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ABSTRACT

Measurement of the neutron energy spectrum above ~16 MeV will yield information on the spatial and energy distributions of confined fast alphas in DT tokamaks.[1] The energetic neutrons result from fusion reactions involving the energetic ions created by alpha-fuel ion knock-on collisions. Standard two-gas bubble neutron detectors, designed to only detect neutrons with energies above a selectable threshold determined by the gas mixture, were used in preliminary attempts to measure the knock-on neutrons from DT plasmas in TFTR and JET. Subsequent measurements at accelerator neutron sources showed an unexpected below-threshold detector response that prevented observations of the alpha-induced neutron tails. Spontaneous bubble nucleation measurements show that the majority of this below-threshold response is due to slight variations in the gas mixture, and is not present in single-gas detectors. Single-gas detectors will be tested at UC Berkeley to determine the neutron energy threshold as a function of detector operating temperature and to confirm their suitability for alpha knock-on tail measurements. An array of single-gas detectors operating at different temperatures should allow measurements of the alpha knock-on neutron tail during planned DT experiments on JET.

I. INTRODUCTION

In magnetic confinement fusion experiments, achieving ignition requires that the 3.5 MeV α particles from deuterium-tritium (DT) reactions deposit a large fraction of their energy in the reacting plasma before they are lost. The α's must be confined for a time scale longer than their classical slowing-down time (~1 s). Instabilities such as fishbones or TAE modes can lead to rapid α losses. Large sawteeth are observed to redistribute α's and can make ignition more difficult. The study of the physics of burning plasmas and alpha particle effects is an essential purpose of the planned DT experiments on JET and the proposed FIRE, IGNITOR and ITER projects. Because of the importance of α-particles in fusion research, a number of diagnostic techniques are under development.[2] All of the proposed techniques have limitations, especially when application to large tokamaks is concerned.

Measurements of the energetic knock-on tails resulting from alpha particle-fuel ion collisions have been proposed to provide information on the spatial and energy distributions of fast confined α's in fusion plasmas.[1] Preliminary experimental observations of the knock-on tails have been reported on JET using two approaches. Evidence of an energetic tail is observed in the neutron energy spectra measured by a magnetic proton recoil spectrometer.[3] In a second approach that we first proposed[1] in 1994, energetic neutrals that result from the charge exchange interactions of the knock-on fuel ion tails with intrinsic impurities in JET have been observed using a high-energy neutral particle analyzer.

This paper will describe the results of our research on using bubble neutron detectors for measurements of the knock-on DT neutron tail. The strengths of this approach include the ability to gain information on the alphas in the hot plasma core where the interesting ignition physics will occur, and the relative ease of implementation of the bubble neutron detector technique. Prospects for successful knock-on neutron tail measurements on JET look promising.

II. PRODUCTION OF KNOCK-ON TAILS

The presence of α-particles in a DT fusion plasma will produce energetic tails on both the deuterium and tritium plasma ion distributions due to high energy transfer or knock-on elastic scattering collisions between the α's and the plasma ions. A 3.5 MeV α-particle can create a 3.4 MeV tritium ion or a 3.1 MeV deuterium ion in a single collision. Previous papers[1] present the results of calculations of the fuel ion energy distributions in a tokamak due to alpha knock-on collisions. The alpha-induced knock-on ion tails become larger than the Maxwellian thermal ion populations at ion energies above ~250 keV. Under plasma conditions near those needed for fusion ignition, the alpha-induced knock-on tritium ion tail is several times larger than the 1 MeV tritons from D–D fusion reactions. Hence measurement of the ion tail can be used to learn about the α's. The knock-on tail produced in the deuterium ion distribution is similar in size.

Some of the resulting energetic fuel ions will undergo DT fusion reactions with the background plasma, producing neutrons with energies significantly above 14 MeV due to the excess kinetic energy of the reacting ions in the center-of-mass frame. As discussed in earlier papers,[1] the DT neutron energy spectrum above ~15.5 MeV is dominated by neutrons resulting from the α knock-on collision effects. The magnitude of the energetic neutron tail is linearly proportional to the α population at the spatial location where the neutrons are generated. Measurements of the neutron energy spectrum can be unfolded to obtain information on the α energy spectrum. Note that the knock-on neutron tail is very small, with only $\sim 2 \times 10^{-4}$ of the total DT neutrons above 15.5 MeV for a tokamak under plasma conditions near those needed for fusion ignition.

III. BUBBLE DETECTORS

Previous studies examined a number of neutron spectroscopy techniques for knock-on tail measurements,[1,4] including magnetic proton recoil spectrometers,[5] time-of-flight spectrometers,[6] and threshold neutron activation detectors. This paper describes research on a new approach, the bubble detector (BD), which in principle appears to be an almost ideal candidate detector for measurement of the knock-on neutron tails from DT plasmas.[7] BD's should be nearly totally insensitive to the much larger flux of 14 MeV neutrons from the plasma and gamma rays created by (n,γ) reactions in the surrounding structures and yet have a high detection efficiency for neutrons above a threshold energy, which is controlled by the detector operating temperature.

The BD's used to measure knock-on neutrons will be a customized version of the bubble detectors used as personnel neutron dosimeters and sold commercially by Bubble Technology Industries (BTI) in Chalk River, Ontario, Canada. The BTI detectors consist of ~ 10,000 one hundred micron diameter drops of a superheated liquid suspended in an elastic polymer matrix so that the neutron-induced bubbles last for weeks rather than milliseconds. The BTI detectors operate at atmospheric pressure. There is no requirement for an external magnetic field on the bubble chambers since there are no charged particle tracks to measure. The information on the neutron energy comes entirely from the neutron threshold energy condition.

The neutron energy threshold results in the incident neutrons either creating zero or one bubble. Bubble production[8] requires that sufficient heat (critical energy ~1000's of eV) be deposited in a very short distance (critical radius ~10^{-6} cm), locally increasing the vapor pressure of the superheated liquid above the external pressure of one atmosphere. The bubble formation only involves a few thousand atoms. Only the recoil fluorine ions resulting from near head-on collisions by the incident neutrons can produce bubbles as described below. The BTI detectors utilize a freon-like superheated liquid whose composition they keep proprietary. The incident neutrons collide with the atoms in the drops of superheated liquid, creating recoil fluorine and carbon ions of energy $E_A = E_n (4A \cos^2 \theta_A)/(1+A)^2$, where A is the mass of the recoil ion and θ_A is the angle of emission of the recoil ion with respect to the incident neutron direction. Figure 1 shows the specific energy loss dE/dx for the maximum energy recoil fluorine ion that can result from a head-on collision ($E_F^{max} \cong 0.19\ E_n$ at $\theta_A = 0°$) as a function of the incident neutron energy. The recoil carbon ions that also result from neutron collisions, although more energetic than fluorine due to their lower mass, do not produce bubbles because their dE/dx is too small. Similarly, the recoil electrons normally associated with bubble and track production in more conventional bubble chambers do not have sufficient energy to produce bubbles. Hence, only the recoil fluorine ions create bubbles. Since dE/dx is an increasing function of the recoil fluorine ion energy in this energy range as shown in Fig. 1, only neutrons above the threshold energy can produce bubbles.

Bubble detectors are also nearly insensitive to the large background flux of gamma rays resulting from neutron capture reactions in structures surrounding the tokamak. Gamma rays of energies up to 14 MeV will produce electrons via pair production and or Compton scattering. But the resultant electrons have a dE/dx which is too small to create bubbles. In a test of a similar bubble chamber[9] used to detect 2.5 MeV neutrons from D–D plasmas, the measured gamma sensitivity was $\sim 10^{-12}$ of the neutron sensitivity. BTI reports that their bubble detectors show no response to 250 rads of ^{60}Co gamma- rays, or a gamma detection sensitivity of $\leq 10^{-14}$ bubbles per incident gamma ray.

The neutron detection efficiency increases rapidly above the threshold and can be approximated[7] as $\varepsilon_{BD} \simeq (1 - E_{th}/E_n)\ \varepsilon_{BD}^{max}$. The BTI quoted neutron response of $\varepsilon_{BD}^{max} \sim 6 \cdot 10^{-5}$ bubbles per n/cm^2 at energies well above threshold is consistent with the detector thickness of ~ 1 cm, and a packing fraction = volume of supercritical liquid to total volume including polymer support matrix $\approx 5 \cdot 10^{-3}$.

Bubble detectors require careful control of their operating temperature. Bubble formation requires supplying enough energy deposition by the recoil ion from the neutron collision to locally increase the detector liquid vapor pressure above the external pressure (~ 1 atm). Since the vapor pressure is a very strong function of temperature, small changes in the detector

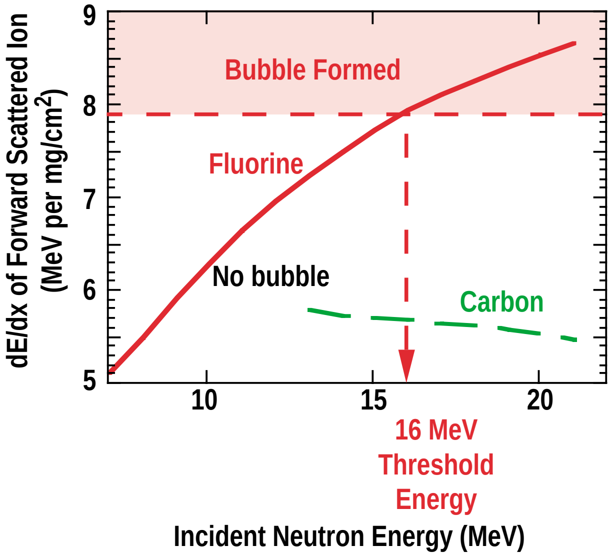

FIG. 1. Calculated specific energy loss dE/dx for the maximum energy recoil ^{19}F and ^{12}C ions versus the incident neutron energy. Only ^{19}F has high enough dE/dx to create bubbles in the 12 to 20 MeV energy range of interest.

operating temperature can result in a large change in the energy deposition required and hence in the detector energy threshold. The variation in the threshold is ~ 0.3 MeV per °C. Hence, control of the detector operating temperature to ~ 0.3°C is required to keep the threshold variation of the order of 0.1 MeV.

IV. MEASUREMENTS ON TFTR AND JET

Standard BTI detectors are designed to operate at room temperature, and are available “off-the-shelf” with thresholds between 10 keV and 10 MeV. They use different mixtures of two fluorocarbons with different critical energies and radii for bubble formation to control the neutron energy threshold. Custom versions of these detectors designed to have energy thresholds of 14, 15, 16, 17, and 18 MeV were tested on TFTR and JET DT plasmas.

The detectors were placed inside an enclosure designed to keep them at fixed temperature. Water from a constant temperature circulator bath set at 24°C was continuously circulated through the walls of the enclosure. Since access to the detectors was not possible during the tokamak run day, this data was integrated over one or more days of tokamak operations. Figure 2 shows the observed number of bubbles plotted versus the design neutron energy threshold for the detectors after a three-day exposure to high power neutral-beam heated DT discharges in JET. The “14 MeV” detectors were usually saturated with bubbles, the “15 MeV” detectors usually showed hundreds of bubbles, and the “16 MeV” detectors had tens of bubbles or less. No bubbles were observed in the 17 and 18 MeV detectors.

Also shown in Fig. 2 is the expected number of bubbles, with the alpha-induced knock-on tail appearing above ~16 MeV. The measured signals (solid triangles) fell with increasing threshold, but the observed numbers of bubbles in the neutron tail region were significantly larger than predicted (small open circles). We will return to the discussion of Fig. 2 in Section VI.

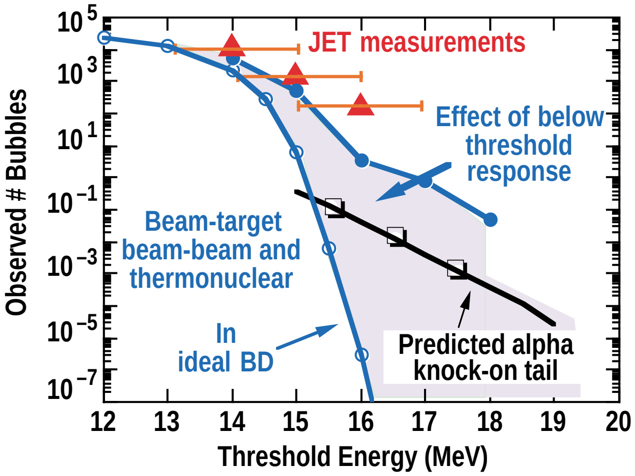

FIG. 2. Measured response of standard two-gas bubble detectors on JET (triangles) is much larger than calculated response of an ideal bubble detector to beam-target, beam-beam, and thermonuclear neutrons (open circles) and alpha knock-on tail (squares). Effect below-threshold response (shaded region) in standard two-gas detectors calculated using the spontaneous nucleation measurements of Fig. 3 increases their predicted response to beam-target, beam-beam, and thermonuclear neutrons (closed circles), and shows that single-gas detectors must be used to observe knock-on tails.

V. CALIBRATION AT ACCELERATOR NEUTRON SOURCES

Time constraints prevented measuring the detector neutron responses until after the DT operations on TFTR and JET. The initial calibration experiments were performed at the Ohio University Edwards Accelerator Laboratory in Athens, Ohio. The 7 MeV Tandem Van deGraaff was run with a D-beam into a T-gas target, producing neutrons with energies between 12 and 25 MeV. While the measured efficiencies well above threshold were of the order of magnitude of the expected values, the detector response data did show the expected rapid fall in the neutron response at the predicted threshold energy. It became clear that obtaining a better understanding of the detector responses would be impractical at the neutron flux levels available using the Ohio University Van deGraff, requiring an exposure of several hours or even days at each neutron energy near threshold.

The Rotating Target Neutron Source (RTNS) at the University of California, Berkeley operates at much higher D-beam currents and is capable of producing up to $6{\cdot}10^{12}$ n/s, which is several hundred times larger than is possible at Ohio University. The upper limit on the neutron energy is approximately 15.2 MeV, due to the approximately 230 keV limit on the D-beam energy. The neutron energy spectrum is comparable to that of a neutral beam-heated tokamak, but without the knock-on tail due to the fusion alphas. Hence RTNS appears ideally suited to look for a response to neutrons with energies below the bubble detector threshold energy.

Measurements were taken at a neutron energy of 15.2 MeV. The detector temperatures were kept at 24°C, as they had been for the JET data and for the most interesting TFTR data. As expected, the measured response of the nominal “17 MeV” and “18 MeV” design threshold detectors was zero. But the responses in the individual “16 MeV” design threshold detectors to 15.2 MeV neutrons from RTNS showed that the detectors were responding to neutrons with energies below the nominal detector threshold energy. The RTNS data provided the first clear indication that the individual ~100 μm diameter drops of superheated bubble detector liquid suspended in the gel may not all have the same effective threshold**.**

VI. SPONTANEOUS NUCLEATION MEASUREMENTS

Spontaneous nucleation of bubbles occurs at very high temperatures, where the local thermal density fluctuations in the liquid density can create clusters of vapor “holes” that reach the critical radius and spontaneously result in a bubble. No neutrons are required. The temperature at which spontaneous nucleation occurs is an indication of the heat deposition required for bubble formation, and hence of the neutron energy threshold for a given detector. We increased the temperature in small steps between 80° and 100°C, and looked for the onset of bubbles. Ideally, all the bubbles will appear within a temperature increase of ~ 0.1°C, which corresponds to a variation in threshold energies of ~ 100 keV. If bubbles spontaneously appear in some of the individual drops of superheated bubble detector liquid at much lower temperatures than others, we would know that they did not have similar heat deposition requirements.

The right hand portion of Fig. 3 shows the results of our spontaneous nucleation measurements on the standard two-liquid detectors that were used in the TFTR and JET measurements. Their design threshold was 15 MeV. The first bubbles appeared at 83°C. The number of additional bubbles rose slowly as we gradually increased the detector temperature. Above 90°C, the number of spontaneous nucleation bubbles began to rise much faster, until the majority (~99%) of the 100 μm diameter detector drops nucleated at ~ 94°C. Measurements performed on the standard two-gas detectors with design thresholds of 14 and 16 MeV showed very similar results, with a small fraction of the detector drops forming bubbles at temperatures several degrees lower than the spontaneous nucleation temperatures for these detectors.

The measured spontaneous nucleation temperatures for the different design threshold detectors were found to increase by ~ 3°C for each MeV of predicted threshold increase. This slope can be used to convert the horizontal axis of Fig. 3 into threshold energy (lowest axis label). The predicted detector response including the effect of the gas mixture variation on the thresholds is $\varepsilon_{BD} \simeq \sum f_d(E_{th})(1 - E_{th}/E)\ \varepsilon_{BD}^{max}$, where the fraction f_d (E_{th}) of the number of

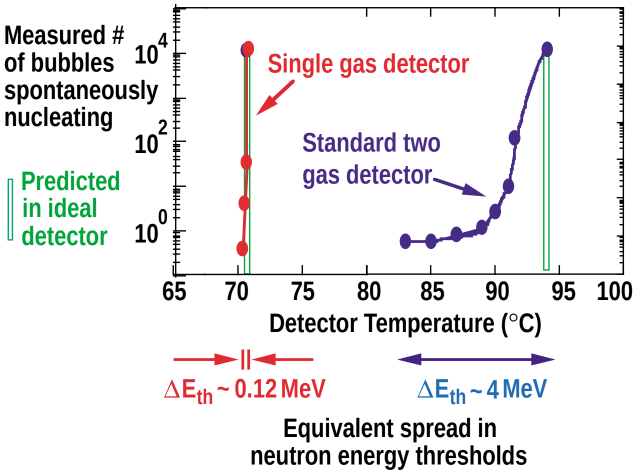

FIG. 3. Spontaneous nucleation measurements on standard two-gas detectors and on single-gas detectors. Single-gas detectors show a very sharp threshold ΔE_{th} *~ 0.12 MeV which is less than the ~0.5 MeV required for alpha knock-on measurements.*

detector drops having a given threshold energy is obtained from the data in Fig. 3. The effect of the variation in the thresholds due to the variation in the liquid mixture effectively acts like a "below threshold response" in the standard two-liquid detectors. Returning to Fig. 2, this "below threshold response" (shaded region) to the beam-target, beam-beam, and thermonuclear neutrons is much larger than the predicted alpha knock-on tail signal, and can explain the larger than expected signals in the tokamak data for the higher threshold detectors. Successful measurements of the alpha knock-on neutron tail will require single liquid bubble detectors, as described in the next section.

VII. SINGLE LIQUID BUBBLE DETECTORS

All of the measurements described so far have been performed on bubble detectors that are made using a mixture of superheated liquids to determine their neutron energy threshold. These two-liquid detectors are all designed to operate at atmospheric pressure and near room temperature, yet can have different neutron thresholds by varying the mixture of the two liquids. Unfortunately, slight variations in the liquid mixture during production of the standard two-liquid detectors are unavoidable, and make them unusable for alpha knock-on measurements. In discussing these problems with BTI, we learned that they can also manufacture detectors using a single liquid. These single-liquid detectors will require varying their operating temperature to vary their threshold. But their response should not vary between detectors or between drops within a detector.

Spontaneous nucleation data on single liquid detectors, shown in the left hand portion of Fig. 3, shows a much narrower variation in the drop thresholds than two-liquid detectors. No bubbles appeared in the single liquid detectors until the detector temperature was within ~ 0.3°C of the spontaneous nucleation temperature. This is equivalent to a variation in the drop thresholds of ~ 0.1 MeV, much less than the ~ 0.5 MeV required for knock-on measurements.

Single liquid detectors can be made using either of the two liquids used in the standard BTI detectors. Using the maximum available heat deposition as a function of neutron energy together with the bubble formation physics, BTI has calculated the bubble detector operating temperature required so that bubbles should only result from neutrons at or above that energy. The calculated neutron threshold energies for two different BD design choices is shown as a function of their operating temperatures in Fig. 4. The required operating temperature for detectors using the more volatile liquid is expected to lie in the range of 3 to 14°C, while a detector based on the higher volatility liquid would have an expected operating temperature range between 34 and 45°C. The thresholds of both detectors should change by ~ 0.3 MeV°C.

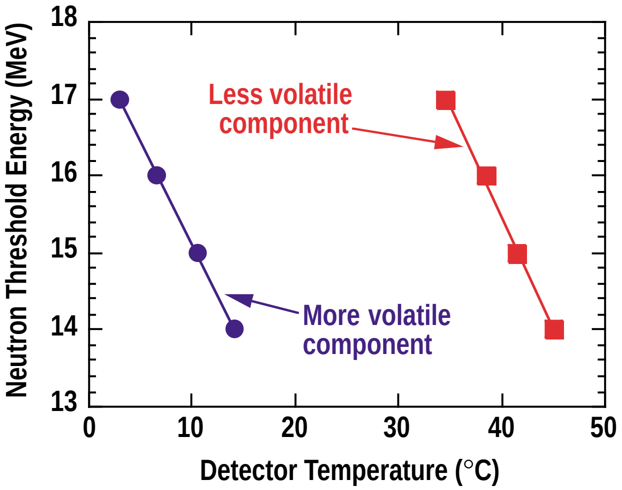

FIG. 4. Calculated neutron energy thresholds as a function of the detector operating temperature of single-liquid detectors made from the two components used in the standard two-liquid BTI detectors.

Using an array of several single-liquid detectors with each detector held at a different known operating temperature, it should be possible to measure the DT neutron spectra and the alpha-induced knock-on tail on JET and other DT tokamaks. With JET DT operations not scheduled to begin until 2002 or later, we will be able to thoroughly characterize the single-liquid detectors and prepare for measurements on JET.

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