Neutron emission from a tritium rich fusion plasma: simulations in view of a possible future d-t campaign at JET

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Abstract

Neutron energy spectra from the t(t,2n)^{4}He (t-t) reaction has been calculated for different fuel ion distributions, in order to assess the possibility to use this reaction when analyzing neutron spectrometry data from plasmas with very high tritium fraction. The shape of the neutron spectrum is determined by three-body kinematics, and is modified by interactions between the reaction products, primarily between the neutron and the ^{4}He. The results indicate that the analysis of a t-t spectrum will be more challenging than for the d-t and d-d reactions. However, for fast ions in the MeV range, produced e.g. by harmonic radiofrequency heating and neutral beam injection, it should still be possible to obtain fast ion information from the neutron spectrum.

Introduction

One possible approach to a future full power deuterium-tritium campaign at JET is to go from a pure hydrogen phase to a pure tritium phase and then gradually increase the deuterium concentration to a 50/50 d-t mixture. This approach is the opposite to the previous d-t campaign at JET in 1997, and would allow for the study of isotope effects in various plasma scenarios.

The behavior and confinement of fast ions will be of great interest in a possible d-t campaign and neutron emission spectrometry is one technique that can provide such information. By measuring the energy spectrum of neutrons emitted from the fusion reactions it is possible to get information about the motion of the fuel ions. JET has spectrometry capabilities which have been used to study fast ions from both the d(d,n)^{3}He (d-d) reaction [1] and the t(d,n)^{4}He (d-t) reaction [2]. The emission from the t(t,2n)^{4}He (t-t) reaction, which has a cross section comparable to the d-d reaction, is normally of little importance since it will be drowned by neutrons from the much more probable d-t reaction. However, for a plasma with very high tritium fraction, signatures of t-t neutrons can show up in the neutron spectrum.

In contrast to the d-t and d-d reactions, the t-t reaction has three particles in the final state, which results in a continuum of neutron energies being produced, even for mono-energetic reactants. The neutron energy spectrum has been measured in accelerator experiments [3, 4] and in inertial confinement fusion experiments [5]. In the accelerator experiments, where the center-of-mass energies were in the 100 keV range, clear indications of interactions between the particles in the final state were observed. The three-body neutron energy continuum, ranging between 0 and 9.4 MeV, was distorted by a peak around 8.7 MeV due to the interaction between the ^{4}He and one of the neutrons. Effects of neutron-neutron interaction was also seen, but on a smaller scale. However, in the inertial confinement fusion experiments, with center-of-mass energies around 20 keV, no signs of final state interactions could be seen, indicating an energy dependence in the importance of these interactions.

This paper presents calculations of the shape of the neutron energy spectrum from the t-t reaction for various JET relevant fuel ion distributions. The idea is to form a starting point for exploiting the t-t reaction in future d-t experiments, by investigating which type of fast ion distributions that can be expected to give clear signatures in the neutron spectrum.

Modelling the t-t neutron emission

From four-momentum conservation, the following equation for the neutron energy E_{n} can be written down:

$$E_{\mathrm{n}} - \left(E_{\mathrm{n}}^2 - m_{\mathrm{n}}^2\right)^{1/2} \frac{\mathbf{p}_0}{E_0} \cdot \mathbf{u} = \frac{m_0^2 + m_{\mathrm{n}}^2 - m_{\mathrm{res}}^2}{2E_0}. \tag{1}$$

Here, E_0 and $\mathbf{p}_0$ are the total energy and momentum of the reacting particles, $m_0 = (E_0^2 - p_0^2)^{1/2}$ the so-called invariant mass, $\mathbf{u}$ the neutron emission direction, and m_{res} is the invariant mass of the residual particles. The neutron energy spectrum can be calculated by integrating this expression over the reactant velocity distributions and the reaction cross section. In this paper the integration is performed by means of a Monte-Carlo simulation.

If there is only one residual particle, which is the case in the d-t and d-d reactions, m_{res} is simply the rest mass of that particle, but for the t-t reaction there is one more degree of freedom due to the three body final state and m_{res} can take on a continuous set of values between $(m_{\mathrm{n}} + m_{4\mathrm{He}})$ and $(m_0 - m_{\mathrm{n}})$ [6]. If there is no interactions between the particles in the final state, the distribution in m_{res} can be obtained from the available phase space (see e.g. [6]).

However, as described in the introduction, there is evidence that the t-t neutron spectrum is significantly affected by interactions between the particles in the final state, at least for center-of-mass energies in the 100 keV range (which is not uncommon for fast particles at JET). We consider here only the n-^{4}He interaction, since this was seen to be the most prominent effect in the experiments. In this reaction channel, the neutron and the ^{4}He form a short lived ^{5}He resonance, and the invariant mass distribution is taken to be a Breit-Wigner distribution,

$$f\left(m_{\mathrm{res}}\right) = \frac{1}{\left(m_{\mathrm{res}} - \hat{m}\right)^2 + \Gamma^2/4}, \tag{2}$$

where the decay width $\Gamma = 648$ keV and $\hat{m} = 4.67$ GeV/c^2 [7].

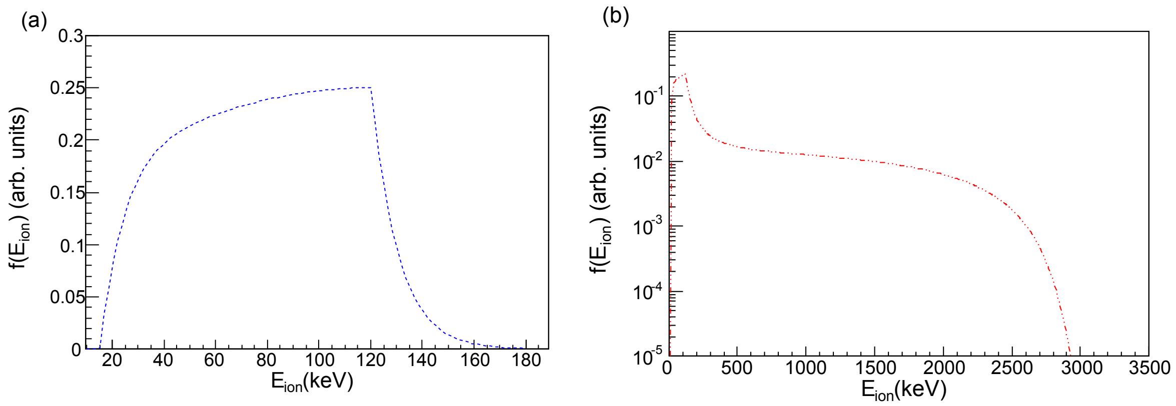

Figure 1: Fast ion distributions used in the neutron spectrum calculations. (a) is a NBI slowing-down distribution and (b) is a distribution from 3rd harmonic ICRH and NBI.

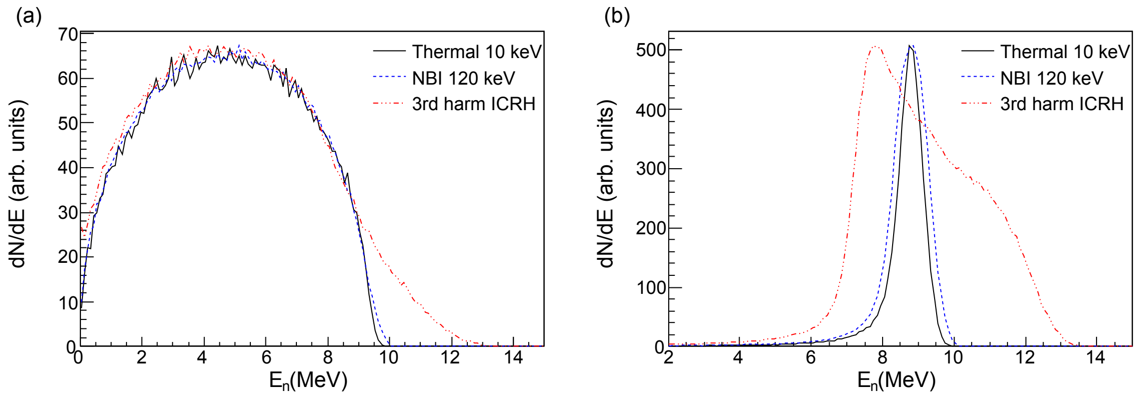

Figure 2: Calculated neutron energy spectra from the $t(t,2n)^4He$ reaction for different fuel ion distributions. (a) is the three-body continuum and (b) is the peak that is obtained when a ^5He resonance is produced. The spectra have been normalized to the same peak intensity.

Neutron spectra were calculated for a thermal tritium plasma at 10 keV, for a tritium neutral beam (NBI) slowing down distribution, and for a distribution arising from the combination of NBI and 3rd harmonic ion cyclotron resonance heating (ICRH). The two latter distributions, shown in Figure 1, were obtained from a 1D Fokker-Planck equation derived in [8], which has been previously used for neutron spectrometry analysis e.g. in [1]. When calculating the distributions it was assumed that the NBI delivered 10^{19} tritons/m^3 to the plasma, with an energy of 120 keV, and that 0.5 MW/m^3 was delivered by the ICRF. Only reactions between the fast ions and the bulk plasma were considered in the calculations.

Results

Examples of calculated spectra are shown in Figure 2, for a viewing angle perpendicular to the toroidal magnetic field of the tokamak. Two graphs are shown, (a) is the broad three-body continuum that arises when no interaction takes place between the reaction products and (b) is the more peaked spectrum that is obtained when the ^4He interacts with one of the neutron and forms a ^5He resonance, as described above.

Discussion and conclusion

In order to obtain fast ion information from a neutron spectrum one must be able to distinguish between the different spectral components. The results presented in Figure 2 indicate two features of the t-t reaction that makes this separation harder than for the d-t and d-d reactions.

First, the three-body continuum has similar shape regardless of the fuel ion distributions, the only difference shows up in the high neutron energy tail. In the presence of background and down-scattered neutrons from the d-t reaction (which produces neutrons around 14 MeV) these differences might difficult to resolve. The three-body component could probably serve as an indicator of t-t reactions, but not to obtain fast ion information.

Second, the spectral features of the ^{5}He-peak are "smeared out" by the decay width of the ^{5}He. This effect is evident when comparing the thermal and NBI peaks, which have very similar shapes and would therefore be difficult to separate from each other in a measured neutron spectrum. However, the results from [5] indicate that the thermal component could be very weak, so this separation might not be needed. Also, the spectrum from 3rd harmonic ICRH has a quite different shape and should be possible to separate from the thermal emission, if present.

The poorly known branching ratio between the three-body and resonance components will also add some complexity to the analysis. It might be necessary to include the energy dependence as an additional parameter when analyzing the data.

In summary, this paper has presented the start of an investigation about the possibility to exploit the t-t reaction in d-t experiments with high tritium fraction. The results indicate that the spectral analysis of a t-t neutron spectrum is more challenging than for the d-t and d-d reactions, but that fast ion information could still be obtainable if the fast ions have high enough energies, such as NBI ions accelerated by harmonic ICRH.

Acknowledgments

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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