Observation of d-^{3}He Fusion Reactions in a Tokamak Plasma

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d-^{3}He reactions have been observed in the Princeton Large Torus by detecting the unconfined 14.7-MeV proton. Reaction rates as high as 2×10^{13} sec^{-1} resulting in 60 W of fusion power were obtained by 500-kW heating of a ^{3}He minority in the ion-cyclotron range of frequencies to energies above 80 keV. The fusion-power multiplication of about 10^{-4} is equal to the highest obtained in any controlled-fusion experiment.

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Fast wave heating in the ion cyclotron range of frequencies (ICRF) is a promising auxiliary heating candidate for producing fusion power. ICRF heating has several advantages for this purpose, such as good overall efficiency, readily available sources in the required frequency range, good energy coupling to the reacting ions, and selective spatial energy placement.[1] In the minority heating regime, fundamental cyclotron heating is expected to produce highly energetic minority ion velocity distributions which could produce sizable "beam-target" fusion reaction rates with the majority ions, similar to the energetic circulating ions injected as neutrals.[2]

To study ICRF minority ion heating, we have performed the first observation of d-^{3}He reactions in a tokamak plasma by detecting the unconfined protons with activation measurements and with a silicon surface-barrier detector. Reaction rates as high as 2×10^{13} sec^{-1} were produced by 500 kW of ICRF power at the cyclotron frequency of a ^{3}He^{++} minority in a predominately deuterium plasma. These reactions rates clearly demonstrate the effectiveness of ICRF heating in producing energetic ^{3}He^{++} minority distributions similar to previous ICRF proton minority heating experiments in the Princeton Large Torus (PLT). In particular, the d-^{3}He yield per discharge was more than 10^3 times larger than has previously been obtained in a plasma device.[3]

The maximum fusion power released by these reactions in the ^{3}He minority heating experiments was 60 W. The fusion-energy multiplication ($Q_{d\text{-}^3\text{He}}$) was $Q_{d\text{-}^3\text{He}} = 1\times 10^{-4}$, which is equal to the highest energy multiplication obtained in a plasma[4]; however, the neutron emission from $d(d,n)^3$He reactions was small (10^{11} sec^{-1}) and carries out less than 10^{-3} of the fusion power. The reactions were also observed during deuterium neutral beam injection into deuterium discharges containing small concentrations of ^{3}He, and the number of reactions was found to have the expected dependence on beam energy and ^{3}He density for beam-target reactions.

In these experiments, PLT (400 kA plasma current, 2.7 T toroidal magnetic field, 40 cm minor radius, 132 cm major radius) was heated by moderate power (~500 kW) ICRF heating at 24.6 MHz or by a deuterium neutral beam (~650 kW beam power, ~37 keV beam energy) injected parallel to the plasma current, resulting in plasma conditions of $\bar{n}_e = (1-3)\times 10^{13}$ cm^{-3}, $T_e(0) = 1.0-1.5$ keV, $T_i(0) = 1.0-1.5$ keV. ^{3}He gas was added to the discharge prior to the ICRF or neutral beam heating, producing $\bar{n}_{^3\text{He}} = (1-3)\times 10^{12}$ cm^{-3}. The plasma current in PLT was sufficient to confine 100-keV ^{3}He^{++} ions or 40-keV deuterons; however, the 14.7-MeV proton produced by the d-^{3}He reaction was completely unconfined (Fig. 1). The d-^{3}He reactions were observed by detecting the unconfined protons. These protons have gyroradii of ~25 cm and a banana width of about four times the plasma minor radius.

The 14.7-MeV protons were first detected by activation measurements. Titanium samples (10 cm^2) located at the bottom of the vacuum vessel were exposed to about 100 PLT discharges with 0.1-sec pulses of 300-kW ICRF heating over two days. The protons produced thick target activation of the titanium by the reaction ^{48}Ti$(p,n)^{48}$V, which has a proton threshold of 4.9 MeV.[5] A high-purity germanium detector was used to observe the 0.983- and 1.312-MeV γ-ray lines from the decay of ^{48}V ($t_{1/2} = 16$ d). The observation of ^{48}V lines is unambiguous identification of d-^{3}He reactions since ^{48}V can be produced only by very energetic protons in our experiment.

Proton activation was also observed on the PLT

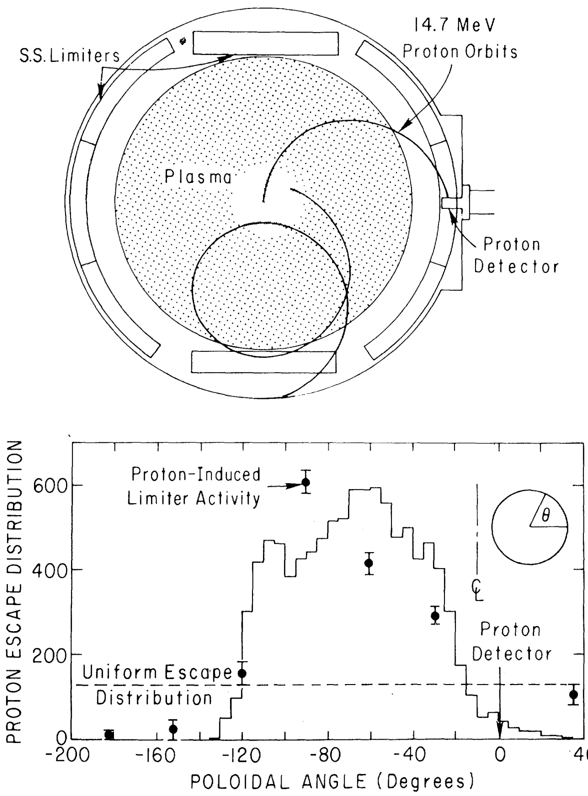

FIG. 1. Poloidal cross section of PLT, showing the locations of the silicon surface-barrier detector, the central proton-emitting region of the plasma, and two particular proton orbits which intercept the detectors. The limiters are displaced 160° toroidally from the detector position. The proton escape distribution shows that most of the protons intercept the lower outside portion of the vacuum vessel. The predicted escape distribution is in reasonable agreement with the ^{56}Co limiter activity due to the reaction ^{56}Fe$(p,n)^{56}$Co.

stainless-steel ring and bar limiters. The limiters were activated by the reaction ^{56}Fe$(p,n)^{56}$Co, which has a threshold of about 5.3 MeV. The limiters were removed from PLT and the germanium detector was used to observe the 0.847- and 1.238-MeV γ lines from the decay of ^{56}Co ($t_{1/2}$ = 79 d). The poloidal variation of the ^{56}Co activity was measured by counting the limiter sections separately. The ^{56}Co activity, shown in Fig. 1, is in reasonable agreement with a Monte Carlo code prediction of the proton escape distribution which was obtained by following the gyro orbits of 10^4 protons started near the plasma center with random direction.

Time-resolved proton emission was measured with use of a silicon surface-barrier detector located on the horizontal midplane about 3 cm inside the vacuum vessel and about 8 cm from the plasma edge. The detector was collimated by a pair of slits to accept protons traveling vertically downward. Stainless-steel foils (330 μm) were used to prevent fusion-produced ions other than the 14.7-MeV proton from reaching the detector and to prevent exposure of the detector to the plasma. The protons lose about 6.5 MeV of energy in passing through the foils and deposit about 2 MeV in the 200-μm depleted region of the detector. A peak was observed in the pulse-height spectrum of the detector with central energy of about 1.7 MeV. The detector was electrically isolated from the vacuum vessel and shielded from electromagnetic noise in the plasma, but was susceptible to vibration due to pulsing of the tokamak.

The silicon detector was calibrated by injecting a deuterium neutral beam into a deuterium plasma containing a small concentration of ^{3}He [Fig. 2(a)]. The counting rate for the d-^{3}He protons and d-d neutrons, shown in Fig. 2(c) as a function of beam energy, varied as the product of the reaction cross section and beam power. The scaling indicates that both neutron and proton emission is due to beam-target reactions[6] and provides a calibration for the detector. The proton detector signal was linear with the density of ^{3}He in the plasma and was negligible when no ^{3}He gas was added. The ^{3}He density, shown in Fig. 2(b), was determined by the electron density rise associated with the ^{3}He gas puffing during Ohmically heated discharges and is uncertain because of residual ^{3}He remaining from previous discharges and the effects of the auxiliary heating on gas influx. The decay of the proton emission near the end of the neutral beam injection is probably due to the nature of the ^{3}He density evolution.

The proton emission was measured during low-power (180 kW) ICRF heating [Fig. 3(a)] of a ^{3}He^{++} minority ($\bar{n}_{^3\mathrm{He}} = 2\times10^{12}$ cm^{-3}) in a deuterium plasma ($\bar{n}_e = 1.5\times10^{13}$ cm^{-3}) [Fig. 3(b)]. The proton emission was about twenty times larger than the neutron emission (because of thermonuclear d-d reactions), indicating the existence of an energetic ^{3}He velocity distribution with cross-section–weighted average energy of 50–60 keV. This ^{3}He tail was consistent with ICRF fundamental heating of the ^{3}He minority similar to the case of ICRF proton fundamental heating, in which an energetic proton tail was measured by a mass-sensitive charge-exchange diagnostic.[7]

The proton emission and the thermal ion heating varied with changes in the central toroidal magnetic field and therefore with the major radius of

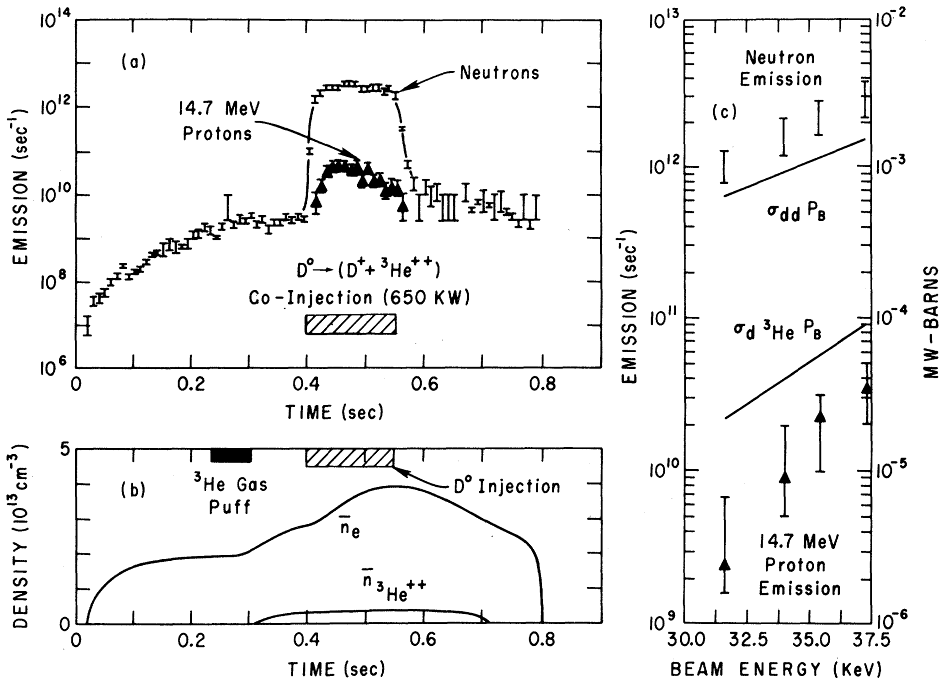

FIG. 2. (a) Time evolution of the 2.5-MeV neutron emission and the 14.7-MeV proton emission during 650-kW deuterium neutral beam injection into a deuterium and ^{3}He plasma. (b) Time evolution of the line-averaged electron density and ^{3}He density. (c) Variation of the 2.5-MeV neutron emission and the 14.7-MeV proton emission with neutral beam energy, together with the variation of the respective cross sections weighted with beam power.

the $^3He^{++}$ cyclotron layer (R_c) [Fig. 3(c)]. The proton emission was largest for $R_c = (143 \pm 4)$ cm, which is about 10 cm from the center of the vacuum vessel.

The proton orbit code indicated that protons which reached the detector through its collimating apertures could have originated at major radii in the plasma within a proton gyrodiameter of the detector and that those major radii are nearly equally accessible to the detector. The cyclotron layer was within a proton gyrodiameter of the detector for the range of toroidal fields in this experiment. In addition, the spread of the energetic ^{3}He orbits broadened the region where the d-^{3}He reactions occurred over most of the plasma center. Hence the strong peaking of the proton emission implies that an energetic ^{3}He tail is created most effectively when the wave damping occurs near the center of the plasma. This result is consistent with wave theory, which predicts that fundamental wave damping is proportional to the temperature of the minority species. The observed peaking for $R_c = (143 \pm 4)$ cm may be explained by either an outward shift of the energetic ^{3}He ions or may be due to the occurrence of wave damping at the two-ion hybrid layer located at ~132 cm.

At the highest ICRF power levels, the detector current was amplified to measure the proton emission. The amplifier was calibrated to the pulse-counting method. Proton emission of about 2×10^{13} sec^{-1}, which represents 60 W of fusion, resulted from 500 kW of ICRF heating at the ^{3}He cyclotron frequency. The electron and ^{3}He densities were 2×10^{13} and 0.2×10^{13} cm^{-3}, respectively. These measurements, together with the measured deuteron temperature of 1.5 keV, imply a cross-section–weighted average energy of 70–80 keV, characteristic of a ^{3}He tail extending above 80 keV.

These initial measurements of d-^{3}He reactions in a tokamak plasma by two independent methods provided the sole direct evidence of energetic $^3He^{++}$ tail formation during ICRF fundamental $^3He^{++}$ minority heating and demonstrated the dependence of ^{3}He tail formation on the position of the cyclotron layer. These results also support the concept of a driven d-^{3}He fusion reactor with a hot ^{3}He-ion component produced by ICRF heating. This would minimize the neutron production and thus minimize many of the neutron-related complications inherent in present tokamak reac-

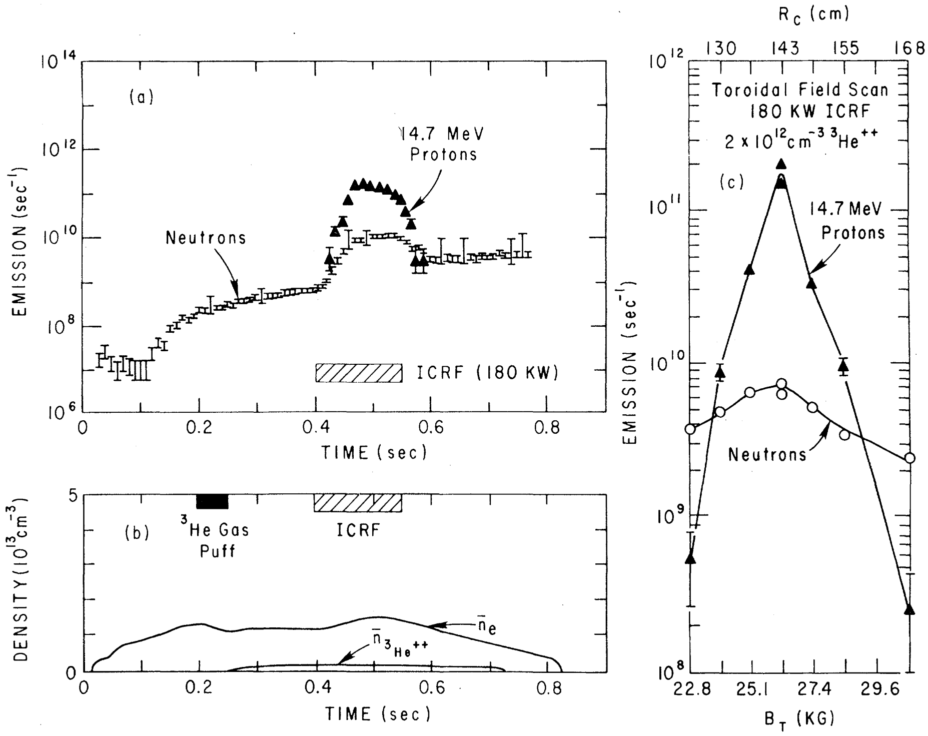

FIG. 3. (a) Time evolution of the 2.5-MeV neutron emission and 14.7-MeV proton emission during 180 kW, 24.6 MHz ICRF heating. (b) Time evolution of the line-averaged electron density and ^{3}He density. (c) Variation of the 2.5-MeV neutron emission and 14.7-MeV proton emission with the central toroidal magnetic field and therefore with the major radius (R_c) of the ^{3}He^{++} cyclotron layer.

tor designs (with the necessity, however, of higher temperature than for a d-t reactor).

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