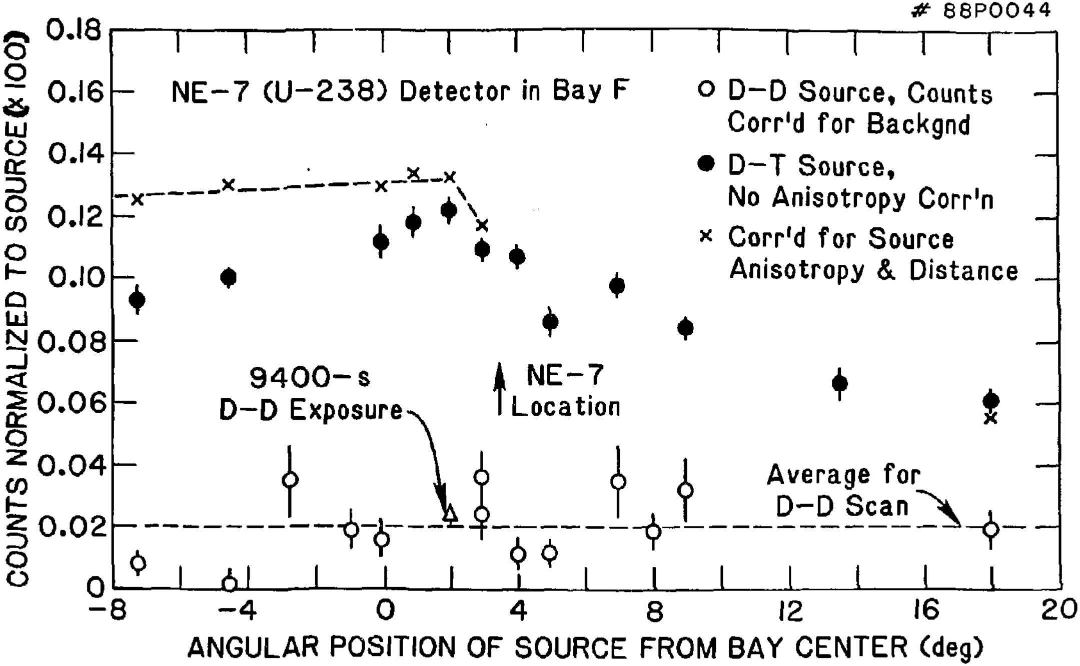

FIG. 3. U-238 (NE-7) detection efficiency versus neutron source position.

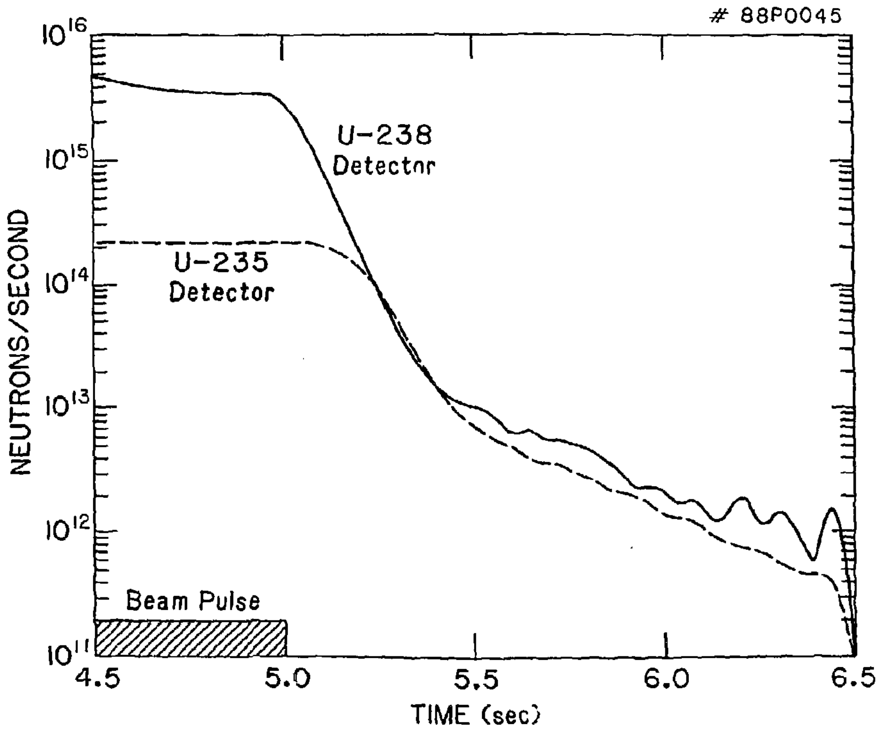

FIG. 4. TFTR neutron intensity measured with 2 fission detectors identical to NE-7 (U-238) and NE-2 (U-235), respectively, but both are in Bay C. Average of 5 similar shots with 50-ms smoothing. The U-235 detector saturates at S > 2×10^{14} n/s.

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