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The effects of ion temperature on the energy spectra of $T+T \rightarrow 2n+\alpha$ reaction products

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ABSTRACT

The effects of ion temperature on the energy spectra of products of the $T+T \rightarrow 2n+\alpha$ reaction are modelled and analysed. A model is derived by assuming that the spectra in the centre of mass (CM) frame for a given reaction energy are known. The model is then applied to two different sets of data for the energy spectra in the CM frame. In both cases, it is shown that varying the ion temperature causes significant changes in the shapes of the n and α spectra. For the n spectrum, the apparent intensity of sequential decay through the ground state of ^5He decreases with increasing temperature. For the α spectrum, the sharp edge in the CM frame spectrum near $3.75MeV$ caused by the dineutron reaction channel results in a thermally broadened spectrum with a high-energy tail at energies $> 4MeV$. Knowledge of such features may help to interpret data from experiments designed to investigate the $T+T$ reaction at low reaction energies.

1. Introduction

The $T+T \rightarrow 2n+\alpha$ (TT) reaction is of interest for a number of reasons. It is one of the principal sources of neutrons in inertial confinement fusion (ICF) experiments, together with the $D+T \rightarrow n+\alpha$ (DT) and $D+D \rightarrow n+{}^3He$ (DD) reactions. The TT reaction is also related to the ${}^3He+{}^3He \rightarrow 2p+\alpha$ via isospin symmetry. This reaction is the dominant energy-producing step in the solar proton–proton chain [1], and so studying the TT reaction can improve our knowledge of stellar nucleosynthesis.

The TT reaction produces three particles in the final state. This results in product energy spectra that are broad with a number of features that depend on the intermediate states through which the reaction proceeds. This is in contrast to the DT and DD reactions that are two-body reactions and so neutrons are produced in the CM frame with a specific energy. The only source of spectral broadening for these reactions is due to motion of the reactants. The shape of the TT spectra depends on both the motion of reactant particles and the intermediate states of the reaction. The reaction channels of interest in the TT reaction are as follows

$$T+T \rightarrow n+n+\alpha,$$

$$T+T \rightarrow n+{}^5He\,(GS),$$

$$T+T \rightarrow n+{}^5He\,(ES),$$

where (GS) denotes the ground state of a ^5He nucleus and (ES) denotes the first excited state. The Q value for the reaction is $11.33MeV$. The neutrons produced from each channel have different spectral features. The $n+n+\alpha$ channel (referred to as the dineutron channel) results in neutrons distributed broadly between 0 and $9.4MeV$ with a peak just below $4MeV$. The ${}^5He\,(GS)$ channel produces a spectrum peak at $8.7MeV$ while the ${}^5He\,(ES)$ channel produces a broad, near-elliptical neutron spectrum. Further details of the different spectral features, for both the n and α particles, may be found in the recent work of Brune et al. [2].

A major question regarding the TT reaction is the relative strengths of the reaction channels and how the relative strength varies with reaction energy. This has been the focus of much research. Experiments using an accelerator suggested that at a reaction energy of $250keV$ the relative strengths of the different channels were 0.7, 0.2 and 0.1 for the dineutron, ${}^5He\,(GS)$ and ${}^5He\,(ES)$, respectively [3], while experiments at a reaction energy of $110keV$ suggested that the relative strengths to two significant figures were 0.95, 0.05 and 0.00 [4]. More recently, the TT reaction has investigated using laser-driven spherical capsule implosion experiments. In one set of such experiments it was concluded that there was a negligible ${}^5He\,(GS)$ channel at a mean reaction energy of $23keV$ since no peak in the neutron spectrum near $8.7MeV$ was detected [5]. However, another

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set of experiments at a mean reaction energy of 16*keV* did observe such a peak [6] and this result was supported by theoretical calculations [2]. The lack of clear trends in existing experimental data highlights the need for further investigation of the *TT* reaction.

The use of inertial confinement implosions for the investigation of nuclear reactions is a relatively new technique that offers a number of advantages over conventional accelerator based approaches [7]. The reactions take place in a thermonuclear plasma rather than the beam-target system of an accelerator. This means that particle fluxes are significantly higher and it is easier to access lower reaction energies. Furthermore, free electron screening in the thermonuclear plasma means that inertial confinement implosions are a much better model of the stellar environment than beam-target systems. However, the thermonuclear plasma environment also has a number of complications that are not present in accelerator experiments. The thermonuclear plasma contains a Maxwellian distribution of the reactant particle energies (characterised by the ion temperature) and, therefore, nuclear reactions cannot be investigated at a specific reaction energy but, instead, at a distribution of reaction energies. This also means that the energy spectra of product particles are affected by thermal broadening that must be accounted for when interpreting experimental data.

In addition, some of the key diagnostics in ICF experiments involve measurements of neutrons in the 3–10*MeV* range. For example, images of scattered *DT* neutrons with energies between 6 and 12*MeV* are used to study the shape and structure of cold fuel at stagnation [8], while the fuel areal density (ρR) can be inferred from *DT* neutrons that are scattered to energies below 6*MeV* [9]. Accurate interpretation of the data from these diagnostics requires a precise knowledge of the *TT* spectrum shape and intensity so that the contribution of *TT* neutrons to measured signals can be distinguished from scattered *DT* neutrons.

In this work we study the effect of thermal broadening on the *TT* product particle energy spectra. It is shown that thermal broadening can have a number of effects on both the spectra of neutron and α particles emitted by the reaction. Most notably, it is shown that thermal broadening can affect the apparent intensity of different features of the spectra even if the temperature does not change the relative strengths of the reaction channels. These effects may complicate the accurate identification of the relative strengths.

The contents of the paper are as follows. In Section 2, a semi-analytic expression for thermal broadening of the *TT* product particle spectrum is derived. In Sections 3 and 4, the major effects of thermal broadening on the neutron and α spectrum, respectively, are identified and quantified. Section 5 studies spectra produced by a multi-temperature plasma. Finally, some conclusions are discussed in Section 6.

2. Calculating thermal broadening of the *TT* product particle spectra

Thermal broadening in a Maxwellian plasma is due to two separate effects. First, the Maxwellian distribution of reactant velocities gives rise to a distribution of centre of mass (CM) frame velocities. This means that a given spectrum in the CM frame will have to be transformed into the lab frame according to this distribution of CM frame velocities in order to obtain the thermally broadened spectrum.

Secondly, the Maxwellian distribution of reactants gives rise to a distribution of reaction energies in the CM frame. The reaction energy, E_r, is defined by

$$E_r = \frac{1}{2}\mu v_r^2, \tag{1}$$

where μ is the reduced mass of the two reactant species and v_r is the relative velocity between a given pair of reactants. As mentioned in Section 1, the shape of the product particle spectra in the CM frame is a function of the reaction energy. Therefore, the spectrum in the CM frame is a weighted mean of the spectra corresponding to each reaction energy in the distribution. We note that in thermonuclear plasmas, a mean value for the reaction energy is often used when calculating reaction rates and product spectra. This mean reaction energy is referred to as the Gamow energy and is obtained by weighting the Maxwellian distribution with the barrier penetration factor [1]. In this work we use the distribution of reaction energies rather than the Gamow energy in order to improve accuracy of the calculations.

We quantify these two effects in the calculation that follows. The calculation is of a similar nature to those previously carried out for the neutron spectra from *DT* and *DD* reactions [10]. However, due to the presence of three particles in the final state, the calculation for spectra from *TT* reactions differs in a key manner. For reactions with two particles in the final state then, for a given pair of reactants, the product particles have a unique value of energy in the CM frame that is given by conservation of mass–energy. For reactions with three particles in the final state, the product particles have a distribution of energies in the CM frame for a given pair of reactants. We introduce a term $F_{E_r}(E_p', \theta_s)$ to account for this fact. This term represents the energy spectrum of product particles in the CM frame as a function of reaction energy and direction of emission. It can be obtained either from theoretical calculations or from existing experimental data. It is normalised such that:

$$\int F_{E_r}(E_p', \theta_s) dE_p' d\Omega_s = 1. \tag{2}$$

Here, E_p' represents product particle energy in the CM frame, θ_s represents the scattering angle of a product particle in the CM frame and $d\Omega_s$ is the unit of solid angle for this vector.

We start with the general expression:

$$\frac{dR}{dE_p' d\Omega_p'} = \frac{n_1 n_2}{1+\delta_{12}} v_r \sigma(E_r) F_{E_r}(E_p', \theta_{p'}) f_1(\mathbf{v_1}) f_2(\mathbf{v_2}) d^3\mathbf{v_1} d^3\mathbf{v_2}. \tag{3}$$

This expression represents the number of reactions occurring between reactants with velocities $\mathbf{v_1}$ and $\mathbf{v_2}$ per unit volume per unit time resulting in a product particle with an energy in the CM frame of E_p' and direction Ω'. Here, $\sigma(E_r)$ represents the cross-section for the reaction. The variables n_1 and n_2 are the reactant species number densities, $f_1(\mathbf{v_1})d^3\mathbf{v_1}$ and $f_2(\mathbf{v_2})d^3\mathbf{v_2}$ are the reactant distribution functions and $\delta_{12} = 1$ for intra-species reactions, 0 otherwise. We use non-relativistic kinematics throughout. Although, it has been shown that a relativistic treatment introduces non-negligible corrections [11,12], these corrections are significantly smaller than the effects of thermal broadening that we identify here.

We choose both reactant distribution functions to be Maxwellian with the form

$$f(\mathbf{v}) = \left(\frac{m_t}{2\pi T_i}\right)^{\frac{3}{2}} \exp\left(-\frac{m_t v^2}{2T_i}\right), \tag{4}$$

where m_t is the tritium particle mass and T_i is the ion temperature. We therefore have

$$\frac{dR}{dE_p' d\Omega_{p'}} = \frac{n_1 n_2}{2}\left(\frac{m_t}{2\pi T_i}\right)^3 v_r \sigma F_{E_r} \times \exp\left(-\frac{m_t}{2T_i}\left(v_1^2 + v_2^2\right)\right) d^3\mathbf{v_1} d^3\mathbf{v_2}. \tag{5}$$

The velocities of the reactants are related to the relative velocity $\mathbf{v_r}$ and velocity of the CM frame $\mathbf{v_{cm}}$ by

$$\mathbf{v_1} = \mathbf{v_{cm}} + \frac{1}{2}\mathbf{v_r}, \tag{6}$$