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Measurement of the D-D fusion neutron energy spectrum and variation of the peak width with plasma ion temperature

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We report a set of neutron spectrum measurements made at the Alcator-*C* tokamak under Ohmic-heating conditions. It has been found that the width of the D-D fusion neutron peak increases with the plasma ion temperature consistent with the theoretical prediction. In particular, the neutron spectra resulting from the sum of many plasma discharges with ion temperatures of 780 and 1050 eV have been obtained. The width for the 780-eV case is 64^{+9}_{-11} keV and that of the 1050-eV case, 81^{+10}_{-14} keV (full width at half maximum), corresponding to ion temperatures of 740 and 1190 eV, respectively.

The measurement of the neutron spectum emitted from a thermonuclear D-D plasma can serve as a valuable diagnostic tool. In an Ohmically heated tokamak such as Alcator *C*, the plasma ion velocity distribution is known to be essentially Maxwellian. Lehner and Pohl[1] have shown that the neutron energy spectrum as a result of a three-dimensional Maxwellian ion distribution is Gaussian in shape and has a full width at half maximum (FWHM) given by

$$\Delta E = 82.5(kT)^{1/2} , \tag{1}$$

where the width and ion temperature (kT) are both in keV. This work reports on two sets of measurements made at two different ion temperatures which show agreement with Eq. (1).

A number of measurements of neutron spectra from tokamak-produced plasmas have been reported recently.[2-6] Most of the measurements were for beam-heated plasmas with ion temperatures greater than or near 2 keV.[2,5,6] Strachan and Jassby[3] reported a spectrum during Ohmic heating at the Princeton Large Torus (PLT), but the 2.45-MeV fusion peak was distorted by nonthermonuclear sources of neutrons. One measurement of the neutron spectrum during Ohmic heating at Alcator *C* was reported before ours,[4] but the resolution at 2.45 MeV was not sufficient to obtain the true width of the peak. To our knowledge, this is the first report of a successful measurement of the 2.45-MeV peak width for an Ohmically heated tokamak plasma. The measurement has been possible at Alcator *C* at this time for four reasons: (1) The ratio of the number of fusion neutrons to nonfusion neutrons is more than two orders of magnitude higher than the Ohmic-heating case mentioned above[3] because the plasma density at Alcator *C* is an order of magnitude higher than that of PLT. (2) A substantial improvement has been obtained in the 2.5-MeV peak count rate performance as compared with Ref. 2 as a result of better thermal neutron shielding of the detector. (3) While the resolution is similar to that of Ref. 2, it is substantially better than the measurement of Pappas, Wysocki, and Furnstahl at Alcator *C*.[4] Neutron production rates at Alcator *C* are now large enough that the ion chamber used in Refs. 2, 3, and 5 could be used.

The neutron spectrometer system used for these measurements is described in detail in Refs. 7 and 8. It utilizes a ^{3}He ionization chamber[9] as the neutron detector.

Figure 1 shows a comparison between a pair of neutron spectra; the top is due to a Li(p,n)Be accelerator neutron source and the bottom is due to a sum of 303 plasma discharges. The energy resolution of the spectrometer in-

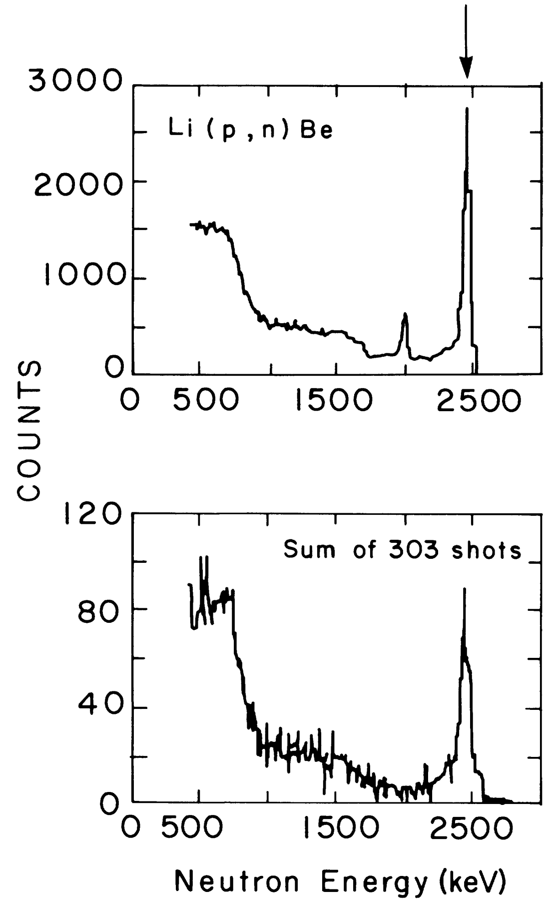

FIG. 1. Neutron spectra from the ^{3}He spectrometer. Here the Q value of the ^{3}He(n,p)t reaction has been subtracted from the energy scale. Top, the spectrum due to the sum of 303 plasma discharges. Bottom, the spectrum due to a calibration neutron source from the Li(p,n)Be reaction. The proton energy was adjusted to yield 2.45-MeV neutrons. The small peak is due to an excited state of Be. The arrow shows the position of the 2.45-MeV peak.

ferred from the calibration peak is 46 keV FWHM. The neutron source linewidth is estimated to contribute less than 10 keV to the FWHM. The energy calibration at 2.45 MeV has an uncertainty of 10 keV. The small peak near 2.0 MeV in the calibration spectrum is due to an excited state of Be.

This calibration spectrum is a good indicator of the spectrometer response function to 2.45-MeV neutrons. The peak corresponding to 2.45-MeV neutrons is indicated by an arrow in the figure. The continuum between 2.5 and 1.7 MeV is due to neutrons from the reaction $^3\mathrm{He}(n,p)t$, in which the entire energy of the proton and triton is not collected in the ion chamber. The shoulder beginning at 1.7 MeV is due to proton recoils in the ion chamber, and the shoulder beginning at 0.8 MeV is due to ^{3}He recoils. A peak due to thermal neutrons, which corresponds to an energy of 0.76 MeV deposited in the chamber, occurs at 0 MeV, is an order of magnitude larger than the 2.5-MeV peak, and has not been included in the figure. The ratio of the number of counts from the energy range of 1.15 to 2.25 MeV to the energy range from 2.25 to 2.6 MeV has been computed for both cases. For the calibration this ratio was 1.9 and for the fusion spectrum the ratio is 1.4. The similarity of the plasma neutron spectrum and the calibration spectrum indicates that the bulk of the neutrons produced in the plasma are from D-D reactions.

As might be noticed from the plasma spectrum in Fig. 1, a large number of plasma discharges were required to obtain even moderate statistics. This was primarily due to the low intrinsic efficiency of the ion chamber and to the present neutron production rate of Alcator-*C* plasmas. Thus only a few counts have been obtained in the D-D fusion peak per plasma discharge. The count rate was as high as 11 counts in a 250-msec counting time during a single discharge. The total ion chamber count rate, which includes counts from γ rays, thermal neutron capture, and neutron elastic scatter was 4×10^3 counts/sec for the same discharge. This rate is very near the maximum count rate at which the ion chamber can be operated.[2,10] While this is an improvement over a previous design,[2] at least 20 plasma discharges are required and measurements of this type will require relatively long data acquisition times even if the neutron production rate of fusion devices is increased.

In order to determine whether the width of the D-D peak varied as described by Eq. (1), neutron spectra for two sets of plasma discharges with different ion temperature were measured. The plasma conditions are summarized in Table I. Note that in the "low"-T_i case the central ion temperature is 780 eV and in the "high"-T_i case, 1050 eV. The ion temperature has been determined from the total neutron rate and neutral particle charge-exchange diagnostics.[11] Both these diagnostics have measurement uncertainties of 10% and the temperatures represent the maximum temperature at the center of the plasma during each discharge. The width determined from our measurements is an average over the spatial and time distributions of the plasma ion temperature. The effect of this average has been calculated for the discharges above, and we have found that the ion temperature corresponding to the measured peak width is approximately 0.8 times the central ion temperature and is insensitive to plasma parameters, particularly to the value of limiter q. The shot-to-shot variation in the temperature was about 10% to 15%.

TABLE I. Plasma conditions for low- and high-T_i cases.

	Low-T_i case	High-T_i case
Number of discharges	169	38
Plasma current (kA)	350–400	550–625
Toroidal field (kG)	80	110
Line averaged electron density (m^{-3})	2.5×10^{20}	2.3×10^{20}
T_i from neutron rate and charge exchange (eV)	780	1050

A standard pulse-height analysis system has been used with the ion chamber to obtain the neutron spectra.[7,8] To provide sufficient resolution on a pulser generated peak used to measure noise pickup during the plasma discharge, it was necessary to collect spectra such that there were approximately 40 channels at the FWHM of the 2.45-MeV peak. Because there were so few total counts in the peak (generally less than 300), it is helpful to reduce the number of channels by adding groups of channels together until about five of these collapsed channels occur at the FWHM of the peak. The two data sets are plotted after such a collapse in Fig. 2. This method of presentation emphasizes the

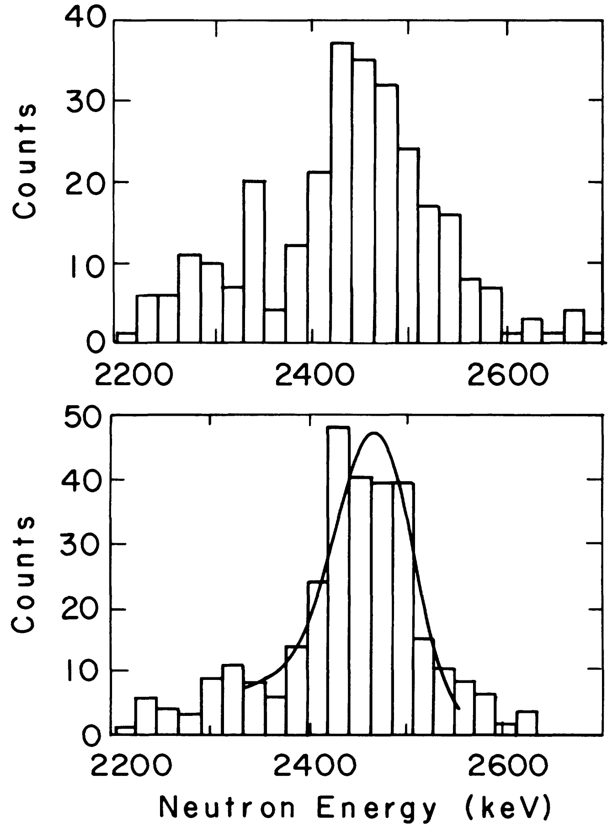

FIG. 2. Neutron spectrum data for low- and high-T_i cases. Top, high-T_i case. Bottom, low-T_i case. The original number of data channels has been reduced by a factor of 9 for presentation purposes. The curve in the lower figure is the result of fitting the original data, with use of the method of Cash (Ref. 12).

difference between the low- and high-temperature cases, but is not well suited for quantitative analysis.

Peak width is determined following the method suggested by Cash.[12] The data are fitted by minimizing the statistic

$$C = 2 \sum_{i=1}^{N} (y_i - n_i \ln y_i) \ , \tag{2}$$

where n_i is the number of counts in channel i, N is the number of channels, and y_i is the value of the fitting function evaluated for the channel i. The fitting function used is

$$\begin{aligned} F(i) &= P_1 \exp\left[-0.5\left(\frac{P_1 - i}{P_3}\right)^2\right] + P_1 P_4 W \exp\left[-0.707\left(\frac{P_2 - i}{P_5}\right)^2\right] + P_6 W \ , \\ W &= 0.5\,\mathrm{erfc}\left(1.0 - \frac{P_2 - i}{P_3}\right) \ , \end{aligned} \tag{3}$$

where P_1 is the magnitude, P_2 the centroid, P_3 the σ of the Gaussian representing the neutron peak, and erfc the complementary error function. Parameters P_4 and P_5 are needed to fit the response function of the ion chamber and are fixed from the calibration spectrum, and P_6 is a background term needed to model the background on the low-energy side of the peak. In the minimization, P_1–P_3 and P_6 are free parameters. The confidence limits of the fit are calculated as suggested by Cash.[12] The error bars shown in Fig. 3 are based on a 68% confidence limit.

The contribution due to the ion temperature can be found, once the peak width and associated uncertainty is known, by use of the relation

$$\sigma_n = (\sigma_{\mathrm{peak}}^2 - \sigma_{\mathrm{noise}}^2 - \sigma_{\mathrm{resolution}}^2)^{1/2} \ , \tag{4}$$

where σ_n is the thermal broadening, σ_{peak} is the fitted peak width, σ_{noise} is the noise contribution determined from the pulser peak, and $\sigma_{\mathrm{resolution}}$ is the measured resolution of the detector. The central ion temperature is calculated with the use of Eq. (1) and the time and spatial averaging correction discussed earlier.

The corrected peak width is plotted against the central ion temperature in Fig. 3. The dotted line represents the expected variation in the width for ion temperatures measured by the total neutron rate and neutral particle charge-exchange diagnostics. The equivalent central ion temperature determined from the linewidth is shown on the scale to the right of the figure. The width was determined to be 64^{+9}_{-11} keV for the low-T_i case and 81^{+10}_{-14} keV for the high-T_i case. This may be compared with the predicted values of 66 for the low-T_i case and 76 for the high-T_i case. The constant in Eq. (1) can be estimated from the data, assuming a value of 0 for the width at a 0-keV ion temperature, and is 90 ± 10. The agreement is consistent within the run-time limited statistical accuracy of the measurement.

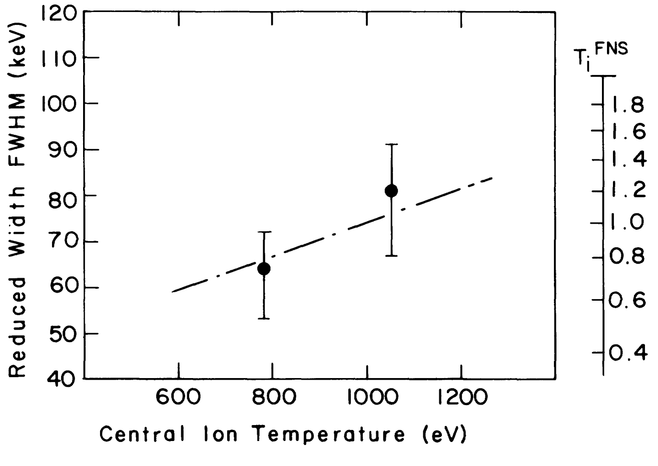

FIG. 3. Reduced width of the 2.45-MeV fusion peak and corresponding temperature plotted against the central ion temperature determined from the total neutron rate and neutral particle charge-exchange diagnostics. The dotted line shows the expected dependence.

These measurements demonstrate the feasibility of using the linewidth technique to determine both the absolute ion temperatures and changes as small as 200 eV and provide evidence that the neutrons are thermonuclear in origin. Since high resolution is essential to this measurement, a critical aspect of this work was the development of a detector shielding and collimation system allowing the ion chamber used to be operated at a tolerable count rate for the 2.45-MeV peak. Despite this improvement, the technique of obtaining the ion temperature from the linewidth of the 2.45-MeV peak does not presently constitute a routine diagnostic. Obtainable plasma parameters dictate that at least 25 identical discharges are required to determine a temperature within statistical significance. The maximum count rate of the detector could be increased by use of a shorter amplifier time constant, but the resultant degradation of resolution would make the system unsuitable for 1-keV ion temperatures. Future machines, with hotter plasmas, longer discharges, and increased access may find this technique of substantial value. Additionally, the sensitivity of the spectrum shape to nonthermal ion distribution functions is of great value in evaluating the degree to which the ions approximate a Maxwellian distribution. The feature should prove especially useful in radio frequency heated plasma discharges.

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