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By

R.E. Chrien and J.D. Strachan

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OBSERVATION OF d(d,p)t REACTIONS IN THE PRINCETON LARGE TORUS

R. E. Chrien*, J. D. Strachan

Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544

Protons from d(d,p)t fusion reactions have been observed in the Princeton Large Torus (PLT) using a surface-barrier detector. The time evolution of the escaping protons agrees with the d-d neutron evolution. The proton energy spectrum was measured during ohmic, lower-hybrid, and ICRF heating. The proton spectrum during lower-hybrid heating indicates non-thermal enhancement of the d-d fusion rate.

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*Present Address: Los Alamos National Laboratory, Los Alamos, New Mexico 87545

In a deuterium plasma, 3.0 MeV protons are produced by d(d,p)t fusion reactions in nearly equal numbers as 2.45 MeV neutrons from d(d,n)^{3}He reactions. These protons have previously been detected in plasma experiments using emulsions[1-3] and with a silicon surface barrier detector.[4] In this work, the first time - and energy - resolved measurements of these protons escaping from a tokamak plasma have been used as a diagnostic of the reacting deuterons during ohmic and auxiliary heating experiments.

The proton time evolution agreed with the evolution of the d-d neutron emission. The proton energy spectrum during ohmic or ^{3}He minority Ion Cyclotron Range-of-Frequency (ICRF) heating was consistent with thermonuclear d-d reactions. The width of the proton spectrum during lower hybrid heating was much broader and indicated that the reactions were due to a non-Maxwellian deuterium distribution. Non-thermal fusion production was previously inferred in the Alcator A lower hybrid heating experiment.[5]

These proton measurements were performed in the Princeton Large Torus (PLT) (major radius = 132 cm, minor radius = 40 cm, magnetic field $\leq$ 32 kG, plasma current $\leq$ 500 kA) using a silicon surface barrier spectrometer located at the bottom of the vacuum vessel. Near - perpendicular d-d protons are unconfined in PLT and have the same orbits as 1.0 MeV d-d tritons.[6] The detector accepts protons with zero parallel velocity and 40° elevation whose banana orbits intersect the torus midplane outside the magnetic axis (Figure 1).

The detector efficiency was established by comparison with BF_3 neutron counters which have been absolutely calibrated with an uncertainty of 40%.[7] The proton detector efficiency was 2×10^{-8}, using five 0.17 cm diameter entrance apertures. The protons lose about 0.4 MeV passing through a protective beryllium foil (12.7 μm thick) and deposit their remaining energy in the detector. The finite width of the collimating entrance holes of the spectrometer permits the protons to pass through the foil with a range of angles, which contributed 0.15 MeV to the detector resolution. The detector bias was 50 V, resulting in a 350 μm thick depleted region.

The proton energy spectrum measured during ohmic heating [Figure 2(a)] was peaked at 2.6 MeV with a FWHM of 0.18 MeV, in agreement with the spectrum calculated from the proton energy loss in the beryllium foil and the thermal broadening (T_i = 0.8 keV) of the proton emission. The proton peak did not appear when the magnetic field was reversed, causing the protons to drift away from the detector.

The d-d proton emission was investigated during heating experiments using 800 MHz lower hybrid waves excited by a phased waveguide array located 120° toroidally from the proton detector. The fusion reaction rate was largest for 90° phasing of adjacent waveguides,which is expected to produce a $k_{\parallel}$ spectrum favoring wave propagation in one toroidal direction. The d-d neutron and proton emission (Figure 2) during 0.1 MW lower hybrid heating ($\bar{n}_e = 1.5 \times 10^{13}$ cm^{-3}) each show a factor of four enhancement over the ohmic heating level.

The d-d proton spectrum during lower hybrid heating [Figure 2(b)] is peaked at 2.6 MeV and has a FWHM of 0.43 MeV. The detector noise, monitored with a pulser signal connected to the preamp, was 0.10 MeV. The detector spectrum was consistent with a proton spectrum centered at 3 MeV with a FWHM of 0.39 MeV, which is much wider than the spectrum during ohmic heating. The proton spectrum width would imply a temperature of 18 keV for a maxwellian deuterium distribution, compared with T_d = 0.8 keV measured during the ohmic heating phase. This hypothesis is inconsistent with the increase in neutron and proton emission ($\propto T^4$ for maxwellian reactivity) which implies a 40% increase in temperature. Therefore, the enhancement in d-d reactions was due to a deuterium tail excited by the lower hybrid waves. Fast neutral charge - exchange measurements also showed a deuterium tail ($T_{tail} = 12$ keV) extending up to 60 keV.[8]

The average energy of the deuterons producing the d-d reactions can be estimated from the proton spectrum width using reaction kinematics. The proton energy E_p is given by

$$E_p = 3.03 \text{ MeV} \{ 1 + \cos\theta((2/3)E_d/4.04 \text{ MeV})^{1/2} \},$$

where θ is the angle between the deuteron of energy E_d and the detected proton. Assuming that the deuterons are isotropic ($\langle\cos\theta\rangle \approx 1/3$) and that the rms deviation of E_p determines the width of a gaussian distribution,[9] we find that $\langle E_d \rangle \approx 50+55$ keV.

Energy spectra of both d-d protons and 14.7 MeV d-^{3}He protons[10] were observed during second harmonic ICRF heating of $^3He^{++}$ ions in a deuterium plasma. The ICRF fast waves were launched from the large major radius side with a pair of half-turn antennae excited at 42 MHz. The second harmonic ^{3}He layer was located near the magnetic axis by using a toroidal magnetic field of 21 kG. The line-averaged deuterium and ^{3}He densities were 2.5×10^{13} cm^{-3} and 0.2×10^{13} cm^{-3}, respectively.

The measured spectrum (Figure 4) shows the d-d proton peak at 2.6 MeV with FWHM of 0.25 MeV, which is consistent with the detector response for thermonuclear d-d reactions. A peak due to d-^{3}He protons appears near 14 MeV with FWHM of 2 MeV reflecting the energetic ^{3}He tail produced by the second harmonic heating. The peak at 6 MeV is a pulser, connected to the detector preamp, used to monitor the noise contribution (0.15 MeV) to the detector resolution. More low energy counts (below 2 MeV) are present in this spectrum. A possible explanation is that the 1000 μm thick depleted region needed to collect the d-^{3}He proton energy increases the energy which can be deposited by Compton electrons from hard X rays.

The d-d proton spectrum measured during lower hybrid heating shows broadening characteristic of deuterium tail formation. In general, these measurements duplicated the d-d neutron time histories but provide advantages for d-d spectral measurements over neutron spectrometers[11] (although with poorer resolution in these preliminary measurements). These advantages include greater dynamic range than ^{3}He ionization chambers, moderate spatial resolution, and reduced influence of scattering without the need for massive collimators. The energy resolution of the proton detectors can be improved by reducing the foil thickness and narrowing the entrance apertures.

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FIGURE CAPTIONS

Figure 1. d-d proton orbit in PLT (poloidal cross section) which can enter the collimating holes of the proton detector.

Figure 2. (a) d-d proton spectrum during ohmically heated discharges, together with calculated spectrum based on measured ion temperature, detector noise, and proton energy loss in the beryllium foil. (b) d-d proton spectrum during lower hybrid heating.

Figure 3. (a) d-d neutron and (b) d-d proton time evolutions during lower hybrid heating.

Figure 4. Proton spectrum during ^{3}He second harmonic ICRF heating, showing the d-d proton peak at 2.6 MeV and the d-^{3}He proton peak near 14 MeV. The peak at 6 MeV is a pulser line. The low energy counts are due to hard X rays.

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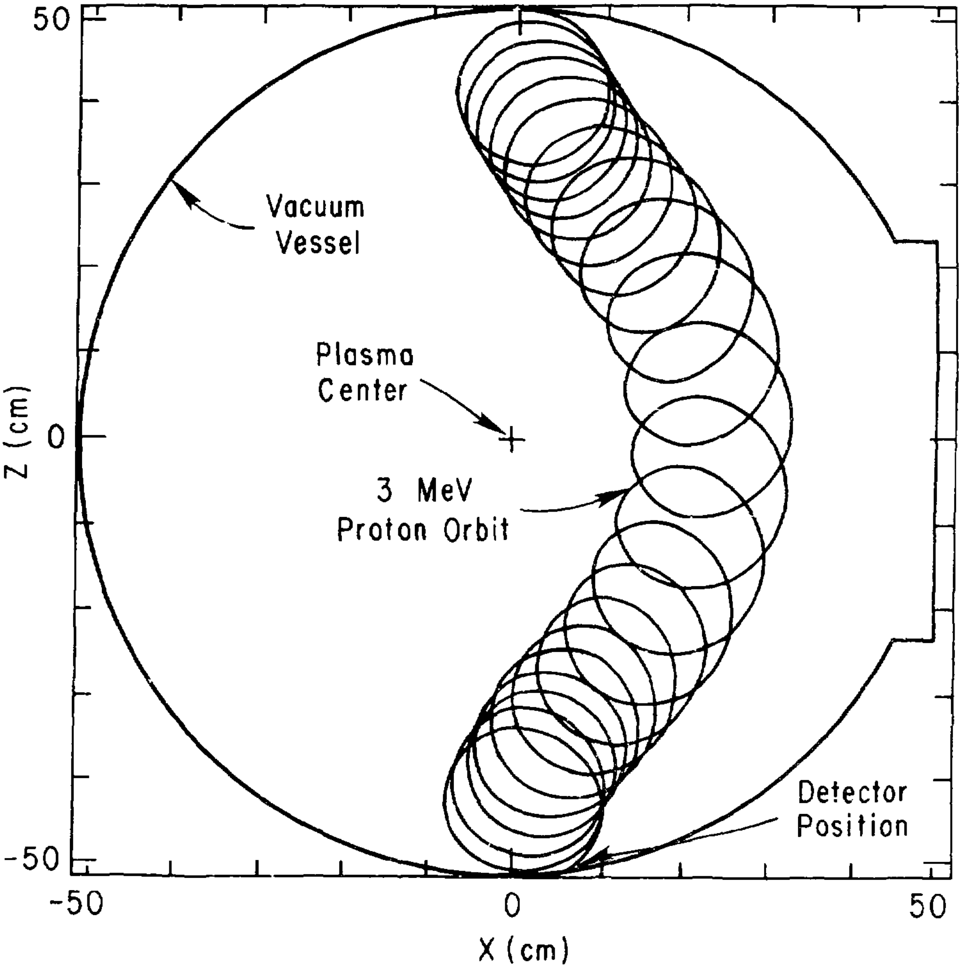

Fig. 1

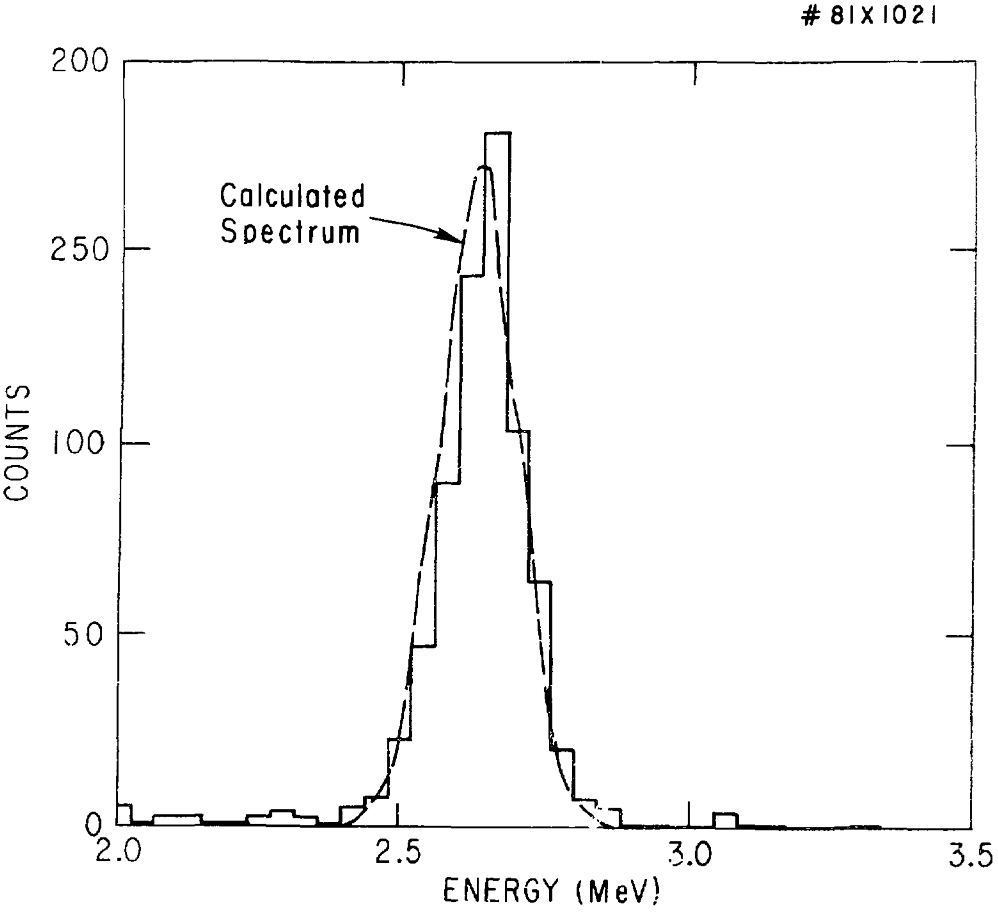
81X1021
Calculated
Spectrum
200
250
100
50
0
COUNTS
2.0
2.5
3.0
3.5
ENERGY (MeV)

Fig. 2a

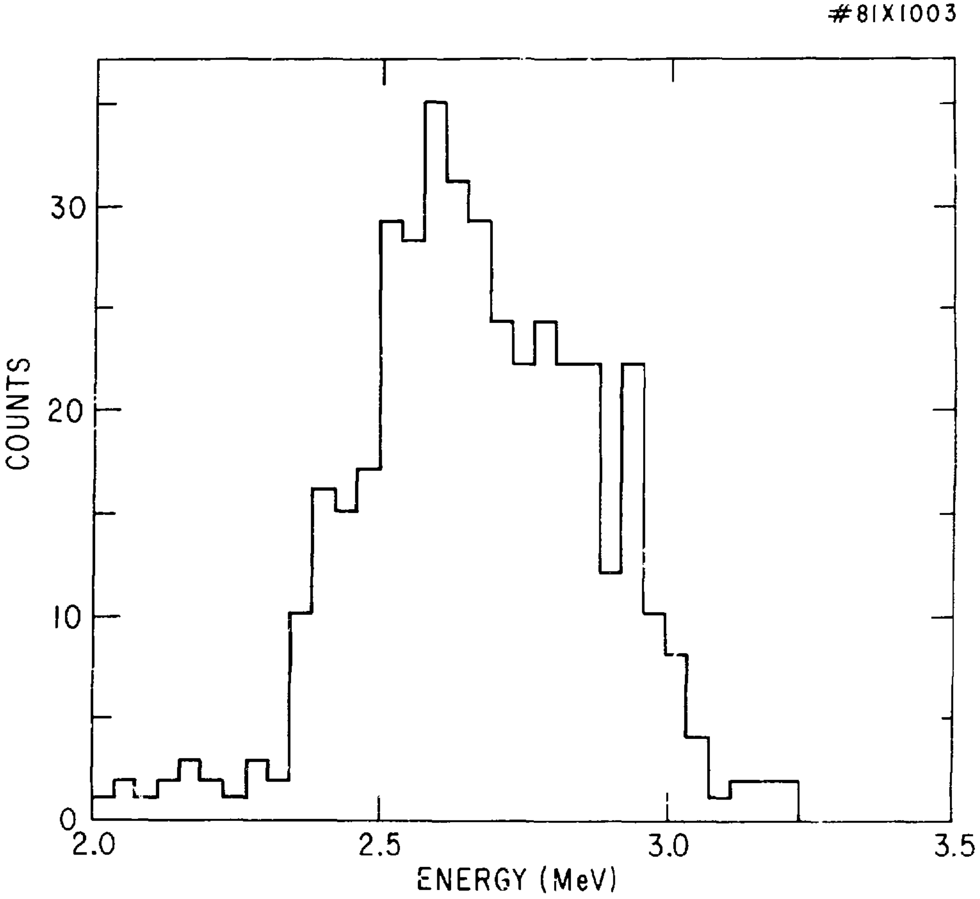

Fig. 2b

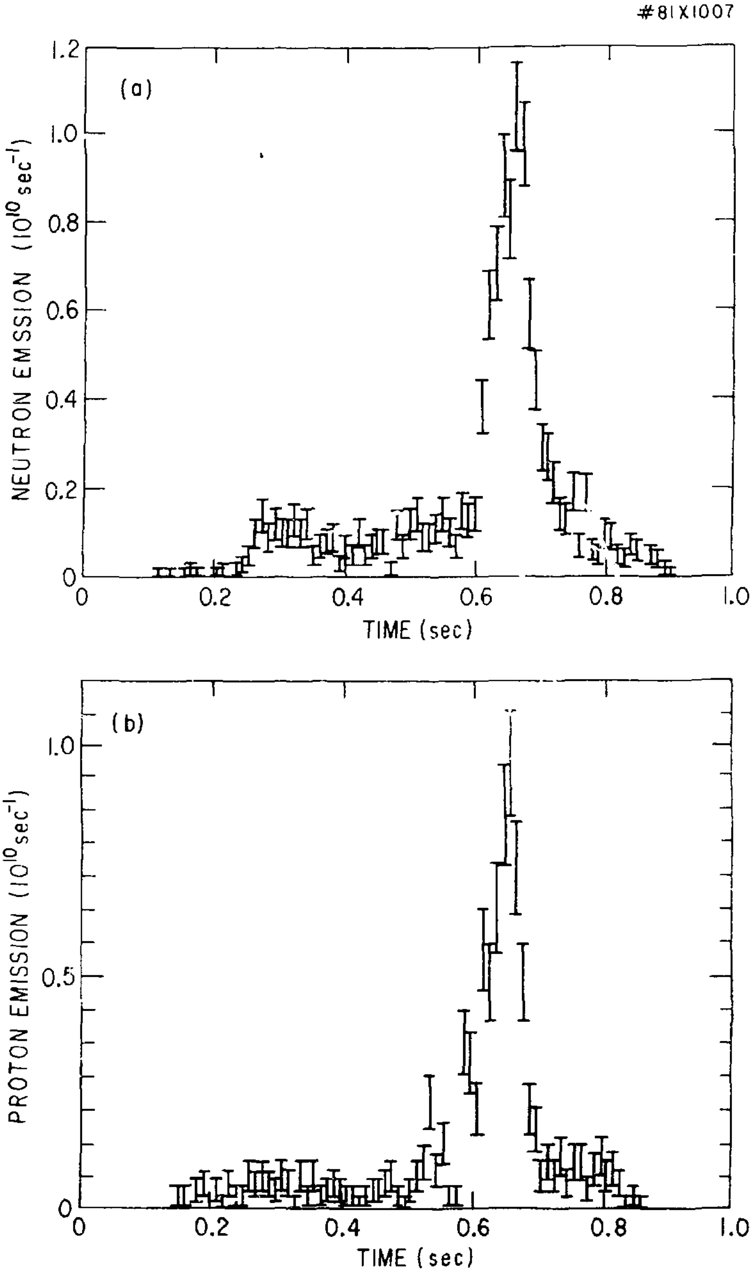
#81X1007
(a)
NEUTRON EMSSION (10^{10} sec^{-1})
0
0.2
0.4
0.6
0.8
1.0
1.2
TIME (sec)
0
0.2
0.4
0.6
0.8
1.0
(b)
PROTON EMISSION (10^{10} sec^{-1})
0
0.5
1.0
TIME (sec)
0
0.2
0.4
0.6
0.8
1.0

Fig. 3

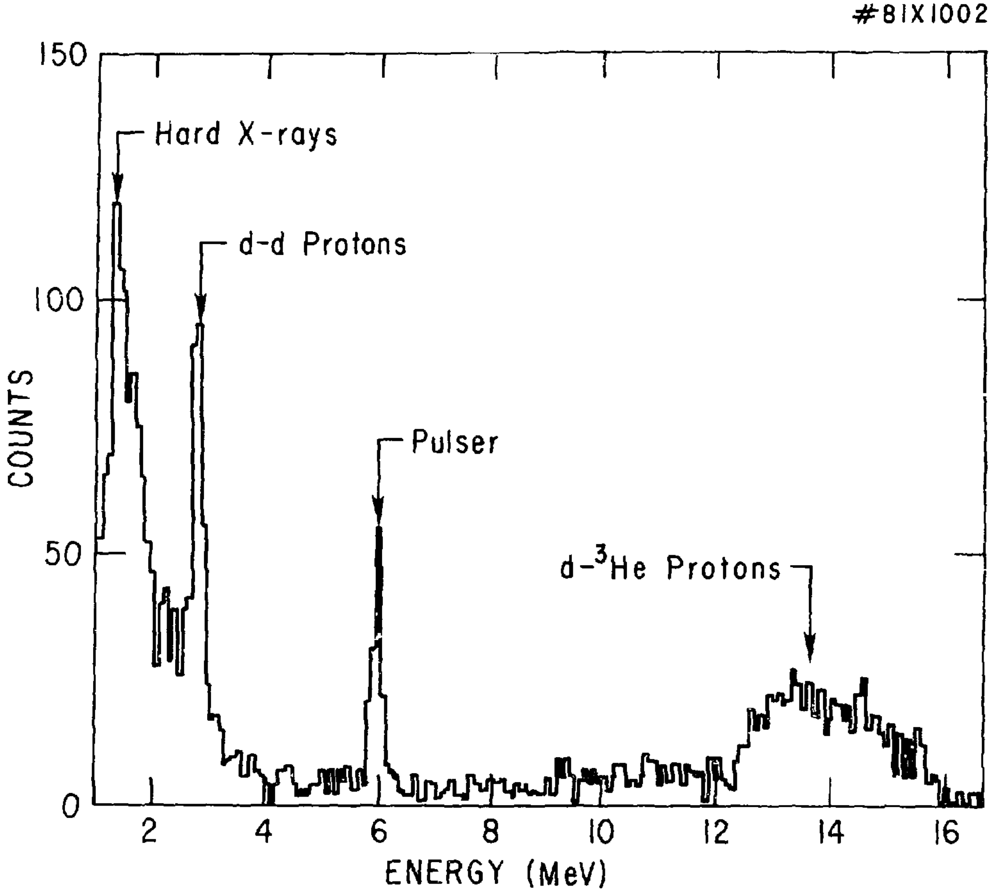
#81X1002
150
100
50
0
COUNTS
Hard X-rays
d-d Protons
Pulser
d-^{3}He Protons
2
4
6
8
10
12
14
16
ENERGY (MeV)

Fig. 4