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FUSION GAMMA DIAGNOSTICS

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ABSTRACT

Nuclear reactions of interest in fusion research often possess a branch that yields prompt emission of gamma radiation in excess of 15 MeV. This branch can be exploited to provide a new fusion reaction diagnostic having applications similar to conventional neutron emission measurements. Conceptual aspects of fusion gamma diagnostics are discussed with emphasis on application to TFTR during deuterium neutral beam heating of D-T and D-³He plasmas. Recent measurements of the $D(T, \gamma)^5\text{He}$, $D(^3\text{He}, \gamma)^5\text{Li}$, and $D(D, \gamma)^4\text{He}$ branching ratios at low center-of-mass energy (30-100 keV) and of the response of a large volume Na226 detector for gamma detection in high neutron backgrounds are presented. For a well-shielded Na226 detector, the $D(T, \gamma)^5\text{He}$ gamma signal level during 20 MW ~ 120 keV deuterium neutral beam heating of a TFTR tritium plasma was estimated to be 3.5×10^5 CPS.

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INTRODUCTION

The branching ratios of the prompt gamma emission channels are generally several orders of magnitude below those for the well-known neutron and charged particle reactions. Thus, until recently, the fusion reaction rates attained in experimental devices have not been adequate to exploit fusion gamma emission for diagnostic purposes. With the advent of strong auxiliary neutral beam and ICRF heating, fusion reaction rates sufficiently high for application of fusion gamma diagnostics have been obtained on PDX and PLT,¹ for example, and are projected for TFTR as will be discussed in this paper.

The fusion gamma diagnostic concept was first proposed by Medley *et al.*^{2,3} using counting techniques to measure fusion reaction rates in two-component plasmas containing a non-Maxwellian ion energy distribution generated by neutral beam or ICRF auxiliary heating. An extension of the concept was proposed by Cecil and Newman⁴ wherein high resolution gamma ray spectroscopy is applied to obtain ion temperature measurements in Maxwellian plasmas. The first observation of fusion gamma rays was reported by Newman and Cecil⁵ who detected 5.5-MeV gamma rays from the $D(p,t)^3\text{He}$ reaction during hydrogen neutral beam heating of a deuterium plasma in Doublet ~ III.

In principle, fusion plasmas can yield a plethora of diagnostically interesting prompt gamma radiation involving low-Z reactants which are conveniently categorized as: 1) thermalized bulk plasma ions, 2) non-thermalized, energetic ion populations resulting from auxiliary heating or creation of charged fusion reaction products, and 3) impurity ions which may be either indigenous or injected (such as boron or lithium) for diagnostic purposes. Of the candidate reactions presented in Table I, attention will be focused on the $D(T, \gamma)^5\text{He}$ and $D(^3\text{He}, \gamma)^5\text{Li}$ reactions which offer the following advantages: 1) the reaction cross sections are relatively large, 2) the 16-MeV

gamma ray is energetically isolated above other fusion product energies and typical runaway electron induced gamma radiation, and 3) interesting near-term applications exist on TFTR where 120-keV deuterium neutral beams injected into ^3He or T plasmas can be transiently pumped to energies of ~ 250 keV by magnetic compression.

Potential exists for application of fusion gamma diagnostics to the difficult measurement of alpha particle confinement. Confined 3.6-MeV alpha particles produced by $\text{D}(^3\text{He}, \text{p})^4\text{He}$ reactions in a ^3He plasma heated by deuterium neutral beam injection undergo burn-up through $^4\text{He}(^3\text{He}, \gamma)^7\text{Be}$ and $^4\text{He}(\text{D}, \gamma)^6\text{Li}$ reactions producing 1.6- and 1.5-MeV gamma emission, respectively. This topic will be addressed in a future report.

I. DIAGNOSTIC DEVELOPMENT

Prior to the implementation of fusion gamma diagnostics on TFTR, efforts have concentrated on obtaining reliable measurements of the $\text{D}(\text{D}, \gamma)^4\text{He}$, $\text{D}(\text{T}, \gamma)^5\text{He}$, and $\text{D}(^3\text{He}, \gamma)^5\text{Li}$ cross sections (or equivalently the gamma branching ratios) at low energies and characterization of a large volume (5" diameter $\times$ 5" long) cylindrical Ne226 liquid scintillator.

The details of the branching ratio measurement are reported elsewhere⁶ and only the results will be presented here. Using a large NaI(Tl) crystal spectrometer characterized for response to high energy gamma rays,⁷ the branching ratios of the gamma ray reaction to the corresponding dominant charged particle reactions were measured. The resulting branching ratios for the $\text{D}(\text{D}, \gamma)^4\text{He}$, $\text{D}(\text{T}, \gamma)^5\text{He}$, and $\text{D}(^3\text{He}, \gamma)^5\text{Li}$ reactions are plotted in Fig. 1.

The Ne226 liquid scintillator gamma ray detector was selected for implementation of fusion gamma diagnostics of TFTR because of its neutron insensitivity and rapid decay constant (~ 3 nsec) which allows count

rates $\sim 10^6$ CPS for 16-MeV gamma rays in the presence of significant residual neutral/gamma fluxes of energy $\lesssim 14$ MeV anticipated for even a well-shielded detector during $D(T, \gamma)^5\text{He}$ measurements.² The Ne226 detector was observed to yield a relatively narrow full energy peak when exposed to monoenergetic gamma rays of 4.4-MeV (from a PuBe source) and 19.8-MeV gamma rays (from the reaction $T(P, \gamma)^4\text{He}$). From these and other gamma ray sources, measurement of the FWHM peak energy resolution and the absolute peak detection efficiency were obtained for the Ne226 scintillator as shown in Fig. 2.

II. FEASIBILITY ESTIMATES FOR TFTR

Deuterium beam heated tritium plasmas in TFTR will generate intense radiation backgrounds with flux levels of $\sim 2 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$ extending from thermal to ~ 14 -MeV energies for both neutrons and gamma rays. For $D(T, \gamma)^5\text{He}$ gamma diagnostics, massive shielding is required to reduce the background radiation at the detector by a factor of $\sim 10^{-6}$. Figure 3 shows a shielding scheme of conventional design except for a 1.5-m ^6LiH plug in front of the detector which attenuates 14-MeV neutrons by $\sim 10^{-6}$, but high energy gammas by only ~ 0.2 followed by 2 cm of lead which attenuates low energy ($\lesssim 300 \text{ keV}$) gammas by $\sim 10^{-6}$ and high energy gammas by only ~ 0.5 . Even with shielding, measurement of the $D(T, \gamma)^5\text{He}$ 16-MeV gamma radiation requires a detector characterized by: 1) modest energy resolution ($\lesssim 15\%$) to reject the residual neutron and gamma events at energies $\lesssim 14 \text{ MeV}$, 2) low neutron sensitivity, and 3) high count rate capability to enable $\lesssim 10 \text{ ms}$ time resolution.

An estimate of the $D(T, \gamma)^5\text{He}$ 16-MeV gamma count rate, S , at the Ne226 detector is obtained using:

$$S = R_n \cdot \frac{\sigma_{D(T, \gamma)}}{\sigma_{D(T, n)}} \cdot \frac{d\Omega}{4\pi} \cdot v \cdot \xi_A \cdot \xi_D \quad (1)$$

where $R_n = \sigma_D(T, \gamma) / \sigma_D(T, n)$ ($\#/\text{cm}^3/\text{sec}$) is the product of the 14-MeV neutron reaction rate and the gamma-to-neutron branching ratio, $d\Omega$ is the solid angle subtended by the detector at the plasma, $V(\text{cm}^3)$ is the viewed plasma volume, ϵ_A is the collimator attenuation loss, and ϵ_D is the detector sensitivity for 16-MeV gamma radiation. The 14-MeV neutron flux density as a function of plasma temperature ($T_e = T_i$) shown in Fig. 4 is obtained from code calculations³ for 20-MW, 120-keV deuterium beam injection into a TFTR tritium plasma of density $n_e \sim 7 \times 10^{13} \text{ cm}^{-3}$. The spread in reaction rate reflects a range of subsidiary parameters (such as impurity concentration and charge exchange particle losses) which affect the beam slowing-down energy distribution and hence the neutron yield. For an exemplary count rate estimate, we take $R_n = 4 \times 10^{11} \text{ n/cm}^3/\text{sec}$, $\sigma_D(T, \gamma) / \sigma_D(T, n) = 5.4 \times 10^{-5}$, $d\Omega/4\pi = 4.0 \times 10^{-5}$ ($a = 6.4 \text{ cm}$ at $L = 500 \text{ cm}$), $V = 5 \times 10^5 \text{ cm}^3$, $\epsilon_A = 0.1$, and $\epsilon_D = 0.08$ giving $S = 3.5 \times 10^5 \text{ sec}^{-1}$. Thus even for conservative TFTR plasma conditions, this estimate predicts ample count rates for statistically good measurements with time resolution of 1-10 msec. On the basis of relative cross sections, the count rate for $D(^3\text{He}, \gamma)^5\text{Li}$ gamma rays under similar plasma conditions will be lower by a factor of $\sim 10^{-2}$, but this reduction can be partially offset by increasing the viewed plasma volume. Also, for deuterium beam heated ^3He plasmas, experimental conditions are more benign since the background neutron and gamma radiation fluxes will be lower by $\sim 10^{-3}$ with energies $\leq 2.5 \text{ MeV}$, which significantly simplify shielding requirements.

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FIGURE CAPTIONS

- Fig. 1 Gamma ray branching ratios for the $D(T,\gamma)^5\text{He}$, $D(^3\text{He},\gamma)^5\text{Li}$, and $D(D,\gamma)^4\text{He}$ reactions as a function of center of mass energy.
- Fig. 2 Absolute detection efficiency and relative energy resolution of the Ne226 liquid scintillator for high energy gamma radiation.
- Fig. 3 Conceptual detector shielding scheme for $D(T,\gamma)^5\text{He}$ 16-MeV gamma ray measurements on TFTR.
- Fig. 4 Calculated $D(T,\gamma)^4\text{He}$ 14-MeV neutron flux density for 20-MW, 120-keV deuterium neutral beam injection into an $n_e = 7 \times 10^{13} \text{ cm}^{-3}$ TFTR tritium plasma.

Table IFusion Gamma Reactions

REACTION	GAMMA RAY ENERGY (MeV)
$P + D \rightarrow \gamma + {}^3\text{He}$	5.5
$P + T \rightarrow \gamma + {}^4\text{He}$	19.7
$D + D \rightarrow \gamma + {}^4\text{He}$	23.8
$D + T \rightarrow \gamma + {}^5\text{He}$	16.6
$D + {}^3\text{He} \rightarrow \gamma + {}^5\text{Li}$	16.4
$D + {}^4\text{He} \rightarrow \gamma + {}^6\text{Li}$	1.5
$T + T \rightarrow \gamma + {}^6\text{He}$	12.3
$T + {}^3\text{He} \rightarrow \gamma + {}^6\text{Li}$	15.8
$T + {}^4\text{He} \rightarrow \gamma + {}^7\text{Li}$	2.5
${}^3\text{He} + {}^3\text{He} \rightarrow \gamma + {}^6\text{Be}$	11.5
${}^4\text{He} + {}^3\text{He} \rightarrow \gamma + {}^7\text{Be}$	1.6
$P + {}^7\text{Li} \rightarrow \gamma + {}^8\text{Be}$	18.0, 15.0
$P + {}^{11}\text{B} \rightarrow \gamma + {}^{12}\text{C}$	16.1, 11.7, 4.4

Fig. 1

Fig. 2

Fig. 3

Fig. 4

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