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FUSION REACTION SPECTRA PRODUCED BY ANISOTROPIC ^{3}He IONS DURING ICRF

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ABSTRACT. For 'beam-target' fusion reactions, collimated measurements of the energy spectrum of one of the reaction products can provide information on the degree of anisotropy of the reacting beam ions. Early measurements of the spectrum of 15 MeV protons produced by reactions between energetic ^{3}He ions and relatively cold deuterons during fast-wave minority heating in the PLT tokamak found an asymmetric, downward-shifted fusion spectrum. New spectral measurements with a thicker detector that collects the full proton energy indicate that the velocity distribution of fast ^{3}He ions is peaked perpendicular to the tokamak magnetic field.

During fast-wave (ICRF) heating in the PLT tokamak [1, 2], ^{3}He minority ions with energies of 200 keV produce 15 MeV protons through d(^{3}He,p)α fusion reactions with the majority deuterium species [2, 3]. 15 MeV protons are unconfined in PLT and can be detected by using silicon surface barrier detectors mounted near the vacuum vessel wall [3, 4]. In previous measurements of the energy spectrum of the 15 MeV protons produced during ICRF [2, 3], the highest proton energies were cut off by the finite depth of the surface barrier detector. When the full energy of all the protons is measured, the asymmetric, downward-shifted spectrum reported previously becomes a spectrum with two peaks separated by about 2 MeV. Analysis of this spectrum in terms of a model two-component distribution function that has one component purely perpendicular and the other purely isotropic in velocity space indicates that $\gtrsim 90\%$ of the high-energy ^{3}He ions created by the waves have velocities perpendicular to the tokamak toroidal field.

In the experiment, 15 MeV protons produced by the d(^{3}He,p)α fusion reaction were detected with a proton spectrometer used previously on PLT [3]. The spectrometer was modified to use a surface barrier detector with a depleted region of 1800 μm, so that protons with energies up to 20 MeV deposited their full energy in the depleted region of the detector. The previous apparatus only collected the full energy of protons with less than 15.5 MeV. The spectrometer was collimated to measure perpendicular protons (collimator FWHM = 6.5°) produced in the plasma between major radii of approximately 102 cm and 140 cm, with nearly constant detection efficiency over this range [3]. The ^{3}He cyclotron layer was at major radii of 125–143 cm for these discharges.

The measured 15 MeV proton spectra exhibit a broad, two-lobed structure (Fig. 1a) for discharges characterized by plasma currents of 500–550 kA, toroidal fields of 28–32 kG, line-average electron densities of $(1.7–3.0) \times 10^{13}$ cm^{-3}, ICRF powers of

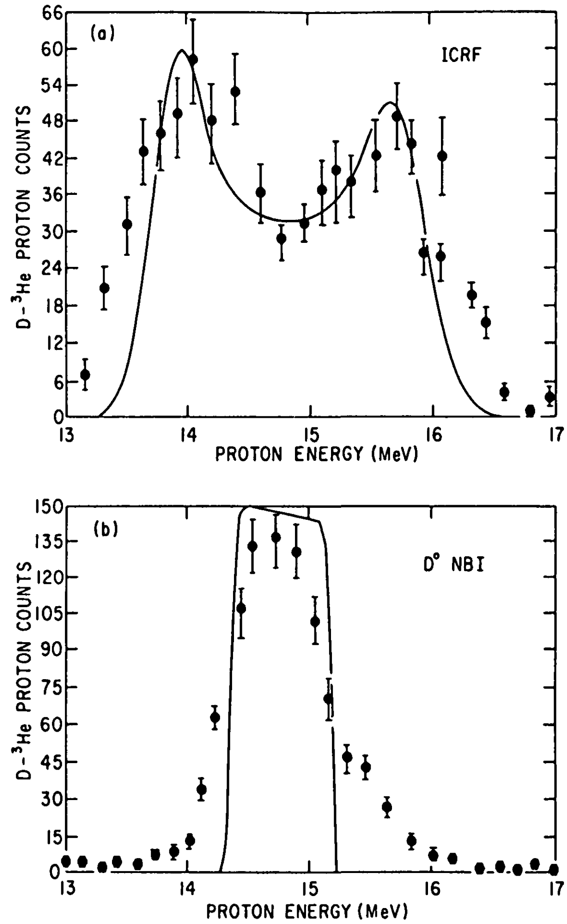

FIG.1. (a) Proton spectrum during ^{3}He minority ICRF heating (240 kW) in a discharge with I_ϕ = 500 kA, $\bar{n}_e = 2.7 \times 10^{13}$ cm^{-3}, and B_ϕ = 30.5 kG. The curve is the spectrum produced by an anisotropic perpendicular ^{3}He beam with maximum energy of 400 keV and temperature of 30 keV [5]. The absolute accuracy of the energy measurement is ± 2.5%; the resolution of the spectrometer is 0.5 MeV (full line-width). (b) Proton spectrum during co-injection of a 40 keV deuterium neutral beam into a deuterium and ^{3}He plasma in the absence of ICRF. The curve is the spectrum produced by an isotropic 40 keV deuterium beam with a classical slowing-down distribution ($f(v) \propto v^{-3}$) [5].

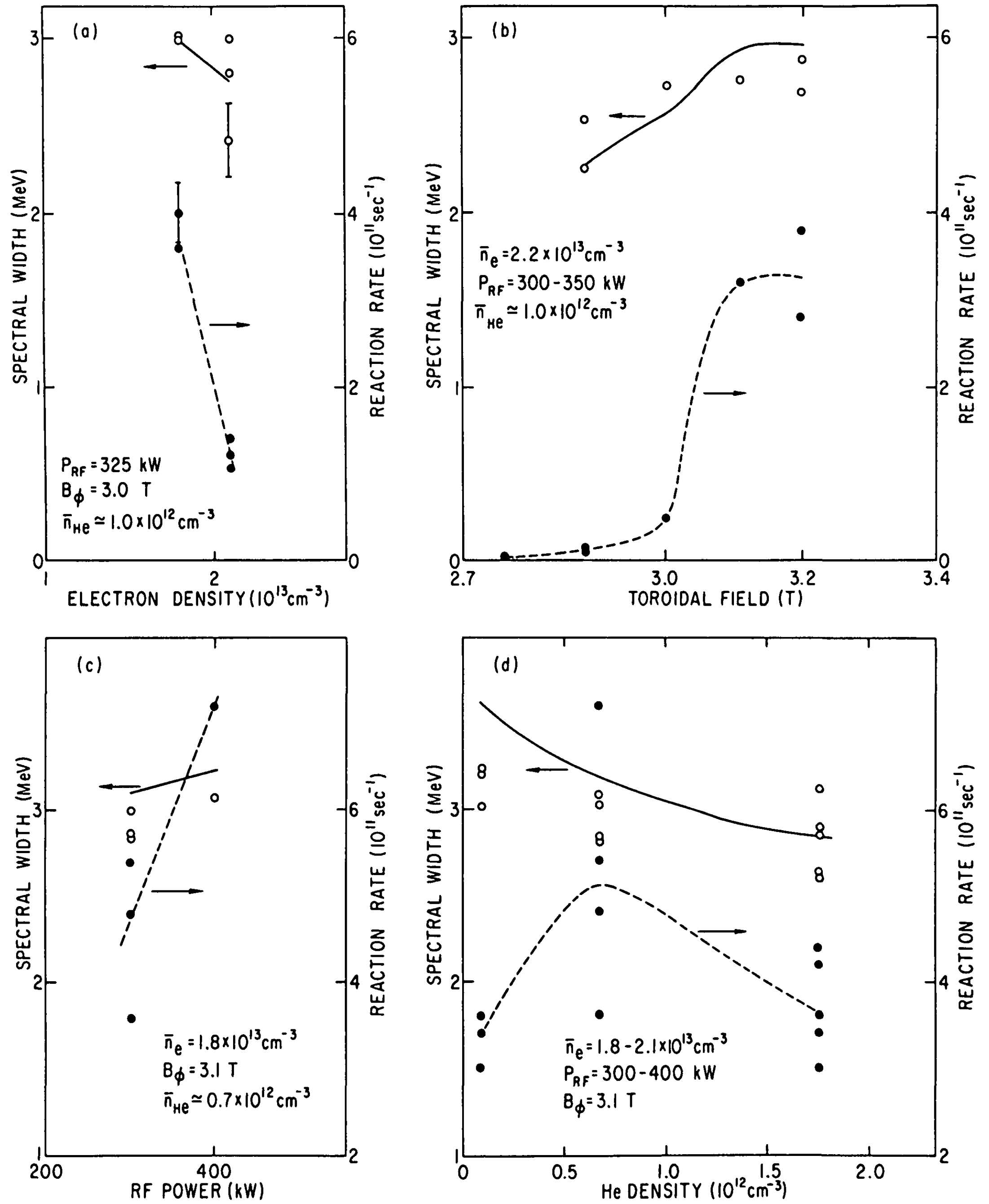

FIG. 2. 15 MeV proton spectral width and d(^{3}He,p)α reaction rate versus line-average electron density (a), toroidal field (b), ICRF power (c), and estimated line-average ^{3}He density (d) with the other parameters held constant. $I_\phi \approx 500$ kA. The dashed curve through the reaction rate data is the fit used to calculate the spectral width predicted by Eq.2 (solid curves).

100–500 kW at 30 MHz, and d(^{3}He, p)α reaction rates of $\gtrsim 10^{11}$ s^{-1}. In contrast, co-injection of a 40 keV deuterium neutral beam into a deuterium and ^{3}He plasma in the absence of ICRF produced a relatively narrow 15 MeV proton spectrum with a single peak (Fig.1b). The width of the proton spectrum during ICRF was found to depend less sensitively on electron density, ICRF power, toroidal magnetic field, and ^{3}He density than the d(^{3}He,p)α reaction rate (Fig.2). Operation of the spectrometer was restricted to a relatively narrow parameter regime by the requirement that the reaction rate be sufficiently large for statistically significant measurements but sufficiently small to avoid appreciable pulse pile-up. The ratio of counts in the low-energy peak to the number of counts in the central minimum was 1.68 ± 0.29 for discharges with full spectral width $\geqslant 2.7$ MeV; the ratio of counts in the high-energy peak to counts in the central minimum was 1.38 ± 0.22.

A twin-lobed spectrum cannot be produced by an isotropic beam of ^{3}He ions. Although these spectral measurements of protons at a single angle of escape do not provide sufficient information to determine uniquely the direction of anisotropy of the ^{3}He tail, they are consistent with theoretical predictions of a perpendicular anisotropic tail [3, 6]. Twin lobes are produced by a perpendicular ^{3}He distribution because, although the probability of undergoing a fusion reaction is constant throughout a ^{3}He ion's gyro-period, more of the protons detected in the poloidal plane make an angle parallel or antiparallel to the ^{3}He velocity vector than perpendicular to the ^{3}He velocity, resulting in a proton distribution that has more protons with a maximal Doppler shift than without any shift [5]. The spacing of the lobes implies that perpendicular ^{3}He ions with energy of about 40 keV in the case of the most closely spaced peaks and of about 300 keV in the case of the most widely spaced peaks made the dominant contribution to the observed proton spectra. Theoretically, the ^{3}He distribution is predicted to be perpendicular for energies $\gtrsim 20\ Z_{\mathrm{eff}}^{\frac{2}{3}} T_e \approx 30$ keV [6]. The instrumental resolution was too poor in these experiments to determine the minimum energy at which anisotropy exists. The ratio of counts between lobes to the number of counts in the peaks implies that the isotropic contribution to the observed spectrum is less than 10% of the perpendicular contribution.

The observation that the proton spectral width is less sensitive to the parameters affecting ^{3}He tail heating than the d(^{3}He,p)α reaction rate (Fig.2) is consistent with theoretical expectations. The proton energy distribution F(E$_p$) can be approximated as

$$F(E_p) \propto \int dE_{He}\, \sigma(E_{He})\, E_{He} f(E_{He}) \hat{F}(E_p, E_{He}) \qquad (1)$$

where E$_p$ is the proton energy, σ the fusion cross-section, f(E$_{He}$) is the energy distribution of the ^{3}He ions, and $\hat{F}$(E$_p$, E$_{He}$) the proton energy distribution produced by helium ions of energy E$_{He}$. Analytical expressions for $\hat{F}$ for isotropic and anisotropic ^{3}He distributions are given in Ref. [5]. For a ^{3}He distribution that decreases rapidly with energy, such as f(E) ∝ exp(−E/T), where T is the tail temperature, the weighting factor σ(E$_{He}$)E$_{He}$f(E$_{He}$) peaks strongly for some energy E$_{He}$ = E$_{peak}$ and the proton energy distribution function is approximately $F(E_p) \approx \hat{F}(E_p, E_{peak})$. Asymptotic analysis [7] of Eq.(1) using an analytical fit to the cross-section σ [8] indicates that the energy E$_{peak}$ for which the weighting factor σEf is maximized depends on tail temperature according to $E_{peak} \approx 14\,(\mathrm{keV})^{\frac{1}{3}} T^{\frac{2}{3}}$. Since the spectral width scales like $\sqrt{E_{He}}$ [5], this implies that the spectral width scales approximately as $T^{\frac{1}{3}}$. In contrast to this weak algebraic dependence on tail temperature, the analysis predicts a strong exponential dependence of the d(^{3}He,p)α reaction rate R$_{dHe}$ on tail temperature, $R_{dHe} \propto \exp[-43(\mathrm{keV}/T)^{\frac{1}{3}}]$. The reaction rate also depends on the number density of ^{3}He tail ions, while the proton spectrum produced by the minority tail depends on tail temperature alone. Combining expressions, the spectral width W is expected to scale with reaction rate R and ^{3}He density n as

$$W_2 = W_1 \left[1 + 0.023 T_1^{\frac{1}{3}} \ln \left(\frac{n_2 R_1}{n_1 R_2} \right) \right]^{-1} \qquad (2)$$

The predictions of Eq. (2) are plotted in Fig.2 by using the measured value of the reaction rate and a single normalization (W$_1$ = 3.0 MeV, R$_1$ = 4 × 10^{11} s^{-1}, n$_1$ ≈ 1.0 × 10^{12} cm^{-3}. T$_1$ ≈ 40 keV is implied by W$_1$ = 3.0 MeV). A major uncertainty in the application of Eq. (2) is determination of the ^{3}He density, which was estimated from the rise in electron density when neutral ^{3}He was puffed into the vacuum vessel about 50 ms before the ICRF pulse, but which differs from this value due to ^{3}He pumping and desorption [9]. The measured scaling of spectral width with reaction rate is consistent with the theoretical prediction of Eq. (2) within the experimental error (Fig.2). When the ^{3}He gas puff was reduced so that the density rise was below the minimum detectable level ($\Delta \bar{n}_e \lesssim 0.2 \times 10^{12}$ cm^{-3}) (Fig.2d), the spectral width broadened slightly, implying that the tail temperature continued to rise with decreasing ^{3}He concentration;

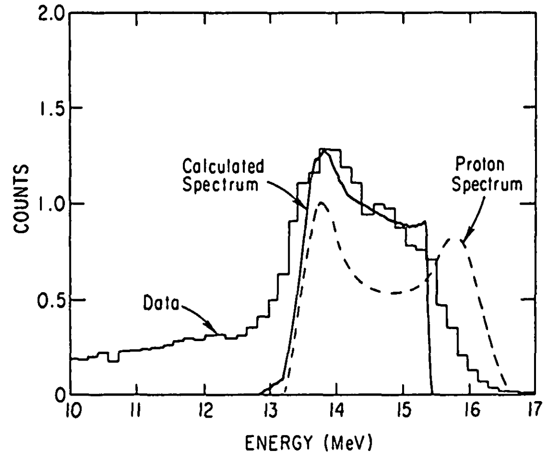

FIG.3. A good fit to the asymmetric proton spectrum measured previously [3] *is found by assuming that the true proton spectrum was produced by an anisotropic perpendicular* ^{3}*He beam with maximum energy 400 keV and temperature 50 keV but that this spectrum was distorted by a thin detector with the model response*

$$E_{\mathrm{det}} = \begin{cases} E_{\mathrm{p}}, & \text{if } E_{\mathrm{p}} \leqslant 15.4\ \mathrm{MeV} \\ 3(15.4\ \mathrm{MeV} - 2E_{\mathrm{p}}), & \text{if } E_{\mathrm{p}} > 15.4\ \mathrm{MeV} \end{cases}$$

The model detector response is based on calculations summarized in Fig.2.5 of Ref. [10]. *The counts below 12.5 MeV in the data are thought to be protons that lose energy in the walls of the collimator.*

but the reaction rate fell, implying that the reduction in number density of ^{3}He ions had a stronger effect on the reaction rate than the increase in tail temperature.

The probable explanation for the asymmetric, downward-shifted proton spectra observed previously in PLT [3] is that the thinner detector used in those experiments failed to collect the full energy of the protons in the upper lobe of the distribution (Fig.3).

In conclusion, measurements of the spectrum of 15 MeV protons produced during fast-wave minority heating in the PLT tokamak indicate that $\gtrsim 90\%$ of the ≈ 200 keV ^{3}He ions near the major radius of the device are anisotropic in velocity space. The width of the proton spectrum is increased by increasing the RF power, by reducing the electron or ^{3}He density, and by adjusting the toroidal field so that the ^{3}He resonance layer is in the centre of the discharge, but measurements of the d(^{3}He, p)α reaction rate are much more sensitive to changes in tail temperature than are the spectral measurements. The tail temperature implied by the spectral measurements is typically between 30 and 50 keV.

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REFERENCES

[1] HOSEA, J., BOYD, D., BRETZ, N., CHRIEN, R., COHEN, S., et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 8th Int. Conf. Brussels, 1980), Vol. 2, IAEA, Vienna (1981) 95.

[2] HWANG, D., BITTER, M., BUDNY, R., CAVALLO, A., CHRIEN, R., et al., in Plasma Physics and Controlled Nuclear Fusion Research (Proc. 9th Int. Conf., Baltimore, 1982), Vol. 2, IAEA, Vienna (1983) 3.

[3] CHRIEN, R.E., STRACHAN, J.D., Phys. Fluids **26** (1983) 1953.

[4] CHRIEN, R.E., COLESTOCK, P.L., EUBANK, H.P., HOSEA, J.C., HWANG, D.Q., et al., Phys. Rev. Lett. **46** (1981) 535.

[5] HEIDBRINK, W.W., Fusion Reaction Spectra Produced by Anisotropic Fast Ions in the PLT Tokamak, Princeton Plasma Physics Lab. Rep. PPP-L-2079 (Feb.1984).

[6] STIX, T.H., Nucl. Fusion **15** (1975) 737.

[7] A similar analysis for the d(d, n) fusion reaction is found in POST, R.F., Rev. Mod. Phys. **28** (1956) 338.

[8] MILEY, G.H., TOWNER, H., IVICH, N., Fusion Cross Section and Reactivities, Rep. COO-2218-17, University of Illinois, Urbana, Ill. (1974).

[9] CHRIEN, R.E., EUBANK, H.P., MEADE, D.M., STRACHAN, J.D., Nucl. Fusion **21** (1981) 1661.

[10] CHRIEN, R.E., Measurements of Fusion Reactions from a Tokamak Plasma, PhD Thesis, Princeton University (1982) 46.

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