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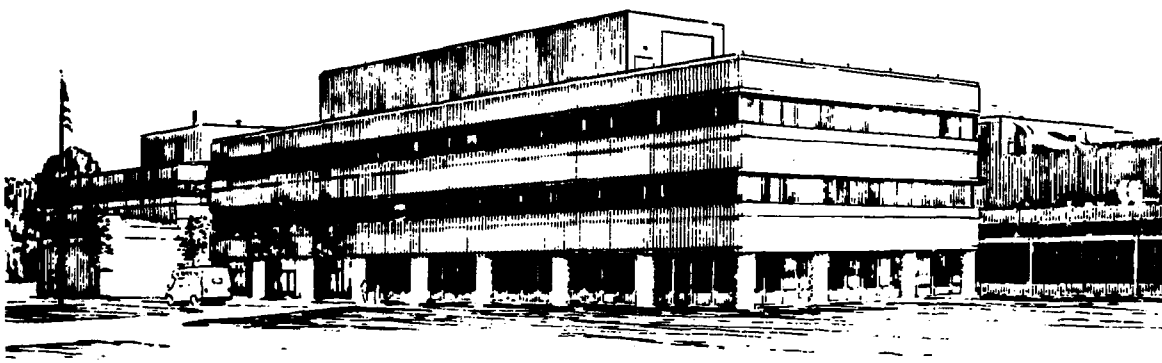

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Measurements of DT and DD Neutron Yields by Neutron Activation on TFTR

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Abstract

A variety of elemental foils have been activated by neutron fluence from TFTR under conditions with the DT neutron yield per shot ranging from 10^{12} to over 10^{18}, and with the DT/(DD+DT) neutron ratio varying from 0.5% (from triton burnup) to unity. Linear response over this large dynamic range is obtained by reducing the mass of the foils and increasing the cooling time, all while accepting greatly improved counting statistics. Effects on background gamma-ray lines from foil-capsule-material contaminants, and the resulting lower limits on activation foil mass, have been determined. DT neutron yields from dosimetry standard reactions on aluminum, chromium, iron, nickel, zirconium, and indium are in agreement within the ±9% (one-sigma) accuracy of the measurements; also agreeing are yields from silicon foils using the ACTL library cross-section, while the ENDF/B-V library has too low a cross-section. Preliminary results from a variety of other threshold reactions are presented. Use of the ^{115}In(n,n') ^{115m}In reaction (0.42 times as sensitive to DT neutrons as DD neutrons) in conjunction with pure-DT reactions allows a determination of the DT/(DD+DT) ratio in trace tritium or low-power tritium beam experiments.

I. Introduction

The highest accuracy determinations of neutron yields and fusion energy production have been provided by nuclear activation techniques.[1] Neutron activation has been used to measure triton burnup in tokamaks[2-5]; it was also used to measure the high DT yields during the Preliminary Tritium Experiments on JET in 1991. This work reports measurements of neutron activation during the DT Program on the Tokamak Fusion Test Reactor (TFTR) between November, 1993 and April, 1994. Neutron activation measurements on TFTR use a computer-controlled pneumatic transfer system.[6,7] While "backup" measurements generally using silicon foils[8] were made at irradiation ends outside the vacuum vessel, all the results of this paper involve elemental foils irradiated at a re-entrant location inside the top of the vessel.[9]

The absolute calibration for converting neutron activation to yield has five components. 1) The mass of the elemental foil is determined from a Mettler H33AR balance calibrated annually; the composition of the high-purity foils is given by the manufacturer. 2) The full-energy-peak efficiency of the high purity Germanium (HPGe) detectors[7] has been updated by use of a NIST-traceable radioactive source[10] and calculations of the self-shielding of the foils using standard attenuation factors.[11,12] 3) A standard reference[13] is used for the nuclear coefficients. 4) The cross-sections are from the ACTL library[14]; in the case of aluminum it has been normalized by 2% to the standard values from Ref. 15. 5) Finally, a 3-dimensional neutronics calculation using the MCNP code[16] is performed to determine the scattering and attenuation at the irradiation location and determine the ratio of energy-weighted fluence to yield from TFTR plasmas.[9] The overall accuracy in the determination of the DT neutron yield is ±8% (one-sigma) *not including* any uncertainties in the cross-section, nuclear coefficients (isotopic abundance or gamma-ray branching ratio), or counting statistics of particular reactions.[9]

II. Operational Effects of High Yields

Backgrounds from contaminants: It is important to use high-purity sources for the elemental foils to avoid competing activity (especially from (n,γ) reactions). In particular, some iron samples were found to have too much manganese in them; hence

the ^{56}Fe(n,p) reaction was affected by ^{55}Mn(n,γ) contributions leading to spurious results.

At the high fluences of TFTR DT operation (up to 10^{12} n/cm^2), relatively low masses of elemental foils are needed to rapidly obtain excellent counting statistics with relatively low deadtime on the HPGe detectors. A worry existed that contaminants in the activation capsules, wadding, or labeling materials could compete with the activation of low-mass foils. To measure the background, capsules without foils but with various combinations of labeling (ink and tape) and wadding were irradiated and counted. Of those components, the wadding (Kimberly Clark 34256 Wipes) was found to be the major source of contaminants. ^{28}Al radiation at 1778 keV was seen, at a level of background equivalent to having an effective mass of silicon of 1 mgram. There is a 10-minute half-live decay of 511-keV radiation; this is believed to be ^{13}N from activated air in the capsule, and it corresponds to an equivalent mass of $\leq$ 1.5 mgram of copper. The capsules were counted for longer counting times as well, including irradiated capsules with the elemental foils removed. ^{24}Na radiation at 1369 keV and 2754 keV was seen, equivalent to 0.6 mgram of effective mass of aluminum. Another form of wadding gave much worse results, with effective masses of several milligrams; care has been taken subsequently to use only the better form of wadding. Based on these results, the elemental foils used were kept around 100 mgram so that the contamination would be a $< 1\%$ correction.

There are two HPGe counting stations used on TFTR.[7] Spectra were taken on one empty counting station while an aluminum foil from a high-yield DT discharge was counted in the other. No cross-talk ($< 10^{-5}$) between the detectors was observed.

Cooling Times: With a lower operational limit of $\sim$100 mgram mass (from background contaminants), silicon foils are "too hot" to be counted within several minutes after a high-yield DT discharge. After waiting several 2.24-minute half-lives of the reaction product (typically 10–15 minutes) the deadtime of the HPGe detector drops to a suitable value of below 5%. With 15–20 minutes between TFTR discharges this causes a delay in the data analysis but does not result in any continually increasing "queue" of samples to be counted.

For longer-lived activities (hours to days half-life) samples are removed from the pneumatic system and "cooled" to allow the short-lived (n,γ) activity to die away. Waiting $\sim$ 1 hour appears sufficient for aluminum and iron: indium foils typically require up to 5 hours of cooling before the 336 keV peak is insignificantly affected by Compton background of other activity.

Safety concerns about activation products and personnel dose have been considered. After DT discharges the activated air inside the pneumatic system is positively flushed into the TFTR Test Cell before capsules are returned; this places a 2-minute minimum time before counting after a DT discharge. The activation foils themselves have mRem/hour contact dose immediately after the shot from short-lived (n,γ) activity, especially observed in so-called "low activation" materials like vanadium or titanium. However, within typically 5–10 minutes this activity decays to rates just similar to low-level radioactive calibration sources, and within an hour they are safe to handle for loading capsules for counting.

III. Comparison of Different Reactions

Elemental foils of Al, Si, Cl and K (in the form of KCl), Ti, V, Cr, Fe, Co, Ni, Cu, Zr, Nb, Mo, In, W, and Au have so far been irradiated by DT discharges on TFTR.[17] Some of these elements feature dosimetry standard reactions that can be used to measure the fusion energy production and compared with high accuracy. Figure 1(a) shows the cross-section vs neutron energy for several standard reactions measured on TFTR. In Table I we show the measured response (measured "activated nuclei per target nuclei" [or "hits"] per source neutron) compared to the calculated response from the MCNP model[9] with "default" plasma conditions used (major radius of plasma source at 2.625 m, a gaussian radial profile with FWHM of 0.155 m, and a Maxwellian fusion burn temperature of 17.5 keV). Also tabulated is the response calculated from the analytic model of Zankl *et al.*[see Eqn. (3) of Ref. 18] using the cross-section value[19] at 14.1 MeV and a fluence-to-yield ratio of 0.0117 m^{-2} for the lower tally and 0.0112 m^{-2} for the upper tally (2.58 m major radius of foil, with toroidal cut-off angle of $\pm 90°$). Foils requiring counting soon after a discharge are

irradiated in the upper tally location and returned directly to the counting station; otherwise they are irradiated in the lower tally location.

The ^{28}Si(n,p) reaction is not a dosimetry standard. Figure 1(b) shows the cross-section vs incident neutron energy from the ACTL library,[14] ENDF/B-V,[19] and as used at JET.[20] Use of the ACTL value gives agreement with the neutron yields from aluminum within 3% (see Table 1). While we have not run MCNP with the other tabulations, we expect the JET values to also be in general agreement; however, the ENDF/B-V values are too low near 14 MeV.

There are some important details in analyzing some of the reactions. The 27.704 day ^{51}Cr activity at 320 keV must be subtracted from the initial 5.76 minute decay of ^{51}Ti at the same energy to determine the ^{54}Cr(n,α) response. The ^{52}Cr(n,2n)^{51}Cr response is dominated by activity from ^{50}Cr(n,γ). Counting of nickel and cobalt foils must wait for the 9.15 hour excited state to fully decay into the 70.916 day ground state of ^{58}Co. The cross-section for the reactions into both the ground and excited state must then be used.

IV. Dynamic Range

In addition to the goal of achieving a high accuracy calibration for fusion energy production on TFTR, the second goal of the neutron activation work was to achieve linear detector operation over a large dynamic range. This is achievable by gradually reducing the masses of the elemental foils (a factor of 20–100 from a few grams down to 100 mgrams) while allowing for some cooling time (providing typically a factor of 10 or less) while accepting greatly improved counting statistics with less counting time (more counts in less time by factors of 10^2–10^3) all while keeping the deadtime of the HPGe counter to less than 5%. A six-order-of-magnitude dynamic range (5 orders for the same element, silicon) has been demonstrated, with the DT neutron yield per shot ranging from 10^{12} to over 10^{18}. Figure 2 illustrates measurements of the 14-MeV neutron yield using silicon and aluminum foils from a sequence of TFTR discharges, including ohmic discharges and tritium neutral beam injection. References 21 and 22 show examples of comparing other detector systems and their linearity to the

activation system. The absolute calibrations of three other neutron detection systems and their uncertainties are compared to neutron activation in Ref. 23.

V. DD neutron yield in the presence of many DT neutrons

Once tritium was injected into the TFTR vacuum vessel, some of it collected on the walls and "recycled" into the plasma on subsequent discharges. Eventually, this has led to the 14-MeV neutron emission being greater than the 2.5-MeV neutron emission on some discharges which have no tritium injection at all. Measuring the yield of DD neutrons in the presence of a significant yield of DT neutrons is a difficult but important problem for determining the recycling coefficients. It is further important in "trace" tritium experiments, or those with low tritium beam power. It also helps constrain the relative detection efficiencies to DD and DT neutrons of fission chambers and other detectors that respond to both types of neutrons.

As shown in Figure 1 the ^{115}In(n,n')^{115m}In cross-section actually *peaks* near 2.5-MeV and decreases a factor of over 3 by 14-MeV. The calculated activation response for this reaction is a factor of $R^{\rm In}_{DT}/R^{\rm In}_{DD}$=2.69/6.35=0.42 lower for DT neutrons than DD. This difference in response is used to measure the DD emission in these mixed DD/DT discharges by subtracting off the DT response measured using (typically) aluminum activation that only responds to the DT component. For a measured activation of aluminum $H^{\rm Al}$ and of indium $H^{\rm In}$, the DT and DD yields are

$$Y_{DT} = \frac{H^{\rm Al}}{R^{\rm Al}_{DT}} \tag{1}$$

$$Y_{DD} = \frac{H^{\rm In}}{R^{\rm In}_{DD}} - \frac{R^{\rm In}_{DT}}{R^{\rm In}_{DD}} Y_{DT} \tag{2}$$

where $R^{\rm Al}_{DT}$, $R^{\rm In}_{DT}$, and $R^{\rm In}_{DD}$ are the response coefficients to DT and DD neutrons for aluminum and indium. Because $R^{\rm In}_{DT}/R^{\rm In}_{DD}$ is a relatively small number the contribution to the DD yield from the DT measurement is not as important as for detectors with *more* sensitivity to DT neutrons. The relative uncertainty of the DD/DT response ratio (the 0.42 factor) primarily comes from uncertainties in the cross-sections at the two energies and secondarily to the possible different behavior of the scattered contribution to the response at the different energies. However, the primary uncertainty from inaccuracies in geometric modeling tend to cancel in this

technique. Thus the response ratio is probably accurate to $\sim \pm 4\%$. With each of the measured activations divided by response accurate to $\pm 9\%$. the Y_{DD} can be determined to a fractional error ϵ_{DD} of

$$\epsilon_{DD} = \sqrt{(9\%(1+\rho))^2 + (9\%^2 + 4\%^2)\rho^2} \tag{3}$$

where $\rho = (R^{\rm In}_{DT}/R^{\rm In}_{DD})(Y_{DT}/Y_{DD})$. As ρ tends to zero the accuracy is just that for a simple DD measurement of 9%: for equal yields or $\rho = 0.42$ the DD yield in known to about 13% accuracy: for $\rho = 4$ or 9.5 times more DT neutrons than DD the accuracy climbs to 63%.

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Table 1: Measured Response of Activation Reactions Compared to Calculated Responses

Reaction	# of Shots	Response (10^{-31} Hits per neutron) Measured	Zankl	MCNP
Lower Tally (1.039 m above midplane)				
$^{27}Al(n,\alpha)^{24}Na$	33	1.54±0.12	1.45	1.54
$^{50}Cr(n,2n)^{49}Cr$	1	0.20	0.12	0.13
$^{52}Cr(n,p)^{52}V$	1	1.2	1.05	1.15
$^{54}Cr(n,\alpha)^{51}Ti$	1	0.16	0.14	0.15
$^{56}Fe(n,p)^{56}Mn$	5	1.56±0.04	1.34	1.44
$^{58}Ni(n,p)^{58}Co$	3	6.0±0.1	1.92	6.49
$^{58}Ni(n,2n)^{57}Ni$	3	0.28	0.30	0.29
$^{59}Co(n,2n)^{58}Co$	3	8.7	7.9	8.0
$^{90}Zr(n,2n)^{89}Zr$	4	7.4±0.3	7.68	7.53
$^{115}In(n,n')^{115m}In$	1	3.0	0.74	2.69
Upper Tally (1.088 m above midplane)				
$^{28}Si(n,p)^{27}Al$	25	3.38±0.28	3.33	3.47
$^{30}Si(n,\alpha)^{27}Mg$	2	0.88±0.08	1.00	0.98
$^{54}Fe(n,2n)^{53}Fe$	1	0.026	0.049	0.075

Figures

FIG. 1. Neutron activation cross-section vs energy. (a) Al. Si. Cr. Fe. Ni. Zr. and In reactions. all from the ACTL library as used in the MCNP modeling. (b) ^{28}Si(n,p) cross-section from the ACTL. JET. and ENDF/B-V tabulations.

FIG. 2. DT neutron yield vs TFTR shot number for a sequence of discharges illustrating the large dynamic range of the neutron activation system. Circles are aluminum foils. and squares are for silicon.

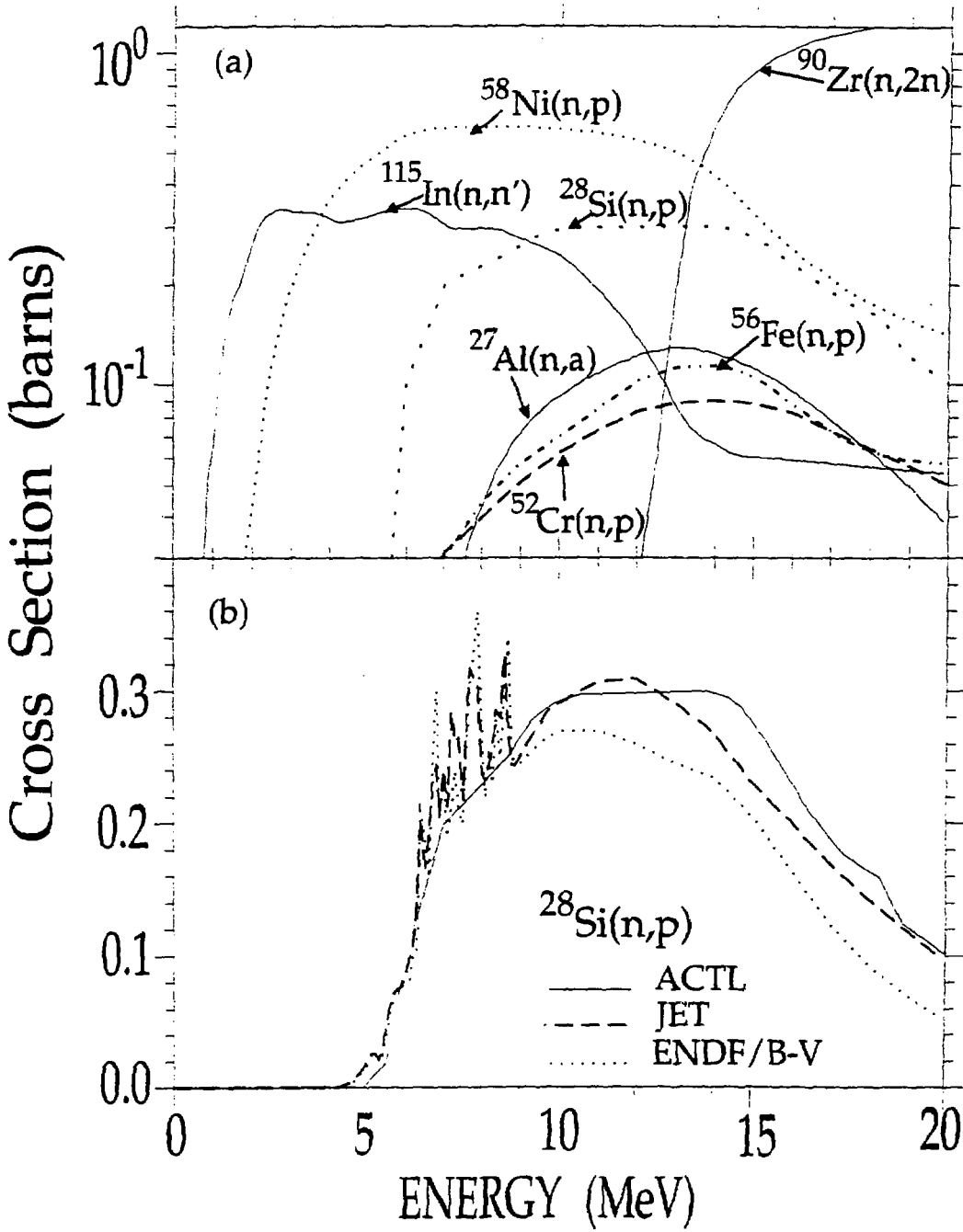
(a)
(b)
Cross Section (barns)
ENERGY (MeV)
10^0
10^{-1}
0.3
0.2
0.1
0.0
0
5
10
15
20
^{58}Ni(n,p)
^{90}Zr(n,2n)
^{115}In(n,n')
^{28}Si(n,p)
^{27}Al(n,a)
^{56}Fe(n,p)
^{52}Cr(n,p)
^{28}Si(n,p)
ACTL
JET
ENDF/B-V

Fig. 1

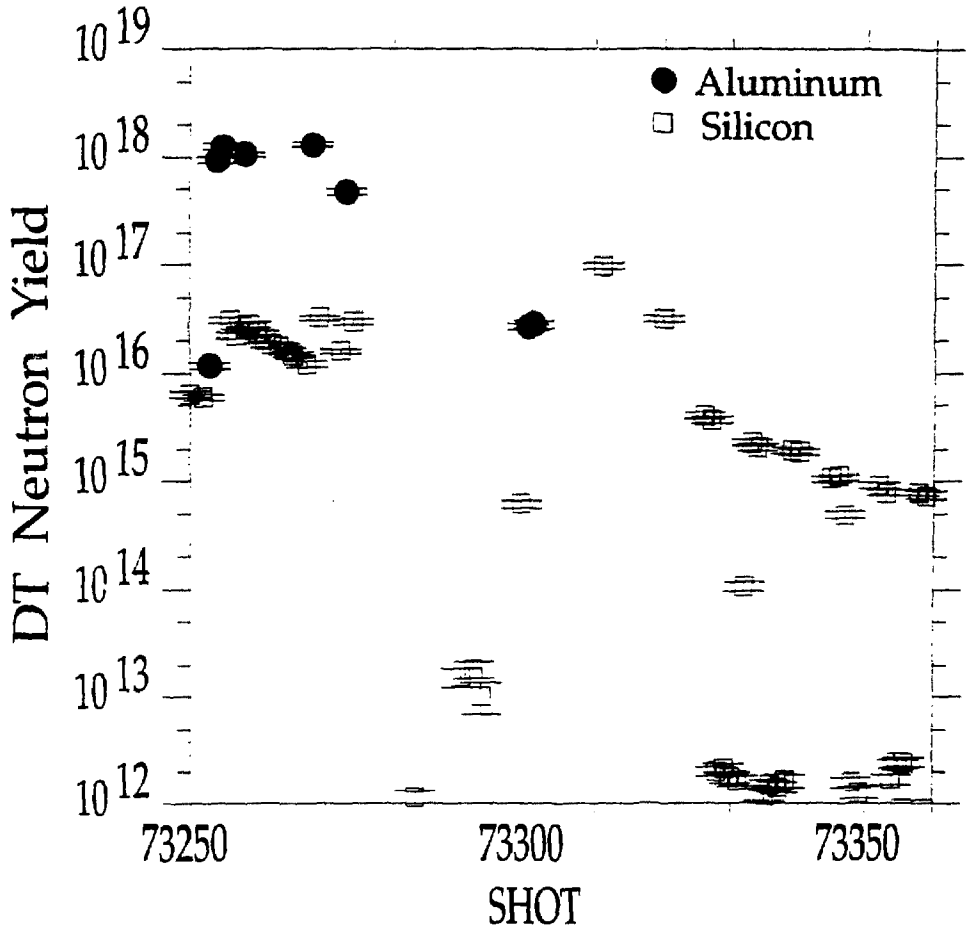
DT Neutron Yield
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
Aluminum
Silicon
73250
73300
73350
SHOT

Fig. 2

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