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SPECTRAL SHAPE OF THE 2.5 MeV NEUTRON
LINE PRODUCED IN D-D FUSION

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Effect of Ion Speed Distribution on the Spectral Shape
of the 2.5 MeV Neutron Line Produced by DD Fusion*

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ABSTRACT

Ion mean energy may be determined from Doppler broadening of the 2.5 MeV neutron line in Maxwellian deuterium plasma. Since many plasmas are non-Maxwellian a Monte Carlo simulation has been used to predict the spectral shape produced by a variety of simple speed distributions with mean energies in the range 1-100 keV. The results are Gaussian to high order and their width varies as the square root of the mean ion energy. However, the line width varies substantially among different ion speed distributions with the same mean energy. The similarity in shape of these spectra prevent the determination of the speed distribution type from detailed measurements of the neutron spectrum.

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INTRODUCTION

One of the critical parameters in fusion experiments is the ion energy distribution and its variation with heating and changes in confinement. To the extent that ions escape the plasma without energy loss, the ion speed distribution may be measured at the vacuum wall of the experiment. However, modern experiments generate dense plasmas which are many ion scattering lengths thick and which confine fast ions with high efficiency. Thus measurement of the speed distribution of ions reaching the wall is a less reliable indicator of the ion speed distribution in the central plasma. In those cases where the form of the ion speed distribution and plasma density profile are known a measurement of the fusion rate is a good indicator of the mean ion energy. However, the density profile is often poorly known so that a more direct measure of ion energy is desired.

Several previous works¹⁻⁶ have shown that, with suitable approximations in the reaction cross section, the Doppler width of the fusion product spectral line for a fusion reaction among Maxwellian ions with two outgoing particles is given by eq. (1) below.

$$\Delta E_3 = \sqrt{\frac{16 \ln 2 m_3 m_4 Q T}{(m_3 + m_4)^2}} \quad (1)$$

where Q is the energy released in the reaction, T the plasma temperature, m_3 and m_4 are the masses of the light and heavy reaction products respectively. These results have been extended to non-Maxwellian plasmas by Lehner and Pohl⁷, to beam driven plasmas by Elevant⁵, Scheffel⁶, and Heidbrink^{8,9} and to rotating plasmas by Scheffel⁶.

Several neutron spectrum measurements have been made to determine the neutron Doppler width in Maxwellian deuterium plasmas¹⁰⁻¹². Some have

also been made to show that the plasmas were not Maxwellian¹³⁻¹⁸.

Similarly, some theoretical work predicts non-Maxwellian plasmas in a variety of circumstances^{9,19-21} and direct measurement of the energy spectrum of escaping neutrals confirms this²².

In general, the energy spectrum of fusion products is not easily calculated analytically for any but the simplest ion speed distributions. Consequently a Monte Carlo computer code has been developed²³ which simulates the reaction kinematics, weights the results of each simulated reaction with the appropriate differential cross section²⁴ and accumulates an energy spectrum of fusion reaction products assuming arbitrary speed and angular distributions for the reacting ions. Of particular interest is the scaling of Doppler width with mean ion energy and whether or not the line shapes produced by various ion speed distributions are distinct. One of the important questions which this work attempts to answer is whether or not a detailed spectrum measurement may be used to distinguish among ion speed distributions with different functional forms.

SIMULATIONS

The Monte Carlo simulations whose results are given below sampled the assumed speed distribution functions producing 10^5 to 10^6 fusion events. In each event the energy of the product neutron was calculated at a fixed angular position in the laboratory coordinate system using non-relativistic kinematics. Each event was then weighted according to the differential reaction cross section²⁴ and the reaction parameters. The weight was multiplied by the relative velocity between the reacting ions and the product added to the appropriate energy bin in the neutron energy spectrum result table. The reaction cross section was assumed

anisotropic in the center of mass system and all weights incorporated the data in reference 7 to simulate the appropriate angular distribution weighting. Upon attaining adequate statistics in the result energy table the mean energy of the reaction product, $\langle E_3 \rangle$, was calculated. In addition, all of the energy moments to order 10 were calculated with respect to the fusion product mean energy. These moments are defined by eqs. 2 to 4 below.

$$M_0 = \int_0^{\infty} \frac{d^2\psi}{dE d\Omega} dE \quad (2)$$

$$\langle E_3 \rangle = \frac{1}{M_0} \int_0^{\infty} E \frac{d^2\psi}{dE d\Omega} dE \quad (3)$$

$$M_i = \frac{1}{M_0} \int_0^{\infty} (E - \langle E_3 \rangle)^i \frac{d^2\psi}{dE d\Omega} dE \quad (4)$$

Finally, an effort was made to establish quantitative parameters which could be used to describe the line "shape" of the simulated reaction product energy spectrum. For this purpose the ratios of each moment to the second moment was calculated according to eq. 5 below.

$$R_i = \frac{M_i}{M_2} \quad (5)$$

It was shown by Brysk³ that a Maxwellian speed distribution function generates a reaction product energy spectrum which is Gaussian. The ratios defined in eq. 5 may then be used to determine the extent to which the resulting spectra are asymmetrical about the mean and the extent to which they are non-Gaussian.

SPEED DISTRIBUTION FUNCTIONS

Several ion speed distributions have been considered in the simulations described below. All consist of combinations of three generic functional forms; the Maxwellian, mono-energetic, and three component Gaussian which will be defined below. They are illustrated in Figure 1. Mono-energetic ions were considered with both isotropic and mono-directional beam angular distributions. The Maxwellian and Gaussian distributions were isotropic in the results to be presented.

The three component Gaussian is formulated as a plausible representation of the speed distribution in a neutral beam heated plasma with relatively poor confinement. In this case ions are introduced at three energies due to the presence of molecular species during acceleration which are ionized in the plasma to form purely atomic species with energy groups at the acceleration energy, half that energy and one third that energy. Diffusion of these groups in velocity space results in three relatively broad peaks in the ion speed distribution when these injected species are trapped in a hot plasma. The speed distribution function used here to represent this case is:

$$f(v) = \sum_{i=1}^3 \frac{B_i}{W_i} e^{-1/2 \left(\frac{v-v_i}{W_i} \right)^2} \quad (6)$$

where v_i are the speeds corresponding to the acceleration energy, E_b , and the partial energy components $E_b/2$, and $E_b/3$. B_i and W_i are parameters describing the relative populations of ions in each energy group and the energy width of each group respectively. In all of the results presented here the width parameters are constrained by:

$$W_i = \gamma v_i \quad (7)$$

so that the distribution function is described completely by the parameters E_b , B_i , and γ . The mean energy of the three component Gaussian speed distribution becomes:

$$\langle E \rangle = E_b \left[\frac{1+6\gamma^2 + 3\gamma^4}{1 + \gamma^2} \right] \frac{\sum_{i=1}^3 B_i/i^2}{\sum_{i=1}^3 B_i/i} \quad (8)$$

RESULTS

A typical simulation result is shown in Figure 2. The width of the neutron line increases approximately as the square root of the mean ion energy for most speed distributions considered. A plot of the line width (FWHM) vs. mean ion energy is given in Figure 3 for each of the speed distributions considered. An attempt was made to fit the line width results with a simple power law for the purposes of interpolation. The form chosen is simpler than that of Elefant⁵ and Scheffel⁶ and slightly less accurate. Most of the line width data may be represented within about 5% by a function of the form:

$$\langle \Delta E_3 \rangle = a (\langle E \rangle)^b \quad (9)$$

where a is the fusion product line width in keV at a mean energy 1 keV. Table I contains a summary of these parameters based on linear least squares fits of eq. 9 to the logarithm of the width data in the simulations. Examination of the table shows that the square root dependence of line width on mean ion energy is a good approximation for the Maxwellian distribution with mean energies in the range 1-100 keV and fairly good for most of the others. However, at mean ion energies below

10 keV, the line widths vary substantially from one form of the speed distribution to another. At 1 keV ion energy the line width varies by a factor of three among these distribution functions. A line width of 75 keV corresponds to a 1.2 keV Maxwellian but also to a 6 keV mono-energetic ion distribution function. These differences are reduced in magnitude at ion energies approaching 100 keV but are substantial even at the highest ion energies. Ratios of the spectral moments, eq. 5, do not reduce the uncertainty in ion energy. For pure Gaussian spectral line shape the even moments about the mean are:

$$M_n = \sigma \left[1.3.5 \dots (n-1) \right]^{1/n} \quad (10)$$

where σ^2 is the second moment. The moment ratios for a pure Gaussian line shape then follow from eq. 10. Their values are given in Table II and appear as dashed lines in Figure 4.

Plots of the moment ratios for each speed distribution as a function of mean ion energy are included in the figure. Their ratios are essentially the same as for the Gaussian spectrum even among the high order moments in all cases at low ion energy and in most cases at high energy. In some cases the result spectra were slightly asymmetrical about the mean as has been predicted^{5,6} but odd order moments were not highly correlated with speed distribution parameters. Consequently only three parameters, the mean energy, the amplitude and the width, may be determined from the measured neutron spectrum.

CONCLUSIONS

The results of fusion product spectrum simulations have shown that spectral line width of the product energy spectrum increases roughly as the square root of mean ion energy for many simple but plausible speed distributions. It is also found that the reaction product spectrum is Gaussian to high order for nearly all cases considered, which may simplify interpretation of measurements where statistics are poor. A simple power law represents the line width data well over the mean ion energy range 1 to 100 keV for any one speed distribution function, but the scale factor for this power law (the width at mean ion energy 1 keV) varies substantially among the different speed distribution functions. The variation at energies below 10 keV is so large that mean ion energies may not be determined from line width data alone without reasonably specific knowledge of the ion speed distribution form. Determining the detailed shape of the fusion product energy spectrum is not helpful here since only a few relevant parameters may be extracted. Nevertheless, in most actual experiments there is some a priori knowledge of the form of the ion speed distribution function and there may even be independent measurements which can be used to reduce the uncertainty.

FIGURES

1. Functional form of the speed distribution functions used in the simulations.
a) Maxwellian, b) Three component Gaussian,
c) Monoenergetic, d) Beam onto Maxwellian, e) Beam onto Gaussian.
2. Typical result of simulated neutron energy spectrum due to D-D fusion. In this result the reacting ions have a Maxwellian speed distribution with mean energy 15 keV.
3. Neutron line width (FWHM) vs. mean ion energy for D-D fusion. Data shown are for a) Maxwellian ions, b) Monoenergetic ions, c) Three component Gaussian ions, d) 80 keV monoenergetic beam directed onto a Maxwellian plasma.
4. Ratio of spectral moments vs. mean ion energy for D-D neutron simulations. Results shown are for: a) Maxwellian,
b) Monoenergetic, c) Three component Gaussian, and d) 80 keV beam onto Maxwellian plasma.

TABLE I

Parameters used to describe dependence
of FWHM on energy from eq. 9

	a (keV)	b
Maxwellian	64.5	.515
Monoenergetic	22.3	.676
Gaussian	33.3	.625
80 keV beam on Gaussian target	49.5	.511
80 keV beam on Maxwellian target	48.6	.548

TABLE II

Moment Ratios for Gaussian Distribution Function

Moments	Ratio
R₄	1.316
R₆	1.570
R₈	1.984
R₁₀	1.984

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Fig. 1

Fig. 2

Fig. 3

Fig. 4