GAMMA RAY MEASUREMENTS DURING DEUTERIUM
AND ^3He DISCHARGES ON TFTR

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ABSTRACT

Gamma ray count rates and energy spectra have been measured in TFTR deuterium plasmas during ohmic heating and during injection of deuterium neutral beams for total neutron source strengths up to 6×10^{15} neutrons per second. The gamma ray measurements for the deuterium plasmas are in general agreement with predictions obtained using simplified transport models. The 16.6 MeV fusion gamma ray from the direct capture reaction $\text{D}(^3\text{He}, \gamma)^5\text{Li}$ was observed during deuterium neutral beam injection into ^3He plasmas for beam powers up to 7 MW. The measured yield of the 16.6 MeV gamma ray is consistent with the predicted yield. The observation of this capture gamma ray establishes the spectroscopy of the fusion gamma rays from the $\text{D}-^3\text{He}$ reactions as a viable diagnostic of total fusion reaction rates and benchmarks the modeling for extension of the technique to D-T plasmas.

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1. INTRODUCTION

Gamma radiation represents a major component of the total radiation in the environment of fusion devices. For the high temperature deuterium plasmas which are presently an important element of the controlled fusion effort and for the anticipated deuterium-tritium plasmas, most of the gamma radiation is produced by neutron inelastic and capture processes in the surrounding structural materials. Because of the obvious radiological impact as well as the potential of radiation damage to instruments, the neutron and neutron-induced gamma radiations have been the object of extensive modelling on TFTR [1,2]. Measurements of the gamma ray background in the TFTR basement area during deuterium discharges have recently been reported [3]. There have been no reported measurements of the gamma ray background in the TFTR test cell or at the perimeter outside the test cell walls.

More fundamental than the neutron-induced gamma ray background is the gamma radiation resulting from the direct capture reactions among the plasma ion constituents. Using measurements of these fusion gamma rays as a diagnostic of the total fusion reaction rate or as a possible method for evaluating the alpha particle confinement in D-T plasmas has been proposed [4-7]. The first evidence for the production of $H(D,\gamma)^3He$ gamma rays from fusion plasmas was detected during neutral hydrogen injection into deuterium plasmas in the D-III tokamak [8]. Recent accelerator-based measurements of the branching ratios of the gamma ray to charged particle yields for the D-D, D-T, and D- 3He [9-12] reactions at low energies (< 100 keV) have facilitated the evaluation of this diagnostic for the corresponding plasmas. Measurements of both the direct capture fusion gamma rays and the neutron-induced gamma radiation are necessary since the latter constitutes a potentially compromising background to the measurement of the former.

In the next section, we report measurements of the spectrum and count rate of the neutron-induced gamma ray background radiation at several sites in the vicinity of TFTR. These measurements were made in deuterium plasmas for both ohmic and deuterium neutral beam injection (NBI) heating during TFTR operation in the 1986 run period. In the following section, we report the first measurement of the 16.6 MeV gamma ray from the $D(^3\text{He}, \gamma)^5\text{Li}$ capture reaction in a fusion plasma. In the last section, we make use of our measurements of the neutron-induced gamma ray backgrounds to suggest ways in which the measurements of the fusion gamma rays might be improved for future applications.

2. BACKGROUND GAMMA RAY MEASUREMENTS

Measurements of the gamma ray energy spectrum and total count rates were made for deuterium plasmas during ohmic and deuterium NBI heating at three sites in the vicinity of TFTR as indicated in Fig. 1. The first site was on the floor of the TFTR test cell at a distance ~ 10 m radially from the machine centerline and ~ 3.5 m below the midplane of the vacuum vessel. At this site, the gamma ray detector was enclosed in a compact blockhouse which has overall dimensions approximately 2 m wide by 2 m long by 1 m high and consists of nested strata of concrete, polyethelene, lithium carbonate, and lead. The detector viewed toward Bay F on the TFTR vacuum vessel through a 1.5 m long by 20 cm diameter cylindrical collimator in the blockhouse. A photograph presented in Fig. 2 shows the blockhouse in the foreground. The detector views the tokamak to the left of the vertical concrete pillar but still views through substantial structural material. The second measurement site was located at a 10 cm diameter hole which was bored perpendicularly through the

test cell wall which adjoins to the TFTR hot cell at a radial distance ~ 15 m from the machine center and ~ 50 cm above the midplane of the vacuum vessel. The detector was well shielded from the direct flux of neutrons streaming down the bore-hole by a 40 cm long plug of borated polyethelene. The third site which was located outside the test cell wall at floor level provided the simplest geometry for comparison of the measured gamma spectra with code modelling.

A 10 cm diameter by 10 cm high NaI(Tl) crystal scintillator manufactured by Harshaw Chemical Co. was used as the gamma detector in the background gamma ray measurements. Calibration of the full energy peak detection efficiency and the resolution of this detector for gamma ray energies up to 16 MeV has been reported elsewhere [13].

A representative pulse-height spectrum of the background gamma radiation measured at Site 2 for a single discharge with deuterium NBI into a deuterium plasma is presented in Fig. 3. The spectrum was accumulated with pulses from the detector anode which were processed by an ORTEC shaping amplifier with a time constant of 0.25 microseconds. The shaped pulses were digitized by a CANBERRA 200 MHz 9-bit ADC, sorted and stored for transfer to the TFTR data processing computer system. Electronic dead-time was measured by feeding a 60 Hz pulser into the digitizer and monitoring the total number of counts in a dedicated channel above the spectrum of interest. During the acquisition of the gamma spectra, the energy scale was calibrated with the 2.61 MeV gamma ray from an in-situ 2 μ Ci ^{228}Th sealed source which was attached to the outside of the detector and with the 4.44 MeV gamma ray from a weak PuBe source. By virtue of the lack of apparent detail in the spectra and to facilitate subsequent comparison with the predicted energy spectra, the measured pulse-height spectra were summed off line into 1 MeV bins. Using the TFTR

epithermal neutron fission detector array [14], the neutron yield for the data shown in Fig. 3 was observed to have a maximum of about 1.6×10^{14} neutrons per second with a total production of about 8×10^{13} neutrons in a plasma pulse. This measured value of the total neutron production was used to convert the ordinate of the original gamma ray spectra from "counts/MeV" to "counts/MeV-source neutron".

In order to extract the gamma ray energy spectrum from the measured pulse-height spectrum, a detector response function derived from the known gamma ray mass attenuation coefficients [15] of NaI(Tl) was assumed. In terms of a continuous gamma ray flux distribution $\phi(E_\gamma)$ and the detector response function $R(E_\gamma, E)$ which gives the probability of a pulse height at energy E for when the detector is exposed to a gamma ray of energy E_γ , the observed pulse-height spectrum $N(E)$ is given by

$$N(E) = A \int_0^\infty \phi(E_\gamma) R(E_\gamma, E) dE_\gamma, \quad (1)$$

where A is the exposed front surface area of the detector. For discrete spectra, the measured pulse-height spectrum is related to the gamma ray energy spectrum by a detector response function which is now a matrix

$$N(E_i) = A \sum_{j=1} \phi(E_j) R(E_j, E_i) \quad (2)$$

The measured gamma ray energy spectrum which is unfolded from the pulse-height spectrum given in Fig. 3 is shown by the solid line in Fig. 4.

For each site, the measured gamma ray energy spectra may be compared to calculated energy spectra which were generated using the TFTR neutron/gamma ray transport code [16]. The predicted gamma ray energy spectrum for Site 2

(including the effect of the borated polyethelene plug) is shown by the dashed line in Fig. 4. Reasonable agreement is observed between these measured and predicted gamma ray energy spectra. One aspect of this agreement which is important to the observation of the high energy fusion gamma rays is the absence of gamma rays at energies approximately of 12 MeV. Similar agreement is obtained between measured and predicted gamma ray energy spectra at Site 3 outside the TFTR test cell. The energy spectrum measured in the blockhouse on the TFTR test cell floor agrees in spectral shape with the predicted spectrum but exceeds the predicted spectrum in magnitude by about a factor of three. By plugging the collimator in the blockhouse, it was determined experimentally that the discrepancy in magnitude between the measured and predicted spectra could be attributed, in large part, to an excess signal arising from the neutron-induced gamma ray flux penetrating through and generated within the lateral walls of the blockhouse itself.

In addition to the measurements of the gamma ray spectra, the total gamma ray count rate at the three sites was measured over a wide range of neutron source strengths. The time evolution of the total gamma count rate during a typical deuterium discharge is shown in Fig. 5 where a two-hundred fold increase in count rate during deuterium NBI between 4.0 and 4.5 seconds is noted relative to the preceding ohmic heating phase. The relationship between the total gamma count rate at each of the three sites and the total neutron source strength is obtained by comparing such measurements obtained over a wide range of neutron yields. This comparison is presented in Fig. 6 for total neutron source strengths between 2×10^{12} and 5.5×10^{16} neutrons per second. In this figure, the measured count rates are shown by the symbols, and the predicted count rates are indicated by the lines. A number of features of the count rate behavior are worth noting.

- (1) An approximately linear relationship between total gamma count rate and total neutron source strength is observed for count rates to approximately 0.6 MHz. The apparent saturation near 1 MHz is consistent with the 0.25 microsecond time constant of the shaping amplifier for the gamma detector.
- (2) Reasonable agreement is obtained between measured and predicted count rates at Sites 2 and 3 whereas a significant disagreement occurs for Site 1 as discussed above.
- (3) The measured gamma ray count rate at a given neutron source strength is nearly two orders of magnitude less at Site 2 outside the test cell compared with Site 1, the blockhouse on the test cell floor.

The agreement between measured and predicted count rates at Sites 2 and 3 is implied by the agreement between the measured and predicted energy spectra discussed earlier. For example, summing over the spectrum in Fig. 3 yields a total count rate at Site 2 of about 4×10^{-11} counts/(cm²-source neutron). Given the 80 cm² front surface area of the detector and a total detection efficiency of about 10%, the total gamma ray count rate expected for a neutron source strength of 1×10^{15} neutrons/sec is about 3×10^5 gammas/sec, which is consistent with the data in Fig. 6 for the same site.

The good agreement between the measured and predicted count rates at Sites 2 and 3 represents an important experimental verification of the transport code used to model the gamma radiation on TFTR. This agreement provides a basis not only for extrapolating the total gamma ray count rates to higher neutron source strengths but also for understanding the background

radiation expected during the measurements of the fusion gamma rays discussed in the next section.

3. OBSERVATION OF FUSION GAMMA RADIATION

Our experiments to observe the gamma rays from the direct radiative capture reactions within the plasma itself were undertaken to provide a proof-of-principle demonstration of gamma ray spectrometry as a diagnostic of the total fusion reaction rate. Measurements were carried out with a 12.7 cm by 12.7 cm cylindrical cell of the liquid fluorocarbon scintillator NE226. This detector was used in our study of the fusion gamma rays rather than the NaI(Tl) crystal scintillator used in the background measurements by virtue of the very fast (2 ns) scintillator decay constant of the NE226 as compared to the relatively slow (250 ns) decay constant of NaI(Tl). The peak energy resolution and detection efficiency of the NE226 detector for gamma rays up to 19 MeV have been reported elsewhere [17]. During deuterium discharges the relationship between the total gamma count rate and the total neutron source strength for the NE226 detector at Site 1 in the blockhouse on the TFTR test cell floor is shown in Fig. 7. We see that the expected linear relation between count rate and neutron source strength survives at count rates in excess of 2 MHz for the NE226 detector. This behavior would only be possible with a fast scintillator decay constant. In order to avoid possible pulse pile-up, our observations of fusion gamma rays were conservatively limited to plasma discharges in which the total neutron source strength did not exceed about 2×10^{14} neutrons per second.

The fusion gamma ray observations were made in the blockhouse on the test cell floor (Site 1) rather than at the 10 cm bore hole in the test cell wall

(Site 2) since the latter site, though well-suited for making background gamma ray measurements, did not afford an unobstructed view through any of the accessible ports on the vacuum vessel. Without a relatively unobstructed view, the fusion gamma rays emerging from the plasma would be severely attenuated and their observation accordingly compromised. The detector count rate for the fusion gamma rays will be determined by the gamma ray production rate and the net detection efficiency. The detector count rate, N_{det} , may be approximated by:

$$N_{\text{det}} = R_{\text{fus}} (r_{\gamma}/r) (V_{\text{obs}}/V_{\text{tot}}) (A_{\text{det}}/4\pi R^2) P_{\text{net}} \xi \quad , \quad (3)$$

where

R_{fus} is the total rate of a given fusion reaction,

(r_{γ}/r) is the gamma ray branching ratio,

$(V_{\text{obs}}/V_{\text{tot}})$ is the fraction of observed volume,

A_{det} is the front surface area of the detector,

$R = 10 \text{ m}$ is the distance from the detector to the observed plasma volume,

P_{net} is the net penetration probability of the gamma rays through the material between the observed plasma volume and the front surface of the detector, and

$\xi \approx 0.1$ the peak detector efficiency [17].

A more precise expression for N_{det} would involve an integral over the plasma volume to account correctly for the spatial dependence of the total fusion reaction rate and the gamma ray penetration probability. For purposes of count rate estimates, $(V_{\text{obs}}/V_{\text{tot}})$ and P_{net} were each taken to be about 10%.

The net uncertainty in the estimated count rate due to the uncertainties in the assumed values of $(V_{\text{obs}}/V_{\text{tot}})$ and P_{net} might be a factor of two and constitutes the most significant source of error. In future measurements of fusion gamma rays on TFTR or other fusion devices, these large uncertainties could be greatly reduced by an in-situ calibration in which a high energy gamma ray source of known strength is transported around the inside of the vacuum vessel. Given in-situ calibration data, the remaining uncertainties would be statistical counting errors and the measurement errors in the gamma ray branching ratios which are approximately 20% for the D-D, D-T, and D-³He reactions [9-12].

The observation of fusion gamma rays from TFTR is possible, in principle, for three separate fusion reactions:

- (1) A 23.8 MeV gamma ray is produced by the $D(D,\gamma)^4\text{He}$ reaction during deuterium NBI heating of deuterium plasmas. Using the measured gamma ray branching ratio for the D-D reaction of 1×10^{-7} [11] and a typical D-D reaction rate of 1×10^{14} reactions per second, we would estimate (Eq. 3) an unacceptably low fusion gamma count rate of ~ 0.06 counts per second and consequently no effort was made to observe this gamma emission.
- (2) A 16.7 MeV gamma ray from the D-T reaction is produced from the burn-up in the plasma of the 1 MeV triton produced in the D-D reactions. An effort was made to observe this gamma ray during a series of thirty-four deuterium plasmas (TFTR Shots 22561-22614) with high neutron yields in which gamma spectra were recorded during the time interval between 0.5 and 1.0 seconds after the neutral beams were turned off. During this time interval, the background gamma ray count rate in the NE226 detector

had dropped to an acceptably low level while the production rate of 14 MeV neutrons from the triton burn-up reactions was measured with an NE213 proton recoil spectrometer [18] to be about 5×10^{11} 14 MeV neutrons per second. This measured production rate is accurate only to approximately a factor of two due largely to the uncertainty in the absolute detection efficiency of the NE213 system for 14 MeV neutrons. From this production level of 14 MeV neutrons and the measured D-T gamma ray branching ratio [9-10], we would expect a detection rate for the 16.7 MeV gamma ray from the D-T reaction to be about 0.2 gamma rays per second using Eq. 3. The expected counting rate is consistent with the observed count rate of 0.24 ± 0.2 gamma rays per second where, because of the long count time, the statistical uncertainty from the cosmic ray background in the detector becomes dominant. Repeating these measurements with a cosmic ray veto detector surrounding the scintillator may allow these gamma rays to be definitively observed.

- (3) A 16.6 MeV gamma ray from the D-³He reaction is produced in ³He plasmas heated by injection of deuterium neutral beams. This gamma ray was observed during a series of fourteen deuterium NBI-heated ³He plasma discharges. With ³He plasmas the gamma ray background at a given level of beam injection power is significantly less than that for the same power levels for deuterium NBI into deuterium plasmas since the D-D neutron production from the direct beam-target interaction will be minimized. In Fig. 8, the total neutron source strengths for ³He and deuterium plasmas heated by deuterium NBI are compared over a wide range of beam power. The total neutron source strengths are lower for the ³He plasmas by nearly a factor of five. As mentioned earlier, gamma ray

spectrometry was restricted to neutron production levels less than $\sim 1 \times 10^{14}$ neutrons per second which limits the useable beam injection power to ~ 7 MW or less according to Fig. 6. Some of the plasma parameters measured during a representative D-³He discharge are presented by the waveforms in Fig. 9. This discharge (TFTR Shot 22827) was analyzed using the 1-D time-independent transport code SNAP [19]. This code was used to verify the expected ion composition in the plasma (Fig. 10) and to estimate the total D-³He reaction rate (Fig. 11). Combining these results with similar SNAP calculations for other discharges, we inferred that the total reaction rate appears to scale roughly with total beam power. We are thus able to estimate that the total D-³He reaction rate corresponds to approximately 2.4×10^{13} reactions/MW of beam power. The gamma ray spectrum obtained by summing data from the eight D-³He shots with beam power less than 7 MW is shown in Fig. 12. Evident in this figure is the 16.6 MeV fusion gamma ray between energies of 15.8 and 17 MeV. The observed line width of the gamma ray is consistent with the 10% measured energy resolution of the detector [17] and the 1.5 MeV natural ground state width of ⁵Li. From the measured beam powers during each of the eight shots, the above estimate of the total D-³He reaction rate versus beam power, and previously reported measurements of the D-³He gamma ray branching ratio [12], we would expect a total of 29 counts in the 16.6 MeV peak in the spectrum in Fig. 12 using Eq. 3. This agrees reasonably well with the observed yield of 20 ± 5 counts.

Thus, of the three possible fusion reactions for which the observation of the associated gamma ray was considered, only the 16.6 MeV gamma ray from the D-³He reaction during deuterium neutral beam injection of ³He was observed with reasonable counting statistics.

4. FUTURE APPLICATIONS

The observation of the $D-^3He$ fusion gamma ray establishes fusion gamma ray spectrometry as a viable diagnostic of total fusion reaction rate. At present, however, its application to total reaction rate measurements on TFTR is limited by virtue of the constraint on the maximum neutron source strength which is experimentally acceptable as discussed in the preceding section. This constraint could be significantly relaxed by: a) providing better shielding against the neutron-induced background radiation than was available in the blockhouse on the TFTR test cell floor, and b) improving the signal processing electronics to allow a higher counting rate capability.

On TFTR, a relatively inexpensive improvement to the neutron shielding available in the blockhouse at Site 1 might be realized by using existing shielding structures. For example, a bore hole through the test cell wall similar to Site 2 described in Sec. 2 but having a clear line-of-sight to the vacuum vessel would constitute such a site. Such bore holes are presently used for the TFTR X-ray PHA system and for the "roof lab" at JET [20]. From Fig. 6, we may conclude that the 1 MHz detector limitation is reached at Site 2 for a total neutron source strength of approximately 6×10^{15} neutrons per second. Referring to Fig. 8, we then conclude for deuterium NBI into deuterium plasmas that gamma ray spectrometry should be possible at beam powers approaching 15 MW. Similarly, for deuterium neutral beam injection into 3He plasmas gamma ray spectrometry should be possible for 25 MW of deuterium beam power. From the estimates of the $D-^3He$ total reaction rate, based both upon the SNAP calculations and our observation of the $D-^3He$ gamma ray, we would expect that at 25 MW measurements of the total $D-^3He$ reaction rate would be possible on TFTR on a single shot basis using only the yield of the 16.6 MeV gamma ray. This ability would facilitate proposed [21] alpha

particle confinement studies on TFTR during D-³He plasmas by providing a measure of the total alpha particle production rate.

However, the shielding provided by the bore hole site discussed above would prove inadequate for D-T operation on TFTR at which time neutron source strengths in excess of 1×10^{18} neutrons per second are expected. From Fig. 6 we would expect count rates above 100 MHz which exceeds the capabilities of existing signal processing electronics. On the other hand, neutron and gamma ray transport calculations [15] suggest that shielding improvements beyond those provided by the bore hole between the TFTR test cell and hot cell may allow the spectrometry of the 16.7 MeV gamma ray from the D-T reaction to be utilized as a diagnostic of the total fusion reaction rate during D-T operation of TFTR. This would provide a method for corroborating the total fusion reaction rate measurements based on neutron data.

The count rate limitation encountered in the present investigation derived from the approximately five microsecond conversion time characterizing commercially available analog-to-digital converters. With the total count rate (background plus fusion gamma events) limited to no more than several hundred kHz, our measurements were constrained to low yield plasmas in which the observation of the fusion gamma emission was likewise constrained by low counting statistics. Efforts are in progress to extend the count rate capability with a CAMAC-based multichannel system consisting of fast discriminators and scalars. Measurements of time-resolved 5-bit gamma ray spectra at total detector count rates of 10-20 MHz with virtually no instrumental dead-time appears to be feasible using commercially available equipment. Such a system would represent nearly a two-order-of-magnitude increase in the maximum count rates at which fusion gamma spectra may be measured compared with the electronics used in the present experiments.

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FIGURE CAPTIONS

Fig. 1 TFTR test cell layout showing the sites at which gamma count rates and energy spectra were measured.

Fig. 2 Photograph taken on the TFTR test cell floor looking toward Bay F of the vacuum vessel showing the fusion gamma concrete blockhouse in the foreground (Site 1 in Fig. 1).

Fig. 3 Gamma ray pulse-height spectrum measured at the aperture of a 10 cm diameter bore hole in the wall of the TFTR test cell (Site 2 in Fig. 1) during deuterium NBI into a deuterium plasma with a maximum neutron yield of 1.6×10^{14} neutrons per second (TFTR Shot 21513).

Fig. 4 Comparison of the gamma ray energy spectrum (solid curve) at Site 2 unfolded from the measured pulse-height spectrum and the energy spectrum calculated using the TFTR neutronics code (dashed curve). The data were obtained during deuterium NBI into a deuterium plasma (TFTR Shot 21513).

Fig. 5 Total count rate in NaI(Tl) detector at Site 1 on TFTR test cell floor during deuterium NBI heating of a deuterium plasma with a total neutron yield of 1×10^{14} neutrons per second.

Fig. 6 Comparison of the measured total gamma ray count rates versus neutron source strengths for the NaI(Tl) detector at Site 1 on the TFTR test cell floor (solid circles), at Site 2 at the aperture to the bore hole in the wall of the TFTR test cell (crosses), and at Site 3 outside the test cell wall (open circles). For each site the measured count rates are compared to the predicted count rates shown by the solid lines.

Fig. 7 Measured count rate versus neutron source strength for the NE226 fluorocarbon liquid scintillator at Site 1 on the TFTR test floor.

Fig. 8 Neutron source strengths versus injected beam power for deuterium NBI into deuterium plasmas (open circles) and ^3He plasmas (solid circles).

Fig. 9 Plasma parameter waveforms for the deuterium NBI into a ^3He discharge (TFTR Shot 22827).

Fig. 10 Radial ion densities during $\text{D}^0 + ^3\text{He}$ as estimated using the 1-D time-independent transport code SNAP (TFTR Shot 22827).

Fig. 11 Radial dependence of $\text{D}-^3\text{He}$ reaction rate density during $\text{D}^0 + ^3\text{He}$ as estimated using the 1-D time-independent transport code SNAP (TFTR Shot 22827).

Fig. 12 Measured gamma ray spectrum with the NE226 detector at Site 1 on the TFTR test cell floor obtained by summing over eight $D^0+{}^3\text{He}$ discharges with beam injection powers up to 7 MW. The 16.6 MeV gamma ray is evident for energies between 15.8 and 17 MeV.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

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