Observations of the T(T,n)^{5}He resonance in NBI heated fusion plasmas

B. Eriksson[1], G. Ericsson[1], J. Eriksson[1], A. Hjalmarsson[1], S. Conroy[1],
C. Brune[2], M. G. Johnson[3], JET contributors[4]

[1]*Department of Physics and Astronomy, Uppsala University, Uppsala, Sweden*

[2]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701, USA*

[3]*Massachusetts Institute of Technology, Cambridge, MA 02139, USA*

[4]*See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al. 2022 Nucl. Fusion 62 042026*

Abstract

The Joint European Torus (JET) has recently performed experiments [4] with fusion plasmas consisting of a majority of tritium (T) with trace amounts of deuterium (D), heated using neutral beam injection (NBI) with T ions. The dominating reactions for fusion plasmas with high T/D fuel density ratios are the $\mathrm{D}+\mathrm{T} \rightarrow {}^4\mathrm{He}+\mathrm{n}$ and $\mathrm{T}+\mathrm{T} \rightarrow {}^4\mathrm{He}+2\mathrm{n}$ reactions. Due to the 3-body end state of the TT reaction, neutrons with a broad continuum of energies are produced. The TT reaction has been shown to go via an intermediate resonant state, $\mathrm{T}+\mathrm{T} \rightarrow {}^5\mathrm{He}+\mathrm{n}$, which promptly decays via ${}^5\mathrm{He} \rightarrow {}^4\mathrm{He}+\mathrm{n}$. Using the neutron time-of-flight spectrometer TOFOR at JET, we present experimental neutron spectra of the TT reaction, and, applying R-matrix formalism to model the neutron energy spectrum, show that our results are consistent with measurements at the National Ignition Facility (NIF).

Introduction

The Joint European Torus (JET) has recently performed experiments employing fusion plasmas with high fuel ion density ratios, $n_\mathrm{T}/(n_\mathrm{T}+n_\mathrm{D}) \sim 0.99$, offering the opportunity to study the T + T $\rightarrow$ ^{4}He + 2n reaction. Given the three-body end state, the reaction produces a wide distribution of α-particle and neutron energies. The reaction has been observed to go via an intermediate two-body state involving a neutron and a ^{5}He nucleus, which decays to form the final three-body state. Measurements of the neutron emission energy spectrum have been conducted at JET using the TOFOR [3, 5] time-of-flight (TOF) neutron spectrometer observing reactions at an average center-of-momentum (CM) energy $E_\mathrm{CM} = 45$ keV. We present here experimental evidence which is consistent with the various neutron emission energy distributions associated with the T + T reaction branches modeled using an R-matrix framework developed in [1].

Theoretical background

The R-matrix model [1] describing the neutron emission components treats the T + T reaction for two different cases: the first case is referred to as dineutron emission (nn) where the reaction occurs through α-particle emission and two neutrons. The three-body end state of the reaction yields a broad spectrum of neutron energies, shown as the green dash-dotted line in panel (a) of figure 1. The second case, referred to as nα emission, makes use of sequential two-body decays where an intermediate state of ^{5}He + n is followed by $^5\text{He} \rightarrow \alpha$ + n. The model assumes an initial spin and parity state of $J^P = 0^+$, and considers transitions with orbital angular momenta $l = \{0, 1\}$ yielding three partial waves $1/2^+$, $1/2^-$, and $3/2^-$. The $3/2^-$ and $1/2^-$ partial waves are resonant states corresponding to the ground state and first excited state of ^{5}He. These are expected to contribute significantly to the neutron emission spectrum, as shown by the blue short dashed and red dotted lines in panel (a) of figure 1. The $1/2^+$ partial wave is non-resonant and contributes less to the neutron emission spectrum, as can be seen by the cyan loosely dotted line in panel (b). The amplitudes of the partial waves are determined using two levels of feeding factors (A_1, A_2) as indicated in the table shown externally [2]. The component due to the interference between partial wave combinations is shown as the black dash-dotted line in panel (b).

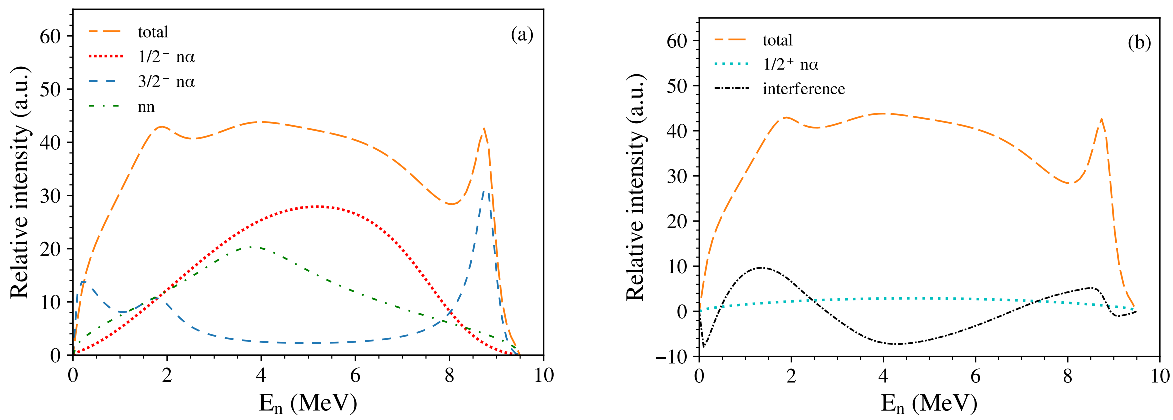

Figure 1: Modeled T + T neutron emission energy spectrum (orange dashed lines visible in both panels), including the contributions from the partial waves and the net interference between the partial waves. Feeding factor values here correspond to fit 16 in the external table [2].

Methods

Measurements using TOFOR have been performed of 90 experimental discharges at JET with T majority plasmas, $n_T/(n_T + n_D) \sim 0.99$, heated with T neutral beam injection (NBI). The discharges are selected from a broad set of experiments with plasma currents ranging from 1.3-2.6 MA (with a majority around 2.3 MA), toroidal B-fields in the range 1.7-3.4 T (with a majority around 2.5 T), and average NBI power in the range 1-17 MW (with a majority of the discharges around 10 MW). The TOFOR data for the experimental discharges is summed to ensure that sufficient counts are gathered to discern the spectral features of interest in the

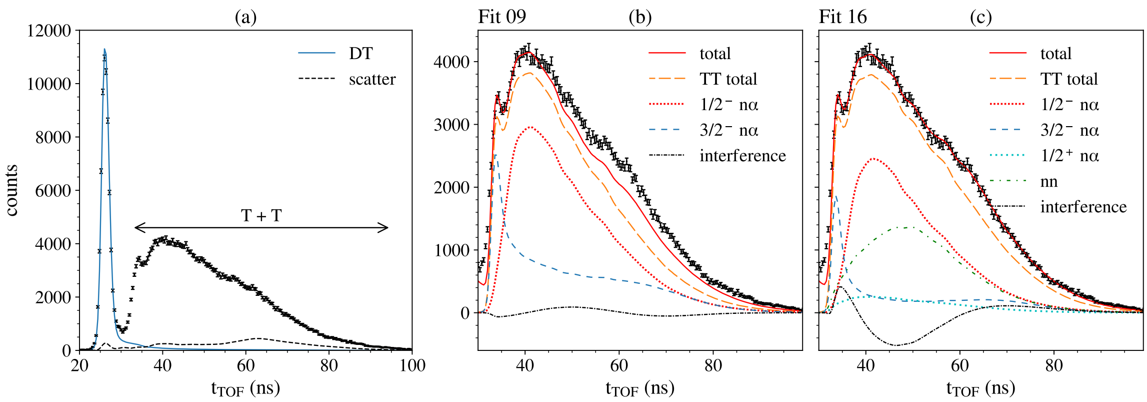

Figure 2: Neutron time-of-flight spectrum measured by TOFOR (black points) with (a) the DT (blue line) and scatter component (black dash-dotted line) applied. The TOF region of interest for T + T neutrons is indicated in the figure and has been expanded in (b) where fit 09 is applied and (c) where fit 16 is applied. The details of the applied components are described in the text.

neutron emission energy spectrum. The data is treated using the methods outlined in [3], and includes background suppression techniques. Two models, denoted fit 09 and fit 16, used in [1] to fit data from the National Ignition Facility (NIF) are considered with the feeding factor values shown in the external table [2]. For fit 09 the $1/2^+$ nα and dineutron emission components are disabled. Fit 16 utilizes all components except the secondary feeding factor for the $1/2^+$ partial wave.

Results

The spectrum acquired with TOFOR for the JET discharges is shown as the black points in figure 2. The 14 MeV DT neutron peak is visible in panel (a) at 27 ns with a fit (blue line) and a component from neutrons scattering on the JET machine into our sightline (black dashed line). TT neutrons are expected in the broad region above 30 ns indicated by the arrow; the region has been expanded in panels (b) and (c). The neutron energy distributions from fit 09 and fit 16 are folded with the TOFOR detector response function, yielding the modeled TT TOF spectrum shown in panels (b) and (c) as the orange wide dashed line. The partial wave components used in the total TT TOF spectrum are included in the panels with the same line styles as in figure 1. The total modeled TOF spectra in panels (b) and (c), shown as the red lines, consist of the different partial wave contributions as well as the DT and scatter component in panel (a).

Conclusions and discussion

Two models of the TT neutron emission energy spectrum, fit 09 and fit 16, used in [1] to fit experimental neutron spectra from NIF, are applied to TOFOR data. We show that fit 16 adequately describes our data without modifications. It should be noted that we have not attempted to find the optimal feeding factor values to determine the shape of the TT neutron spectrum which best describes our data. No fitting is performed in panels (b) and (c) of figure 2 besides a vertical scaling of the total TT spectra. The prominent peak from the intermediate reaction involving the ^{5}He ground state is well described by the $3/2^-$ nα component in both panels (b) and (c), whereas the low energy (high TOF) part of the experimental spectrum requires the inclusion of the dineutron emission component. The interference component has a significant impact on the modeled spectrum. A possible energy dependence of the spectral shape is reported in [6] where the relative intensity of the $3/2^-$ ground state ^{5}He component is observed to increase with CM energy. Investigations of the energy dependence using data from JET will be the subject of future work as well as a detailed fit of the feeding factors to TOFOR data.

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