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THE UTILITY OF SPECTRAL MEASUREMENTS OF SECONDARY REACTION PRODUCTS

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The spectra of 15 MeV protons and 14 MeV neutrons produced in the burnup of 0.8 MeV ^{3}He ions and 1 MeV tritons through the d(^{3}He, p)α and d(t, n)α fusion reactions contain information on the velocity distributions of the energetic ^{3}He ions and tritons.

In a magnetically confined deuterium plasma, the behavior of alpha-like particles can be studied by measuring the number of 1 MeV tritons and 0.8 MeV ^{3}He ions (produced in the d–d fusion reactions) that undergo subsequent d(t, n)α and d(^{3}He, p)α fusion reactions. "Burnup" measurements of 14 MeV neutrons and of 15 MeV protons have been reported for the PLT [1,2] and PDX tokamaks [2,3] and are in progress on the TFTR [4], JET [5], and Frascati [6] tokamaks. The burnup fluence depends on both the energetic ion confinement and slowing-down, while burnup flux measurements are particularly useful for studying the rate of slowing-down. The purpose of this note is to point out that spectral measurements of the trition and ^{3}He burnup also provide useful information about the behavior of alpha-like particles.

Consider a plasma with moderately low impurity levels (Z_{eff}) and electron temperature T_e. The tritons and ^{3}He ions slow down primarily on electrons [7] so pitch-angle scattering of the energetic ions may be neglected. We also assume that the bulk deuterium temperature T_i is small compared to the d(t, n)α and d(^{3}He, p)α resonant energies so that the burnup reactions can be treated as beam-target reactions. Then the energy distribution of 14 MeV neutrons or 15 MeV protons $F(E_3)$ is given by [8]

$$F(E_3) = \tfrac{1}{2}\int \sin\chi_1 \, \mathrm{d}\chi_1 \times \int \mathrm{d}E_1 \sigma(E_1) E_1 f_1(E_1) \hat{F}(E_3, E_1, \chi_1), \qquad (1)$$

where $f_1(E_1)$ is the triton or ^{3}He energy distribution function, σ is the d(t, n)α or d(^{3}He, p)α fusion cross section, and $\hat{F}(E_3, E_1, \chi_1)$ is the reduced distribution function defined in eq. [7] of ref. [8]. For fast ions that slow down on electrons, $f_1(E_1) \propto E_1^{-3/2}$. If all of velocity space is confined, the integration over triton or ^{3}He pitch angle χ_1 is from $\chi_1 = 0$ to $\chi_1 = \pi$.

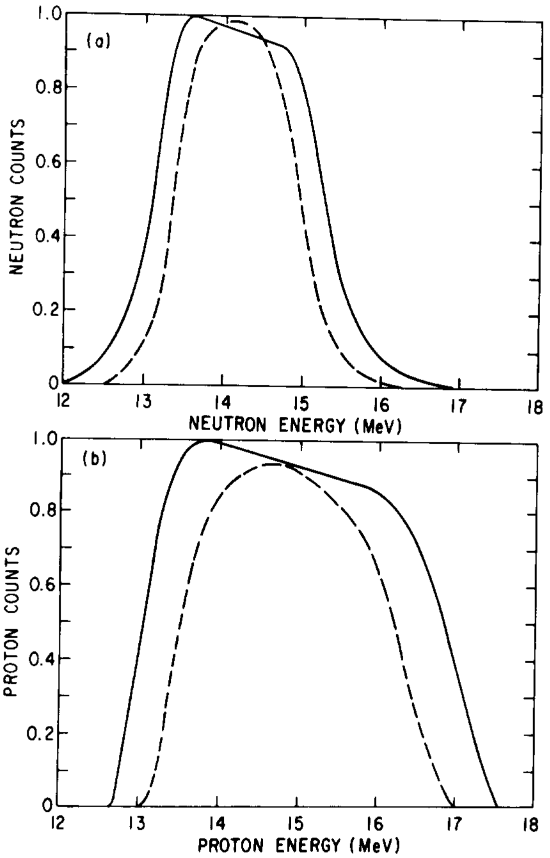

Fig. 1. (a) Spectrum of perpendicular 14 MeV neutrons ($\chi_3 = \pi/2$) produced by 1.0 MeV tritons that slow down on electrons in a cold deuterium plasma. The tritons are assumed to populate velocity space uniformly (solid curve); the dashed curve is for a loss cone in the perpendicular part of velocity space ($|\chi_1 - \pi/2| < 0.63$). (b) Spectrum of perpendicular 15 MeV protons ($\chi_3 = \pi/2$) produced by 0.8 MeV ^{3}He ions that slow down on electrons in a cold deuterium plasma. The ^{3}He ions are assumed to populate velocity space uniformly (solid curve); the dashed curve is for a loss cone in the perpendicular part of velocity space ($|\chi_2 - \pi/2| < 0.63$).

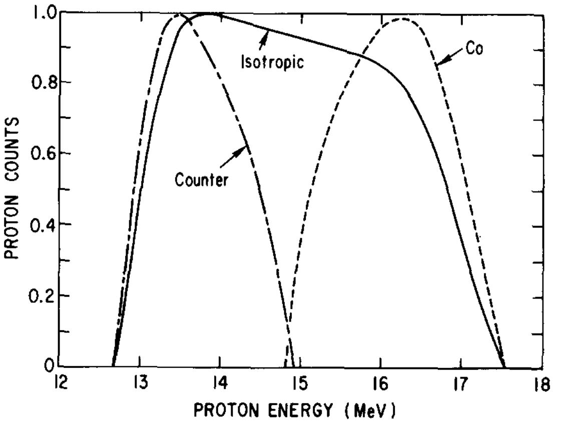

Fig. 2. Spectrum of 15 MeV protons ($\chi_3 = \pi/4$) produced by 0.8 MeV ^{3}He ions that slow down on electrons in a cold deuterium plasma. The solid curve is for an isotropic ^{3}He velocity space distribution, the dashed curve is the spectrum produced by cocirculating ions ($\chi_1 < \pi/4$) and the dotdash curve is the spectrum if only countercirculating ions ($\chi_1 > 3\pi/4$) are confined.

The utility of spectral measurements of the fusion-product burnup is that the spectrum contains information about the velocity-space distribution of the tritons and ^{3}He ions. As an illustration, imagine a vertically viewing neutron spectrometer, or a collimated 15 MeV proton detector that measures protons with velocities perpendicular to the magnetic field [9]. If the triton or ^{3}He confinement is isotropic in velocity space, numerical integration of eq. [1] gives the broad neutron and proton spectra shown in fig. 1. If, however, the velocity space confinement is anisotropic, deviations from this shape are predicted. For example, if a physical mechanism such as ripple losses [10] or fishbones [11] expel energetic ions in the trapped region in velocity space but do not affect the confinement of circulating ions, then more narrow spectra are expected (fig. 1).

The perpendicular detection geometry illustrated in fig. 1 is probably the easiest to implement experimentally. Greater sensitivity to energetic ion anisotropy is available with other viewing angles, however. In fig. 2, this increased sensitivity is illustrated by plotting the contributions to the burnup spectrum from ^{3}He ions in various portions of velocity space for a 15 MeV proton detector that measures protons with pitch angle $\chi_3 = \pi/4$. For this detection geometry, the contributions of cocirculating, perpendicular, and countercirculating ^{3}He ions to the energy spectrum are separated by more than 1 MeV.

In summary, collimated spectral measurements of the triton and ^{3}He burnup are useful for detecting possible anisotropies in the velocity-space distributions of these energetic ions.

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