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Geometrical Effects in X-mode Scattering

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ABSTRACT

One technique to extend microwave scattering as a probe of long wavelength density fluctuations in magnetically confined plasmas is to consider the launching and scattering of extraordinary (X-mode) waves nearly perpendicular to the field. When the incident frequency is less than the electron cyclotron frequency, this mode can penetrate beyond the ordinary mode cutoff at the plasma frequency and avoid significant distortions from density gradients typical of tokamak plasmas. In the more familiar case, where the incident and scattered waves are ordinary, the scattering is isotropic perpendicular to the field. However, because the X-mode polarization depends on the frequency ratios and the ray angle to the magnetic field, the coupling between the incident and scattered waves is complicated. This geometrical form factor must be unfolded from the observed scattering in order to interpret the scattering due to density fluctuations alone. The geometrical factor is calculated here for the special case of scattering perpendicular to the magnetic field. For frequencies above the ordinary mode cutoff the scattering is relatively isotropic, while below cutoff there are minima in the forward and backward directions which go to zero at approximately half the ordinary mode cutoff density.

I. INTRODUCTION

The scattering of microwaves by density fluctuations is usually carried out by launching and scattering ordinary mode radiation.[1,2] When this is done in the plane perpendicular to the magnetic field, the scattered radiation pattern of a single electron is that of a simple dipole oriented along the magnetic field and is, thus, isotropic in the scattering plane. This simplifies the interpretation of the scattering due to electron density fluctuations. Density correlations at different values of k $(=|\mathbf{k}_i - \mathbf{k}_s|)$ determined by the incident (i) and scattered (s) wave vectors only need to be normalized to the relative gain of the launching and receiving antennae. However, much of the interesting phenomena in tokamak plasmas takes place at relatively long wavelengths which can be observed only at small scattering angles (at correspondingly poor spatial resolution) or by using long probe wavelengths. For example, in tokamaks drift waves which most affect transport occur at $k\rho_s \approx 0.3$ where $\rho_s \equiv \sqrt{T_e/M_i}/f_{ci}$. Thus, for a deuterium plasma at a toroidal field B_T of 5 T and T_e = 2 keV, the relevant fluctuation wavelengths have $\lambda = 2\pi/k \approx 1.5$ cm. The scattering condition, $k = 4\pi[\sin\theta/2]/\lambda_i$, where θ is the angle between $\mathbf{k}_i$ and $\mathbf{k}_s$, implies that probe wavelengths on the order of 1 cm are needed if good spatial resolution is required. For the ordinary mode the wavelength limit is set by a cutoff at the plasma frequency and refraction near the cutoff from density gradients which causes distortion of the ray paths. The density which cuts off 30 GHz (1 cm) radiation is 1.1×10^{19} m^{-3}; so the tokamak core is not accessible at the wavelengths of interest.

One way around the limitation imposed by the ordinary (O) mode cutoff is to consider launching and receiving the extraordinary (X) mode. For perpendicular propagation and when the incident wave frequency (f_i) is below the electron cyclotron frequency (f_c), the X-mode cut-off condition is $f_i^2 + f_i f_c - f_p^2 = 0$ giving a substantially higher cut-off density. In the previous example when the incident frequency is 30 GHz and B_T = 5.0 T, then f_c/f_i = 4.7, and the X-mode cutoff occurs at

$6.3\times10^{19}\ m^{-3}$.

However, the X-mode is elliptically polarized perpendicular to the magnetic field, and the ellipticity depends on the ratios f_c/f_i, f_p/f_i, and on the ray angle to the magnetic field. As a result, the coupling between the incident and scattered waves is complicated, and the isotropic scattering form factor for perpendicular scattering characteristic of the O-mode must be replaced by a factor appropriate for the X-mode. The purpose of this paper is to calculate this factor and to examine whether it detracts from the value of using X-mode scattering to examine density fluctuations.

It will be shown that, for the special case of scattering nearly perpendicular to the magnetic field, the geometrical form factor is relatively isotropic at densities above the O-mode cutoff, but for lower densities the form factor has minima in the forward and backward directions. When $f_c/f_i > 1$, these minima go to zero at about half the O-mode cut-off density. At all angles the cross section is reduced by approximately $f_c/2f_i$.

The general form of the scattering cross section for a plasma in the presence of a magnetic field, including the geometrical form factor, has been worked out by Akhiezer et al.[3-5] and by Simonich.[6,7] The two formulations appear somewhat different but agree on the basic coupling term. The essential difference between the two calculations is due to an extra factor in Simonich's expression which accounts for the difference between the phase and group directions and for the curvature of the index of refraction surface. The physical problem considered here requires that all features be included in the final result.

II. FORMULATION

The scattering geometry is shown in figure 1a. The angles of the incident and scattered propagation vector directions $\mathbf{k}_i$ and $\mathbf{k}_s$ to the magnetic field $\mathbf{B}$ are θ_i and θ_s. The magnetic field will be assumed to lie in the z direction and $\mathbf{k}_i$ to lie in the x-z plane. The angle between the $\mathbf{B},\mathbf{k}_i$ plane and the $\mathbf{B},\mathbf{k}_S$ plane is Φ. Characteristic plane waves in a homogeneous cold plasma are described by the equation

$$\mathbf{k}\times(\mathbf{k}\times\mathbf{E}) - \omega^2/c^2\overline{\overline{\varepsilon}}\cdot\mathbf{E} = 0 \quad ,$$

where if $\mathbf{k}$ lies in the x-z plane,

$$\overline{\overline{\varepsilon}} = \begin{bmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{bmatrix}$$

and in the electron approximation $(M_i/M_e >> 1)$

$$S = 1 - \alpha/(1-\beta)$$
$$D = -\beta^{1/2}\alpha/(1-\beta)$$
$$P = 1 - \alpha \quad ,$$

where $\qquad \alpha = f_p{}^2/f^2, \quad \beta = f_c{}^2/f^2.$

Solutions exist when $\left|\left|\mathbf{k}\times\mathbf{k}\times -\omega^2/c^2\overline{\overline{\varepsilon}}\right|\right| = 0$ or when

$$k^2c^2/\omega^2 \equiv n^2 = 1 - \alpha/\{1-\beta\cos\theta[G\pm(G^2+1)^{1/2}]\} \quad ,$$

where

$$G = \frac{\sin^2\theta}{2(1-\alpha)\cos\theta} \quad .$$

The lower sign corresponds to the O-mode and the upper sign to the X-mode. Thus, for O-mode perpendicular propagation

$$n^2 = P = 1-\alpha$$

and $\qquad E = (0, 0, 1) \quad .$

For the X-mode

$$n^2 = (S^2 - D^2)/S = 1 - \alpha(1-\alpha)/(1-\alpha-\beta)$$

and $\mathbf{E} = (1,\ iD/S,\ 0)$.

These are the two characteristic modes which propagate in the direction perpendicular to **B**. Cutoff is characterized by n=0 and resonance by n->∞. The polarization of the O-mode is linear parallel to **B** while the X-mode is elliptically polarized in the plane perpendicular to **B**.

III. SCATTERING CROSS SECTION

The scattering cross section has been calculated assuming that the observer is far from the scattering volume (Born approximation), that there are a large number of fluctuation wavelengths in the scattering volume, and that the scattering or absorption mean-free path is long compared to the plasma dimensions. The notation of Akhiezer et al for the scattering cross section will be used with appropriate modifications for the index of refraction curvature and phase versus group factors. The differential cross section is

$$d\sigma = r_0^2 \Gamma \langle \delta n_e^2 \rangle_{k,f} \, d\Omega \, df \quad ,$$

where $\Gamma = [f_i^2 f_s^2 / f_p^4] R |\xi|^2 H / |C|$ is the geometrical form factor,

r_0 is the classical electron radius,

$\langle \delta n_e^2 \rangle_{k,f}$ is the ensemble-averaged, Fourier-transformed, density autocorrelation function,

$d\Omega$ is the solid angle sampled by the detector,

and df is the frequency interval sampled by the detector.

The terms in Γ are identified as follows

$$R = n_s^2/n_i (|\mathbf{E}_i|^2 - |\mathbf{E}_i \cdot \mathbf{k}_i|^2 / k_i^2) \Sigma_s \mathbf{E}_s^* \cdot \overline{\overline{\varepsilon}}_s \cdot \mathbf{E}_s$$

$$\xi = \Sigma_s \mathbf{E}_s^* \cdot (\overline{\overline{\varepsilon}}_s - \mathbf{I}) \cdot \mathbf{E}_i$$

$$H = \cos\delta_s \cos\delta_i$$

$$C = [1 + \sin^2\delta_s - (n_s^{\cdot\cdot}/n_s)\cos^2\delta_s] \sin\rho_s \cos\delta_s / \sin\theta_s$$

$$\tan\delta_S = -\, n_S^{\cdot} / n_S$$
$$\delta_S = \rho_S - \theta_S$$
$$n_S^{\cdot} \equiv dn_S/d\theta_S$$
$$n_S^{\cdot\cdot} \equiv d^2 n_S/d\theta_S^{\,2}$$

and 1 is the unit tensor.

The matrices in R and ξ must be summed over both of the final state normal modes (O and X) and, of course, the initial polarization may itself be a sum over any linear combination of normal modes for the incident direction and frequency. The term H describes the correction due to the difference in the phase and group velocities, and C is the curvature of the index of refraction surface. The angle between the group velocity and the field direction is ρ, and δ is the angle between the phase and group directions as shown in figure 1b. For high frequencies the term $H/|C|$ reduces to unity and the term $R|\xi|^2$ becomes the familiar angular pattern of a simple dipole. The main coupling term $R|\xi|^2$ is common to both the Akhiezer and Simonich[8] calculations while $H/|C|$ describes the group versus phase and index curvature components introduced by Simonich.

For the coordinate system which has been chosen here the scattered wave does not lie in the x-z plane and must be represented as a rotation on the simpler form in which the normal mode has been expressed. For example, when one considers X-mode scattering and $\theta_i=\theta_S=\pi/2$, the incident wave $E_i = (1,\ iD_i/S_i,\ 0)$ whereas the scattered field is

$$E_S = \begin{bmatrix} \cos\Phi & -\sin\Phi & 0 \\ \sin\Phi & \cos\Phi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ iD_S/S_S \\ 0 \end{bmatrix} .$$

The term containing $E_S^{*}\cdot(\overline{\overline{\epsilon}}-1)\cdot E_i$ contains the primary angular dependence for the form factor, and can go to zero for forward and backward scattering ($E_S = \pm E_i$). Physically this means that the rate of change of the index of refraction with density is zero at some density.

An examination of the index shows that this must occur on the interval $0<\alpha<1$ for $\beta>1$ since $n^2=1$ at $\alpha=0$ and 1, and $n^2>1$ in between.

As given, the cross section expresses the coupling between arbitrary incident and scattered waves. An expression for the general case is possible but is sufficiently complex that important effects would not be revealed easily. The case of interest here is X-mode incident where $\theta_i = \theta_s = \pi/2$ and $f_s = f_i$. It is expected on physical grounds that there will be no O-mode wave scattered since there is no component of the polarization field in the incident wave which is parallel to **B**. In fact, $\xi=0$ for the matrix element corresponding to scattering from X to O-mode. It will be sufficient to focus attention only on the scattered X-mode. This leads to significant simplifications in the general expression. First, the angle δ between the phase and group velocities goes to zero, and the curvature term $H/|C|$ becomes $|2-n^2|$. Furthermore, the conventional scattering angle, Θ, between the wavevectors $\mathbf{k}_i$ and $\mathbf{k}_s$ becomes the angle Φ. In this case, after some algebra

$$E_s^{*}\cdot\varepsilon_s\cdot E_s = S(S^2-D^2)/D^2$$

$$|E_i|^2-|E_i\cdot\mathbf{k}_i|^2/k_i^2 = S^2/D^2$$

$$|\xi|^2 = \{[D(S^2-D^2)-2SD]^2\sin^2\Theta + [S(S^2-D^2)-(S^2+D^2)]^2\cos^2\Theta\}/D^4$$

and $$H/|C| = |1-n_s'/n_s| = |2-n^2| .$$

The final result for the X-mode geometrical form factor Γ_X is

$$\Gamma_X = \frac{\beta[1-\alpha^2-\beta]^2\sin^2\Theta + [(\gamma^2-\beta(\beta-1)]^2\cos^2\Theta}{|\gamma^3(1-\alpha^2-\beta)|} ,$$

where $\gamma = 1-\alpha-\beta$. The form factor is seen to be symmetric about $\Theta=\pi/2$, and in the forward and backward directions the cross section goes to zero when the condition

$$\alpha = \sqrt{\beta(\beta-1)} - (\beta-1)$$

is met. In the example used above $\beta=(4.7)^2$, and $\Gamma_X=0$ at $\alpha=0.49$ which corresponds to a density of about half the O-mode cutoff. This is the same condition which is obtained by setting dn^2/dn_e or $dn^2/d\alpha = 0$. At the O-mode cutoff ($\alpha=1$) the form factor is simply

$$\Gamma_X = (1/\beta^2)\sin^2\Theta + (1/\beta)\cos^2\Theta \quad .$$

And when the density reaches the X-mode cutoff ($\alpha = \beta^{1/2}+1$), Γ_X becomes isotropic and $\Gamma_X = 2/(\beta^{1/2}+1)^2$. This occurs because the X-mode polarization becomes circular at cutoff, and the scattered polarization fields are equally matched in all directions. Figures 2a and 2b show Γ as a function of Θ for various values of α for our example $\beta=(4.7)^2$ and for $\beta=4.0$. From a practical viewpoint the cross section does not change so rapidly for the most interesting values of α and β that unfolding $\langle\delta n_e^2\rangle$ presents large difficulties. However, the cross section is reduced approximately proportional to λ^{-1} which compensates for an increase in the cross section proportional to λ^2 that might be expected to come from $\langle\delta n_e^2\rangle$ for coherent waves.

The corresponding result for the <u>O-mode</u> incident and scattered at $\theta_i = \theta_s = \pi/2$ gives

$$\Gamma_0 = 1/(1-\alpha) \quad ,$$

showing the expected isotropy and resonance at $\alpha=1$. In the high frequency limit ($\alpha=\beta=0$), $\Gamma_X= \cos^2\Theta$ and $\Gamma_0=1$ which is the emission pattern of a simple dipole.

IV. DISCUSSION

In order to apply the idealized calculation given here to the more complex situation in a tokamak, one must know how characteristic modes propagate nearly perpendicular through sheared fields, through density gradients, and in a hot plasma. Fortunately these complications do not change the result significantly. It can be shown that away from resonances and cutoffs the polarization fields of the ray remain essentially those given by the cold plasma relations, and the ray propagates in such a way that the X(O)-mode fields remain perpendicular (parallel) to the <u>local</u> magnetic field. In the case of magnetic fields sheared perpendicular to the ray direction Boyd[9] has shown that when the density is sufficiently high, the modes propagate so that the polarization plane rotates with the local magnetic field. For shears typical of a tokamak and for the conditions in our example, the critical density is $n_e \approx 10^{14}\ m^{-3}$. Thus, in all but a very small region at the edge the mode propagates in a very simple way. Several simulations using modeled tokamak fields and densities have been treated with a ray tracing code[10] and give similar results. That is, an X-mode launched at the edge propagates into the plasma and refracts due to density gradients, but its polarization field remains perpendicular to the local magnetic field. For propagation away from cutoffs and resonances the cold plasma approximation is adequate in describing the ray paths. This means that the scattering cross-section calculated here for pure X-mode scattering is appropriate as long as the coordinate system defined by **B** is taken locally. Ray tracing can be used to infer the local scattering angles and the location of the scattering region as long as the density and temperature (and, therefore, **B**) profiles are known. For many cases of practical interest, and when refraction effects are not too severe, this can be done with sufficient accuracy.

In practice, the choice of λ_i is influenced not only by a desire to observe long wavelength fluctuations consistent with various access and cut-off phenomena, but by plasma emission which can mask the scattered signals near the plasma frequency and harmonics of the electron cyclotron frequency.[11,12] Minima between these emission peaks are good regions to do scattering. However, when there is a small population of runaway electrons, these gaps fill in and there can be significant emission near the plasma frequency.

IV. CONCLUSION

A general formula is given for the angular dependence of the scattering cross section due to the coupling of polarization fields in an anisotropic plasma for the special case in which the incident and scattered waves are X-mode propagating perpendicular to the magnetic field. This form factor has been shown to be symmetric about $\Theta=\pi/2$ and to exhibit minima in the forward and backward directions. When $\beta \equiv f_c/f_i > 1$, there is a density less than the O-mode cut-off density for which the minima go to zero. For $\beta > 2$ this density is approximately half the cut-off density. Above the O-mode cutoff the form factor becomes isotropic and has a value of order $2/\beta$. This result may be used to unfold the scattering due to density fluctuations from observations of the scattering of X-mode radiation in the plane pependicular to the toroidal field of a tokamak plasma. Finally, the results given here show that the two previous treatments of the problem are consistent, but that the work of Simonich, in addition to treating the ray problem, includes significant effects due to the difference between the ray and group velocities and due to the curvature of the index of refraction surface.

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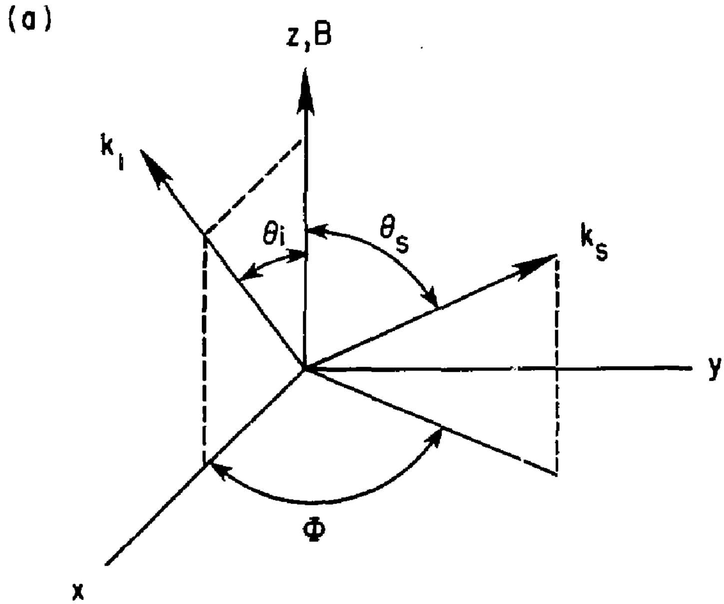
FIGURE CAPTIONS

FIG 1. The relationship between the incident and scattered rays and the magnetic field is shown in 1a. The relationship between the phase and group velocities and the magnetic field is shown in 1b.

FIG 2. The geometrical form factor Γ versus the scattering angle Θ is shown in 2a for the case $\beta=(4.7)^2$ and in 2b for $\beta=4$ for several values of the parameter α.

#86X1380



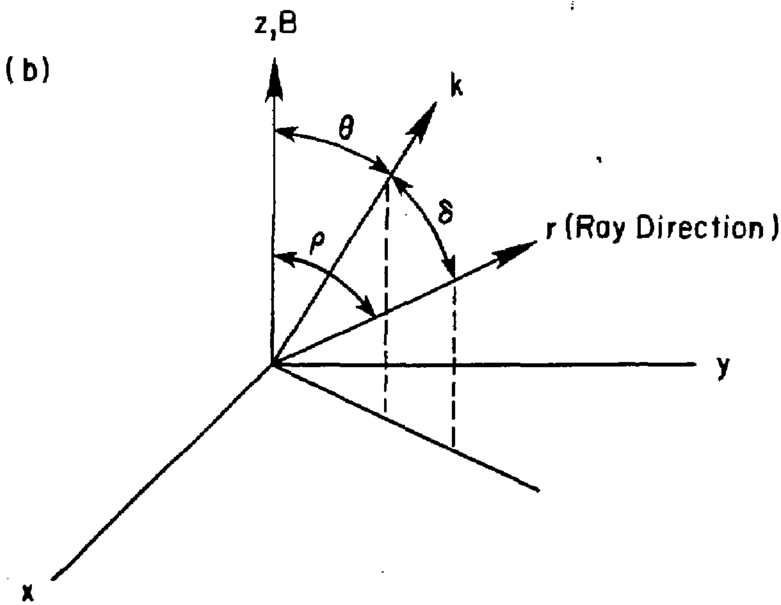
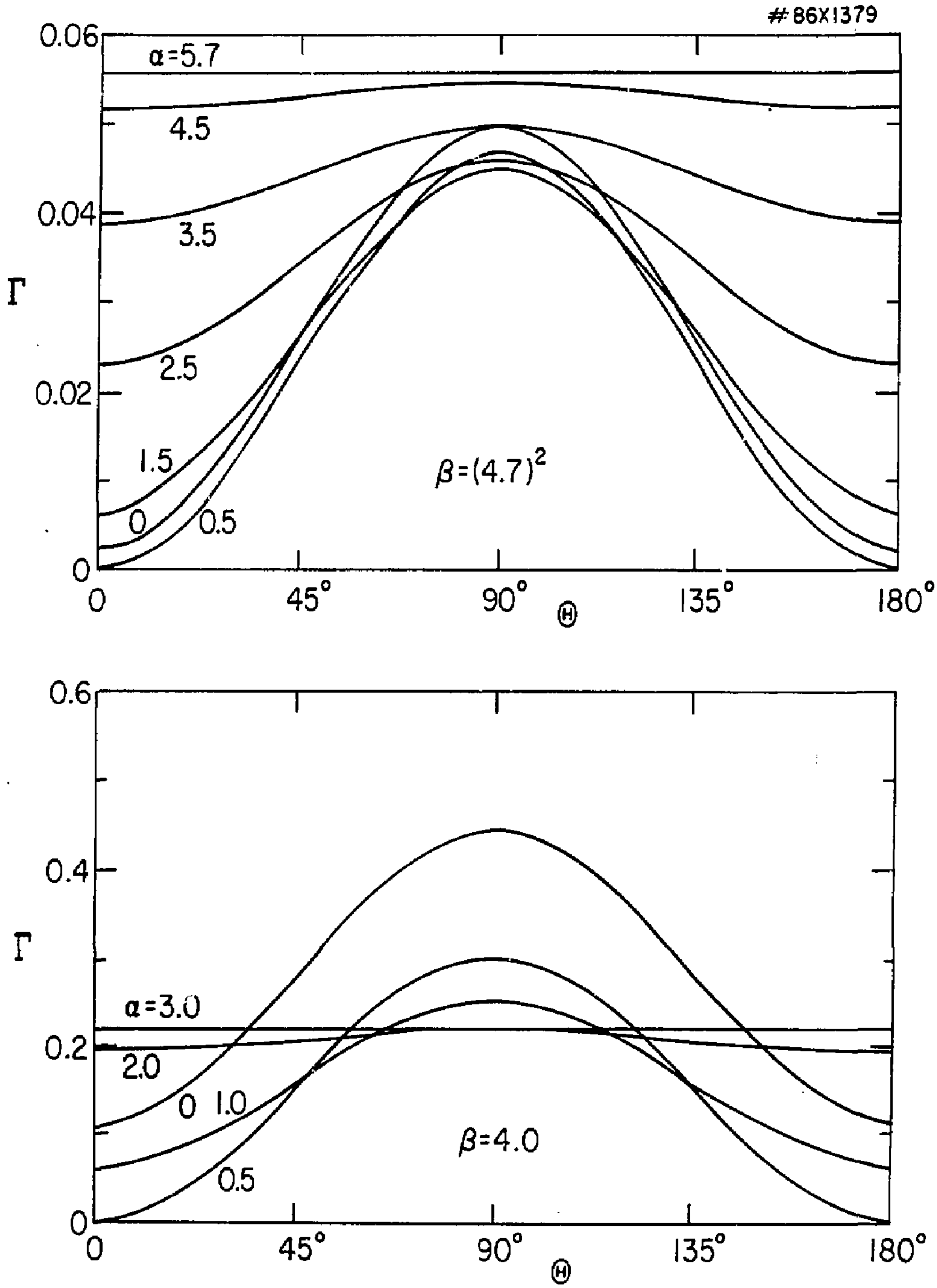


Fig. 1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4.5
0.04
3.5
Γ
2.5
0.02
1.5
0
0.5
β=(4.7)²
0
45°
90°
135°
180°
Θ
0.6
0.4
Γ
α=3.0
0.2
2.0
0 1.0
β=4.0
0.5
0
0
45°
90°
135°
180°
Θ

Fig. 2

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