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THERMALLY EXCITED PROTON SPIN-FLIP LASER EMISSION IN TOKAMAKS

BY

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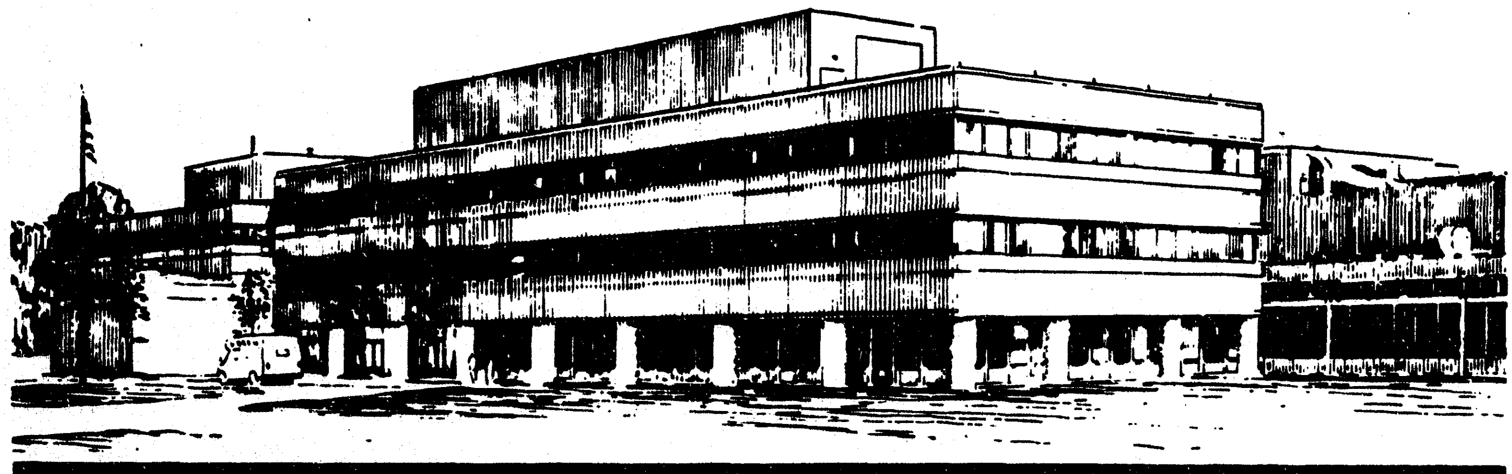
PRINCETON PLASMA PHYSICS LABORATORY



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THERMALLY EXCITED PROTON SPIN-FLIP LASER EMISSION IN TOKAMAKS

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ABSTRACT

Based on statistical thermodynamic fluctuation arguments, it is shown here for the first time that thermally excited spin-flip laser emission from the fusion product protons can occur in large tokamak devices that are entering the reactor regime of operation. Existing experimental data from TFTR supports this conjecture, in the sense that these measurements are in complete agreement with the predictions of the quasilinear theory of the spin-flip laser.

In large tokamak devices that are entering the reactor regime of operation such as TFTR, JT - 60 and JET the fusion products of the primary DD reaction are given by

$$D + D = \begin{cases} ^3He(0.82\ MeV) + n(2.5\ MeV) \\ T(1.0\ MeV) + p((3.0\ MeV) \end{cases} , \qquad (1)$$

and the secondary reactions are given by

$$^3He + D = p(14.7\ MeV) + ^4He(3.7\ MeV) \quad , \qquad (2)$$

$$T + D = ^4He(3.6\ MeV) + n(14.7\ MeV) \quad . \qquad (3)$$

For the present day operating conditions in both TFTR and JET, two of these fusion products, ^4He (i.e., the alpha particles) and protons have large enough energies so as to satisfy the condition $\lambda_i = k_\perp \rho_i > 1$. Here $\mathbf{k}_\perp$ is the wave vector perpendicular to the confining tokamak magnetic field $\mathbf{B} \propto R^{-1}$, ρ_i is the appropriate Larmor radius of the charged fusion product ionic species, and R is the major radius of the torus. Thus, according to the Trubnikov "dressed test particle" emission theory,[1,2] the alpha particles and protons can emit equally intense electromagnetic radiation at all harmonics of their ion cyclotron frequencies $\omega = m\omega_{ci} < \omega_{LH}$, where ω_{LH} is the conventional lower hybrid frequency of the background deuterium plasma and m is the harmonic number. It is shown elsewhere[1] that these radiations are actually fast Alfven waves and are hence subject to Stix-Golant[3] lower hybrid accessibility criterion. Using Stringer's[4] pitch angle analysis of these newly born fusion products, very recent calculations of the radial drift excursions of the banana orbits of the marginally trapped fusion products by Cottrell, Bhatnager, *et.al.*[5] for JET parameters indicate that these excusions occur only to the outer midplane edge of the torus. It should be noted that the fast Alfven wave index of refraction of the background deuterium plasma $\mu = c/V_A \propto n_d^{1/2}/B$ is approximately the same for both the TFTR and the JET present day parameters. Here, n_d is the number density of the background deuterium plasma ions of mass m_d and V_A is the Alfven wave phase velocity. Hence, $\lambda_i = kv/\omega_{ci} = mkv/\omega = mv/V_A = mv\mu/c$ is the same for both TFTR and JET since $\mathbf{k} = \mathbf{k}_\perp$ for cyclotron harmonic emission. Thus, on making use of Stix-Golant lower hybrid accessibility theory in conjunction with Stringer's radial profile analysis of the fusion products, one can clearly understand the localized nature of the ion cyclotron harmonic emission in tokamaks to the outer low-field side midplane plasma edge.[1] This line structure ion cyclotron harmonic emission from TFTR is shown in Fig.1. However, in this figure, it is seen that the main sequence of ion cyclotron harmonic peaks is accompanied by a "broader background continuum component" of the spectrum that begins roughly around the fifth harmonic of $\omega_{cd\text{-}E}$, where $\omega_{cd\text{-}E}$ is the deuteron cyclotron frequency at the outer low-field plasma edge on the midplane of the torus. This background emission exists roughly over the frequency range for which the proton spin-flip resonance is within the plasma. The proton g factor g_p is equal to 5.59 and thus the proton spin-flip resonance frequency $\omega_{sp} = g_p\omega_{cp}/2 = g_p\omega_{cd}$. It is our aim here to show that this background emission of Fig.1 is really the thermally excited proton spin-flip laser emission by using the conventional quasilinear theory to quantitatively estimate the steady state emission power levels.

Let us now examine the entropy S of the ensemble of spin 1/2 protons in a uniform external magnetic field $\mathbf{B} = B_{||} = B\,\mathbf{i}_z$ as a function of its internal energy U. According to the canonical ensemble, the fraction of the population in the upper state $f_u = \exp(-\hbar\omega_{sp}/2\kappa T)[\exp(\hbar\omega_{sp}/2\kappa T) + \exp(-\hbar\omega_{sp}/2\kappa T]$ and the fraction in the lower state $f_l = \exp(\hbar\omega_{sp}/2\kappa T)[\exp(\hbar\omega_{sp}/2\kappa T) + \exp(-\hbar\omega_{sp}/2\kappa T)]$. Hence the fractional excess of protons in the spin-up state $G = (f_u - f_l) = \tanh(-\hbar\omega_{sp}/2\kappa T) \approx -\hbar\omega_{sp}/2\kappa T$ for $\hbar\omega_{sp} << \kappa T$. The internal energy referred to the midpoint between the levels is $U = N_p[(\hbar\omega_{sp}/2)f_u - (\hbar\omega_{sp}/2)(1 - f_u)]$, where N_p is the number of protons in the ensemble. The entropy $S = \int dU/\kappa T = N_p\hbar\omega_{sp} \int(dT/\kappa T)\,(\partial f_u/\partial T)$. The dependence of S on U is shown in Fig.2. The lowest possible energy is achieved with all the protons in the lowest energy state (i.e., point D of Fig.2), which is clearly a highly ordered state with S = 0. Likewise the greatest energy is achieved with all the protons in the highest state (i.e., point A of Fig.2), which also is a highly ordered state with S = 0. At intermediate energies S > 0 and is symmetric about U = 0. The point B of Fig.2 corresponds to the thermodynamic state in which the populations of the spin-up and the spin-down states are equal to each other (i.e., the quasilinear steady state with G = 0). This is very much analogous to the flattening of the electron distribution function in the quasilinear steady state of the well-known beam-plasma two-stream instability.[6] Point C of Fig.2 corresponds to the thermodynamic equilibrium state at a positive temperature T (i.e., the conventional Maxwell-Boltzmann state). Let us now suppose that the system is pumped to the highly ordered negative-temperature state corresponding to S = 0, i.e., to point A. Since the entropy S of an isolated system can never decrease (i.e., a statement equivalent to the Boltzmann H theorem), the nonlinear time evolution of the system must correspond to the movement of the system from A towards B along the curve AB. By the principle of minimum entropy production, it is clear that the quasilinear steady state of an initially inverted spin system is the state corresponding to point B of Fig.2 with G = 0. It is interesting to note that when $T \rightarrow \infty$, $G \rightarrow 0$. That is, as $T \rightarrow \infty$, the two thermodynamically allowed states of *minimum entropy production* (i.e., the conventional Maxwell-Boltzmann state with $G \approx -\hbar\omega_{sp}/2\kappa T$ and the quasilinear spin-flip laser steady state with $G \approx 0$) merge into each other, and the system exhibits thermally excited flip-flop coherence between these two states of minimum entropy production in a manner somewhat anologous to the phase coherence in the well-known Dicke super-radiance.[7] Thus, in general, any two-level quantum system such as an ensemble of spin 1/2 system will tend to behave like a laser at infinite temperatures (with rapid flip-flop between the two minimum entropy production states B and C) since the conventional Maxwell-Boltzmann equilibrium state merges with the quasilinear spin-flip laser steady state. This point will become more clear as we will now proceede to examine the allowed fractional energy fluctuations in the canonical ensemble and the fractional concentration fluctuations in the grand canonical ensemble of statistical mechanics.[8]

It is shown in standard text books on statistical physics[8] that for a perfect gas (of fusion product protons under study here) the fractional energy fluctuations in a canonical ensemble $\mathfrak{I}_E = N_p^{-1/2}$ and the fractional concentration fluctuations in a grand canonical ensemble $\mathfrak{I}_N = N_p^{-1/2}$. That is, $\mathfrak{I} = \mathfrak{I}_E = \mathfrak{I}_N = N_p^{-1/2}$. In large tokamak devices that are entering the reactor regime of operation (such as TFTR, JT - 60 and JET) $\hbar\omega_{sp} << \kappa T_p$, where κT_p is the mean thermal spread in the fusion proton directed energy $E_p \approx 3$ MeV and is given by[9] $T_p \approx [m_pT_iE_p/(m_p + m_t)]^{1/2} \approx (T_iE_p/4)^{1/2}$, where T_i is the temperature of the background plasma ions and m_p and $m_t \approx 3m_p$ are the masses of the proton and triton, respectively. It appears therefore at these large kinetic temperatures T_p where the thermal spread κT_p in the fusion product proton directed energy E_p is extremely large compared to the proton's spin-flip energy $\hbar\omega_{sp}$, the spin system under consideration will flip-flop back and forth between its thermodynamic Maxwell-Boltzmann equilibrium state with $G \approx -\hbar\omega_{sp}/2\kappa T_p$ and its quasilinear spin-flip laser radiative steady state with $G \approx 0$ if the thermodynamic fractional fluctuations $\mathfrak{I} \approx N_p^{-1/2} >> |2G| \approx \hbar\omega_{sp}/\kappa T_p$. That is, it will flip-flop between the points C and B of Fig.2 along the curve CB. Indeed, the system will move from point C to point A along the curve CBA and back again to point C along the curve ABC when $\mathfrak{I} >> \hbar\omega_{sp}/\kappa T_p$. We reiterate that because of the extremely low value of $\hbar\omega_{sp}/\kappa T_p$ in comparison to $\mathfrak{I}$, such a flip-flop of the spin system between these two states of *minimum entropy production* is not only reasonable but also is required to occur on the basis of the allowed energy fluctuations in the canonical ensemble and the concentration fluctuations in a grand canonical ensemble of statistical mechanics.[8]

Arunasalam[1,10,11] has previously presented a detailed study of the nonlinear stability of spin-flip excitations and, in particular, has examined the quasilinear time evolution of a spin-flip maser system[10] leading to the understanding of the spin-flip laser experiments of Patel and Shaw[12]. In essence, the quasilinear time evolution of a spin-flip laser system is governed by a coupled set of master equations , one of them describing the time evolution of the photon (i.e., the spin-flip excitation energy ε_k or number $N_k = \varepsilon_k/\hbar\omega_{sp}$) distribution function and the other describing the time evolution of the particle distribution function, i.e., G(v).[10] These equations are essentially the quantum analogue (of a discrete two-level system) of the familiar coupled equations governing the quasilinear time evolution of the beam-plasma two-stream instability.[6] If at time $t = 0$, the difference in population of the two spin states $G = G^o$, the spin-flip excitations energy $\varepsilon = \varepsilon^o$, and at the quasilinear steady state $G = G^\infty \approx 0$ and $\varepsilon = \varepsilon^\infty >> \varepsilon^o$, one can show from Eq. (4) of Ref.10 that at the quasilinear steady state the spin-flip excitations energy density is enhanced over the corresponding black-body value of κT_p by the factor

$$\beta \approx (\varepsilon^\infty/\kappa T_p) \approx G^o (m_p c^2/\kappa T_p)^{3/2} (\pi \omega_{pi}^2/8\mu^3 \alpha \omega_{sp}^2) \quad , \tag{4}$$

where the fine structure constant $\alpha = (e^2/\hbar c) = (1/137)$, the fast Alfven wave index of refraction $\mu = ck/\omega = c/V_A$, the proton ion plasma frequency $\omega_{pi} = (4\pi n_p e^2/m_p)^{1/2}$, and the Alfven wave phase velocity $V_A = c/(1 + 4\pi n_d m_d c^2/B^2)^{1/2} \approx B/(4\pi n_d m_d)^{1/2}$.

For the TFTR data of Fig. 1, the tokamak plasma parameter conditions are: The background plasma is of deuterium ions with $n_e = n_i = n_d + n_p \approx 5 \times 10^{13}$ cm^{-3}, $T_d \approx T_e \approx 5$ keV, the tokamak's major radius $R_0 \approx 2.65$m, the plasma major radius $R_p \approx 2.45$ m, the plasma minor radius $a_p \approx 80$cm, the scrape-off plasma layer radius $a_{sc} \approx (a_p + 15)$ cm ≈ 95 cm, the confining magnetic field $B \approx 4.45 \times 10^4$ Gauss at $R = R_0$, the directed energy of the newly born protons $E_p \approx 3$ MeV and their thermal spread according to Brysk[9] is $T_p \approx (T_d E_p/4)^{1/2} \approx 60$ keV, and the inferred approximate value of the fraction of the newly born proton population $\eta = n_p/n_i \approx 10^{-6}$. Using these parameters in Eq. (4), we obtain $\beta \approx \eta \times 2.36 \times 10^5$ if all these protons were initially statistically inverted, i.e., $G^o \approx 1$. Since the black-body thermal equilibrium value of κT_p is independent of η, it is apparent from Eq. (4) that this spin-flip laser emission of $\beta \kappa T_p$ is linear in the fusion product proton density. This result is consistent with the TFTR experimental observation that the total frequency-integrated power P_{BBCC} in the "broader background continuum component" of the spectrum of Fig. 1 does follow the time evolution of the neutron flux over about 2.5 orders of magnitude. For $T_p \approx 60$ keV, $(\omega_{sp}/2\pi) \approx 205$ MHz and $\Delta\omega/\omega \approx kv_p/\omega = v_p/V_A \approx 0.32$, the expected black-body emission power $P_B \approx \kappa T_p \Delta f = (\omega/2\pi)\kappa T_p(\Delta\omega/\omega) \approx 6.3 \times 10^{-7}$ W, where $v_p = (2\kappa T_p/m_p)^{1/2}$. Hence, the spin-flip laser emission power predicted by the theoretical Eq. (4) $P_{SL} \approx \beta P_B \approx \eta \times 2.36 \times 6.3 \times 10^{-2}$ W $\approx 0.15\eta$ W. For an η of 10^{-6}, $P_{SL} \approx 1.5 \times 10^{-7}$ W. This is the theoretically expected spin-flip laser emisssion power from Eq. (4) as predicted by the conventional quasilinear theory. By using a triangular approximation to the "broader background continuum component" of the TFTR spectrum of Fig. 1, we find that the total frequency-integrated power in this continuum component is $P_{BBCC} \approx [(2 \times 10^{-10}$ W$)(600$ MHz$/2)]/(300$ kHz$) = 2 \times 10^{-7}$ W, where we have used the fact that the bandwidth of the TFTR receiver is 300 kHz. Thus we see there is reasonable agreement between the existing experimental data from TFTR and the predictions of the conventional quasilinear theory of the spin-flip laser (considering the fact that η is known only approximately).

The spin-flip resonant layer volume near the plasma center $(\Delta\text{Vol.}) = 2\pi R_p \, \Delta R_p \, 2a_{sc} = 4\pi R_p^2 a_{sc}(\Delta\omega/\omega) \approx 7.17 \times 10^7 \times (\Delta\omega/\omega)$ cm^3 $= 2.29 \times 10^7$ cm^3 since $(\Delta\omega/\omega) \approx 0.32$. Thus the total number of protons in this resonant volume is $N_p \approx \eta \times 1.15 \times 10^{21} \approx 1.15 \times 10^{15}$. Hence $\mathfrak{I} = N_p^{-1/2} \approx 2.96 \times 10^{-8}$. The value of $(\hbar\omega_{sp}/\kappa T_p) \approx 1.41 \times 10^{-11}$. That is, the fractional statistical fluctuations both in energy and particle concentration $\mathfrak{I}$ is very much larger than the ratio $(\hbar\omega_{sp}/\kappa T_p)$. Hence the fluctuation laws of statistical mechanics do indeed allow the spin system under consideration to flip-flop between its thermodynamic equilibrium state and its spin-flip laser quasilinear steady state. From a thermodynamic point of view, both these states are indeed *states of minimum entropy production*.[13] Further, unlike the ion cyclotron harmonic emission for which $\mathbf{k}_\perp >> \mathbf{k}_\parallel$ and is subject to the Stix-Golant lower hybrid accessibility criterion, this thermally excited spin-flip laser emission is not a near perpendicular emission (i.e., is a wide angle emission with $\mathbf{k}_\parallel >> \mathbf{k}_\perp$) and is hence fully accessible to the outside receiving antenna (and does not have to obey the Stix-Golant lower hybrid accessibility criterion). Thus, from Eq. (4) and the shape of the broader background continuum component of the spectrum of Fig. 1, one can in principle unfold the total fusion product proton's radial profile. Indeed from Eq. (4), we get $n_p \propto P_{SL} (T_d^{1/4} n_d^{3/2}/B)$ since $T_p \propto T_d^{1/2}$.

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REFERENCES

1 V. Arunasalam, G.J. Greene, and K.M. Young, Princeton University Plasma Physics Laboratory report PPPL-2875 (February, 1993).

2 G. Bekefi, *Radiation Processes in Plasmas* (Wiley, New York, 1966).

3 T.H. Stix, *The Theory of Plasma Waves* (Mc-Graw Hill, New York, 1962); V.E. Golant, Sov. Phys.- Tech. Phys. **16**, 1980 (1972).

4 T.E. Stringer, Plasma Phys. **16**, 651 (1974).

5 G.A. Cottrell, V.P. Bhatnagar, O. da Costa, R.O. Dendy, A. Edwards, J. Jacquinot, M.F.F. Nave, M. Schmid, A. Sibley, P. Smeulders, and D.F.H. Start, Europhysics Conference Abstracts, 1992 International Conference on Plasma Physics (Innsbruck, 1992), Vol. 16C, Part2, Vol.1, p.327, (also private communication).

6 W.E. Drummond and D. Pines, Nucl. Fusion Suppl. Pt. 3, 1049 (1962).

7 R.H. Dicke, Phys. Rev. **93**, 99 (1954); N. Bloembergen and R.V. Pound Phys. Rev. **95**, 8 (1954).

8 C. Kittel, *Elementary Statistical Physics* (John-Wiley & Sons, Inc., New York, 1958).

9 H. Brysk, Plasma Phys. **15**, 611 (1973).

10 V. Arunasalam, Phys. Rev. Lett. **28**, 1499 (1972).

11 V. Arunasalam, J. Appl. Phys. **46**, 3119 (1975).

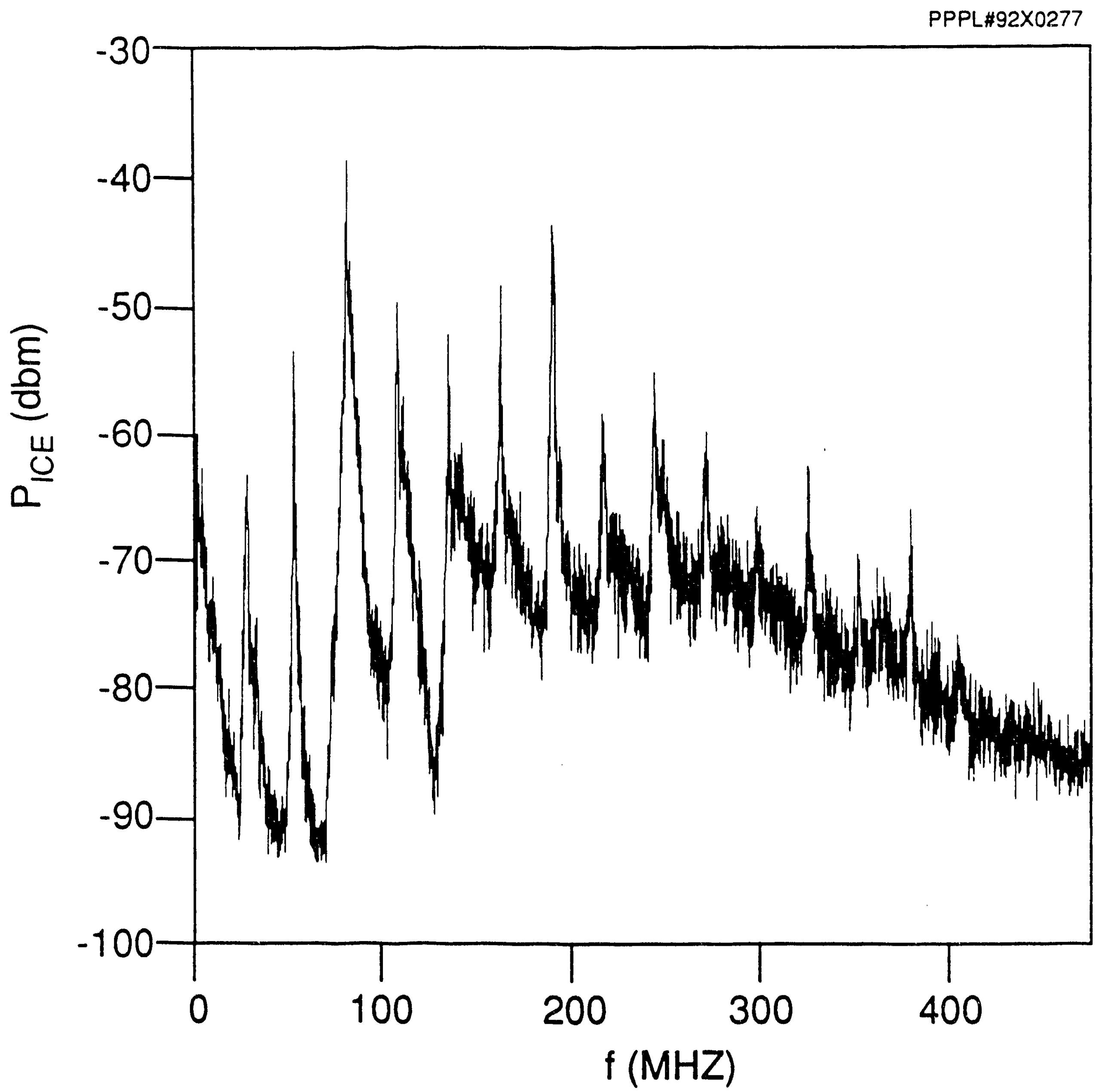
12 C.K.N. Patel and E.D. Shaw, Phys. Rev. Lett. **24**, 451 (1970).

13 E.G. Harris, *A Pedestrian Approach to Quantum Field Theory* (John-Wiley & Sons, New York, 1972).

FIGURE CAPTIONS

Fig. 1. A typical TFTR spectrum showing the ion cyclotron harmonic emission lines riding on the top of the broader background continuum component of the spectrum. Here, 26.4 MW deuterium neutral beams were injected into a deuterium background plasma.

Fig. 2. The entropy S as a function of the internal energy U for a two-level spin system.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-30
-40
-50
-60
-70
-80
-90
-100
P ICE (dbm)
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400
f (MHZ)

Fig. 1

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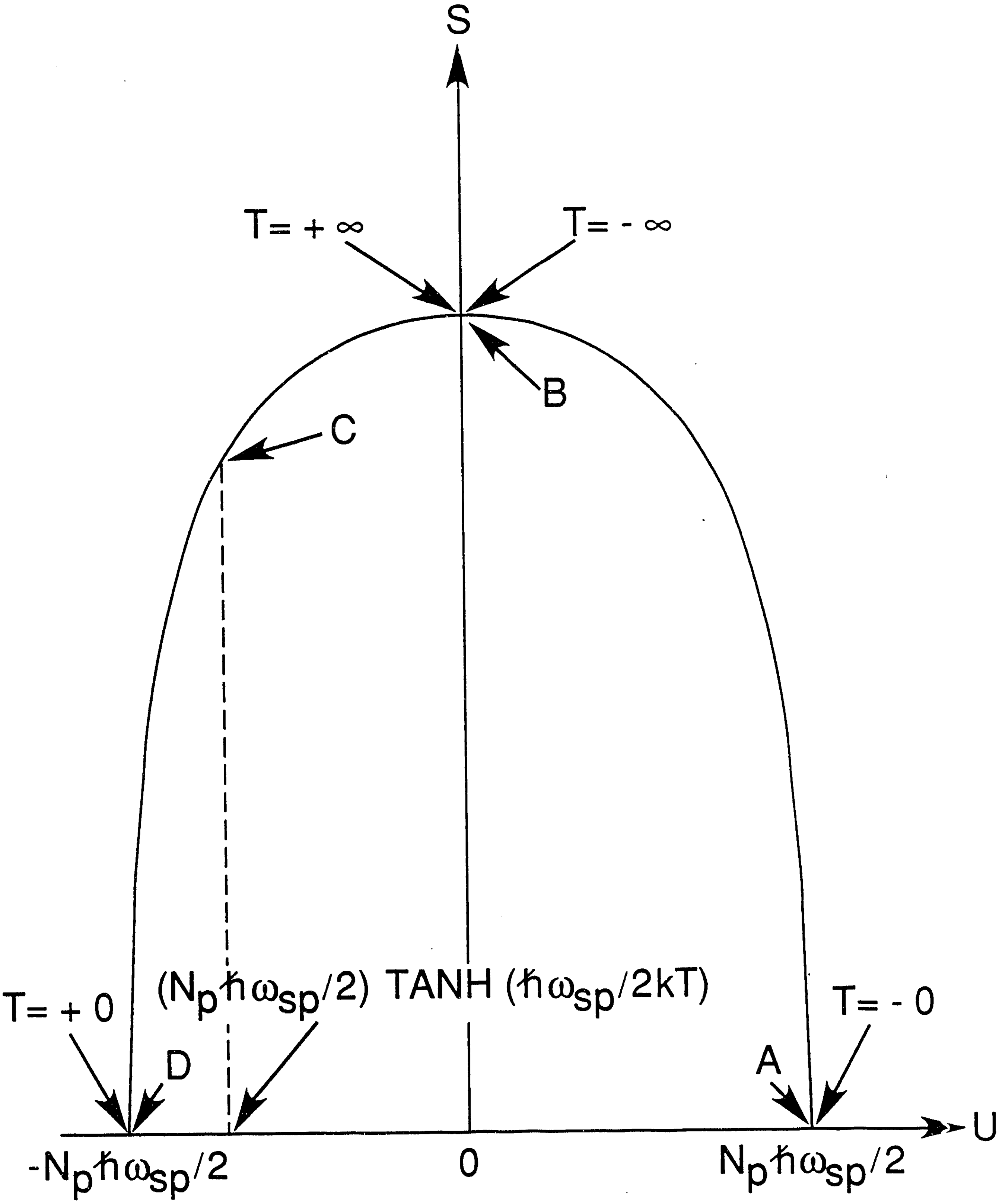

Fig. 2

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