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MAGNETIC MODES IN SUPERLATTICES*

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ABSTRACT

A first discution of reciprocal propagation of magnetic modes in a superlattice is presented. In the absence of an applied external magnetic field a superlattice made of alternate layers of the type antiferromagnetic - Non-magnetic materials presents effects similar to those of phonons in a dieletric superlattice. We show as well the existence of two bands for the surface modes.

The properties of magnetic waves in thin films[1-7] and superlattices[8-11] are currently of great interest. We play particular atention to those modes wich arise from the coupling between the long wavelength magnetic excitations and the eletromagnetic fluctuating fields[12]. For a propagation in the Voigt Geometry (propagation parellel to the surface and perpendicular to the static magnetic field), it has been shown that there is no reciprocity in the propagation when the system is semi-infinite i.e. just a single surface[13]. The presence of double surfaces in a thin film, recorver the reciprocity[2]. In an antiferromegnet, however, the existence of two modes with finite frequency in zero applied field, make the existence of reciprocal propagation possible. Reciprocal magnetostatic surface modes have been study by Camley[14]. Reciprocal retarded modes have been studied by Oliveira and Amato[6], Dias and Oliveira[7]: The results they have obteined are similar to those obtained for a dieletric material i.e. the propagation of those longewavelenth magnetic excitations are more similar to the phonons in a ionic material[15-17] than those of a ferromagnet one. The main objective of this work is to extend these study to the supperlatice case. We shall considerer a infinite superlattice made of alternate layers of antiferromagnet- Non magnetic material, the magnetic material has thickness L and the Non-magnetic material has thickness d. The static magnetization M and the applied external field B_o is in the z - direction and the interfaces are normal to x - direction, as shown in Figure 1. The system has periodicity R = L + d, in the z direction and are infinite in the y and z direction. Using the Blocks equations we get the permeability tensor

$$\mu_{xx} = \mu_{yy} = K = 1 + \omega_A \omega_M \left(\frac{1}{\omega_0^2 - (\omega - H_0)^2} + \frac{1}{\omega_0^2 - (\omega + H_0)^2} \right) \tag{1a}$$

$$\mu_{xy} = -\mu_{yx} = i\nu = i\omega_A \omega_M \left(\frac{1}{\omega_0^2 - (\omega - H_0)^2} - \frac{1}{(\omega_0^2 - (\omega + H_0)^2} \right) \tag{1b}$$

Here $H_A = \omega_A/\gamma$ is the anysotropy field, and $\omega_M = 4\pi\gamma M$, ω_0 is the magnon (k=0) frequency at zero applied field, $\omega_0^2 = \omega_A^2 + 2\,\omega_{ex}\omega_A$, where ω_{ex}/γ is the exchange field. We may label every unity cell by n, and for the infinité superlattice $n = 0, \pm 1, \pm 2...$, so the magnetic material fulfill the regions $nR < x < Rn + L$ and the non- magnetic media lies on $nR + L < x < (n+1)R$. We shall write the magnetic fields as

$$h\,(r,t) = h\,(x)\, e^{i\,(ky - \omega t)} \tag{2}$$

where

$$h_\alpha(x) = h^+_{n,\alpha}\,(x) + h^-_{n,\alpha}\,(x) \qquad \alpha = x,y \tag{3}$$

and

$$h^{\pm}_{n,\alpha}\,(x) = \begin{cases} f^{\pm}_{n,\alpha}\, e^{\pm \beta x} & nR < x < nR + L \\ g^{\pm}_{n,\alpha}\, e^{\pm \alpha x} & nR + L < x < (n+1)R \end{cases} \tag{4}$$

with

$$\beta^2 = k^2 - \frac{\omega^2}{c^2}\mu_v\,\varepsilon_M \qquad (5)$$

$$\alpha^2 = k^2 - \frac{\omega^2}{c^2}\mu\varepsilon \qquad (6)$$

k is the propagation wave-vector for propagation parallel to the surface. $\mu\nu$ is the voigt permeability, ε_M , ε are the dialetric constante of the magnetic and the non-magnetic media. μ is the (constant) permeability of the non-magnetic media (latter on we shall put $\mu = 1$ an $\nu = 0$, we shall keep it here just to obtain more symetrical equations). Since the superlattice is infinite we need just to get the relations between the fields on site n and in the site n + 1. Using a method similar to those of Barnas[11] we get the Transfer Matriz

$$\begin{pmatrix} f^+_{n,y} \\ f^-_{n,y} \end{pmatrix} = \underset{\sim}{T'} \begin{pmatrix} \varepsilon^+_{n,y} \\ \varepsilon^-_{n,y} \end{pmatrix} \qquad (8)$$

$$\begin{pmatrix} \varepsilon^+_{n,y} \\ \varepsilon^-_{n,y} \end{pmatrix} = \underset{\sim}{T''} \begin{pmatrix} f^+_{n+1,y} \\ f^-_{n+1,y} \end{pmatrix} \qquad (9)$$

Explicitly

$$\underset{\approx}{T}' = \begin{bmatrix} \gamma_{11}\,\delta_1 & \gamma_{12} / \delta_2 \\ \gamma_{21}\,\delta_2 & \gamma_{22} / \delta_1 \end{bmatrix} (2\gamma)^{-1} \qquad (10)$$

$$\underset{\approx}{T}'' = \begin{bmatrix} \gamma_{22}\,\delta_3 & -\gamma_{12} / \delta_3 \\ -\gamma_{21}\,\delta_3 & \gamma_{12} / \delta_3 \end{bmatrix} (2\alpha\beta K\ )^{-1} \qquad (11)$$

$$\gamma_{ij} = \ \gamma + (-1)^{i+j}\ \alpha\beta K - \ (-1)^{j}\ \alpha b \qquad (12)$$

here

$$\gamma = k^2 - (\omega^2/c^2)\ \varepsilon_M K$$

$$\delta_1 = \exp\ ((\beta - \alpha)\ L\ )$$

$$\delta_2 = \exp\ ((\beta + \alpha)\ L\ )$$

$$\delta_3 = \exp\ (\alpha\ R) \qquad (13)$$

Equations (10) and (11) shows that except by commom factors and phase factors, T' is the inverse of T'' and it does make sense since it represents the inverse process e $\varepsilon_n \rightarrow f_n$ and $f_{n+1} \rightarrow \varepsilon_r$.

Equations (7) and (8) yield

$$\begin{bmatrix} f^{+}_{n,y} \\ f^{-}_{n,y} \end{bmatrix} = \underset{\sim}{T} \begin{bmatrix} f_{n+1,y} \\ f_{n+1,y} \end{bmatrix} \tag{14}$$

where obviously

$$\underset{\sim}{T} = \underset{\sim}{T}' \underset{\sim}{T}'' \tag{15}$$

and

$$\det (\underset{\sim}{T}) = 1 \tag{16}$$

Now the translational symmetry of the superlattice i.e. $x \rightarrow x + nR$ yields a new componente Q of the wave vector for propagation perpendicular to the film interface. The Bloch theorem for the superlattice reads

$$\begin{bmatrix} f_{n+1,y} \\ f_{n+1,y} \end{bmatrix} = e^{iQR} \begin{bmatrix} f_{n,y} \\ f_{n,y} \end{bmatrix} \tag{17}$$

Combining those results we get

$$\cos (QR) = \cosh (\alpha d) \cosh (\beta L) + \varepsilon \sinh (\alpha d) \sinh (\beta L) \tag{18}$$

where

$$\varepsilon = \mu \frac{k^2 - (\omega^2/c^2)\, \varepsilon_M\, K}{2\alpha\beta\, K} + \frac{\alpha \mu_v}{2\beta\mu} \tag{19}$$

For $\mu = \varepsilon_M = \varepsilon = 1$ We obtain the result of Barnas[11].

For $H_0 \to 0$, $\nu \to 0$, $\mu_v = K$.

$$\epsilon = \frac{1}{2}\left(\frac{\mu\beta}{\alpha K} + \frac{\alpha K}{\mu\beta}\right) \quad (20)$$

Last results is indentical to the result of Ray and Tilley[19] For phonons propagation in superlattices (of course we should change the magnetic permiability by the dieletric constant) i.e. our results reproduces theirs s polarazation for phonons propagation. For those modes (H_0 = 0) the antiferromagnetic propagation is very symmetrical so they are more similar to phonons (in a superlattice make of two alternate isotropic dieletric) than to magnons propagation in, say, ferromagnetic or ferrimagnetic systems. Notice as well that for $d \to \infty$ equations (18) and (19) reproduces previous results[1,2,3]. From now forwords we shall be concerned mainly with those more symmetric (H_0 = 0) modes since they are more simple. Previous works[6,7] in thim films shows that they are as well more stable.

Equations (18) and (20) in the limit $d \to \infty$ combine to give

$$\alpha K = -\beta \coth(\beta L/2) \quad (21)$$

$$\alpha K = -\beta \tanh(\beta L/2) \quad (22)$$

again those modes corresponds to modes with low "ground state" and higher energy "excited state". They have well defined parity (Odd and even respectively). Those modes were firsty obtained by Kliewer and Fuchs[16], Borstel and Falge[15], Oliveira at all[17] for the phonon case, and more recentlly from the works of Oliveira and Amato[6], Dias and Oliveira[7], for zero field antifenomagnetic films.

Our superlattice are make of MnF_2 (H_{ex} = 550 kOe, Ha = 3.8 kOe, M = 0.6 kOe, ε_M = 5.5) and a non-magnetic (μ = 1, ε = 2.5). Figure 2 shows the upper and low surface modes for d → ∞ for some values of the parameters. All the frequencies are in units of ω_s ($\omega_s^2 = \omega_0^2 + 2\omega_A\omega_M$), the wave vectors in units of k_s^2 ($k_s = \varepsilon\omega_s^2/c^2$), and the length in Units of k_s^{-1}. We see that for both modes as k → ∞ ω → ω_s for the highes modes (for some values of L) we may get ω> ω_s, in this case the group velocity becomes negative. Figure 3 shows how the modes converges to only one degenerated mode as L increases. This result is similar to a system compose by two indentical atoms, such as hydrogen, when we let them get close the interaction splits the levels in two. In figure 4 we fix a finite value of L (L = 0.2) and a finite value of k and we plot ω in function of d. We see that when Q assume the values 0 < Q < π/L (the half branch − π/L < Q < 0 yields the some values) the two levels split in two bands for intermediate values of d. For small values of d (d ≤ 0.3 in our case) the two bands interact strongly and we get an only band (that is the reason that leads Barnas to get an only band, he used l=0.1). By another hand for d → ∞ the system convergs to a two level system i,e a film as shown in figure 2.We see as well that for fixed k the uper band increases with Q while the lower one decreases. The similarity with the hydrogen problem is complete since we know that the atoms will bind together in molecules and the molecular crystal will become a metal if the distance between the molecules decrease below a certain criticaly distance d* i.e. there will be a band crossing and a *metal-Isulator transition*[21,22].

In conclusion, we have shown that the propagation of magnetic modes in a antiferromagnetic superlattice in zero apllied field has very similar behaviour to those of phonons in a dieletric superlattice. Those resultes are clearly exposed in equations 18-22. We show as well the existence of two bands (see Figure 4) those are the main results of this work. Those and another results indicate that the study of magnetic layred structure is very promising. Recente experimental works[19,20] show the existence of instability in the parametric excitation of magnetostatic surface modes in ferrimagnets. We have shown as well[18] the existence of instability of retarded surface modes in a ferromagnet for non-reciprocal propagation and it would be interesting to see the stability of those modes in both antiferromagnetic and ferrimagnetic layered structure.

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FIGURE CAPTIONS

Figure 1.

Infinite Periodic Magnetic Superlattice. The system is composed of unity cell of dimension $R = L + d$. Every unity cell are made of an antiferromagnetic filme of thickness L and a non-magnetic one of thickness d. The periodicity is is the x direction. The static magnetization is in the z direction.

Figure 2.

Dispersion relation for the surface modes. Here $\bar{\omega} = (\omega - \omega_0)/(\omega_s - \omega_0)$ is the reduced frequency and k is in units of k_s; $L = 0.2$ (in units of k_s^{-1}) and $d = \alpha$.

Figure 3.

Energy in function of the film thickness L here $k = 2$ and $d = \alpha$.

Figure 4.

Bandwidh in function of d. Here $k = 2$ and $L = 0.2$

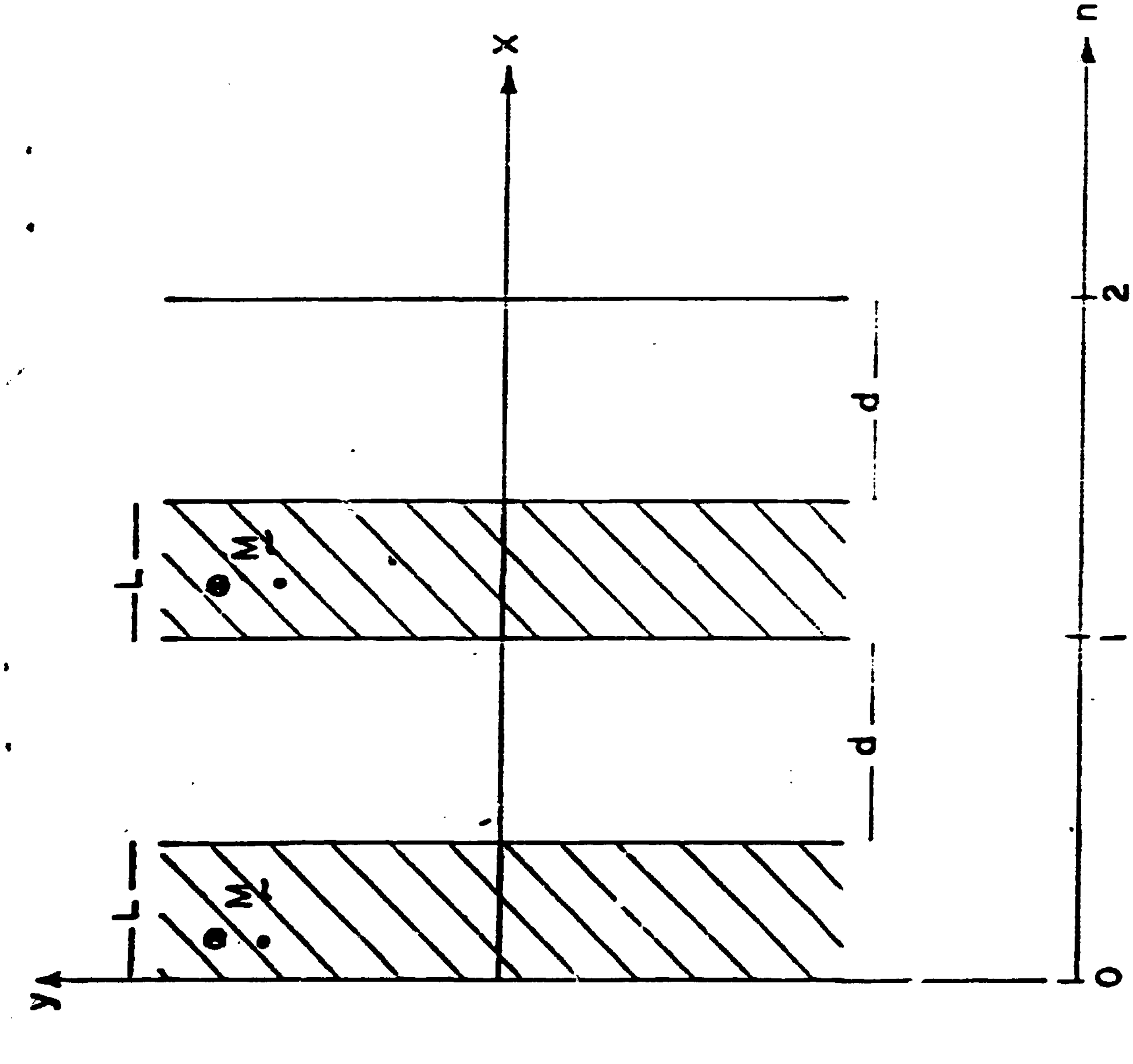
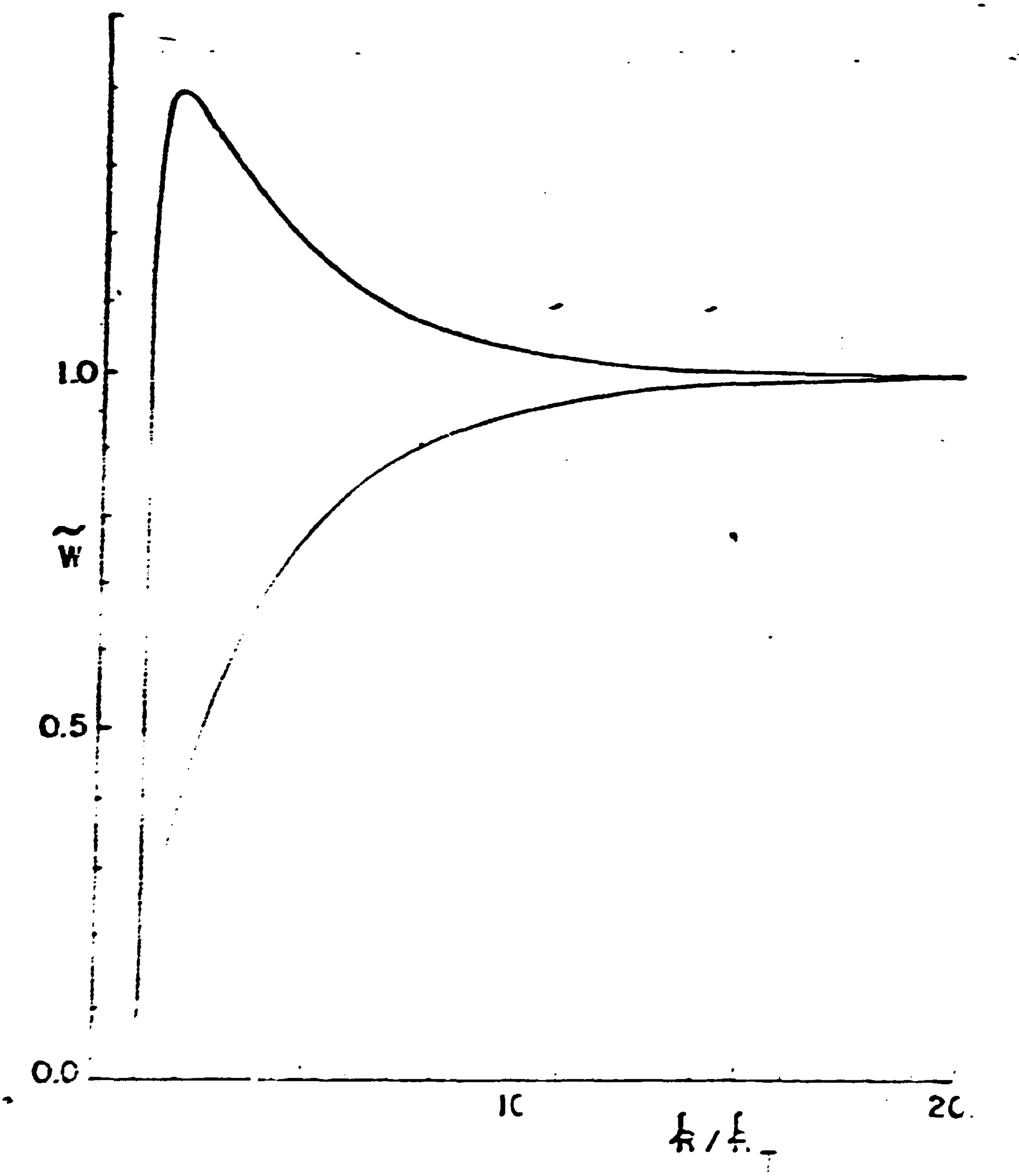
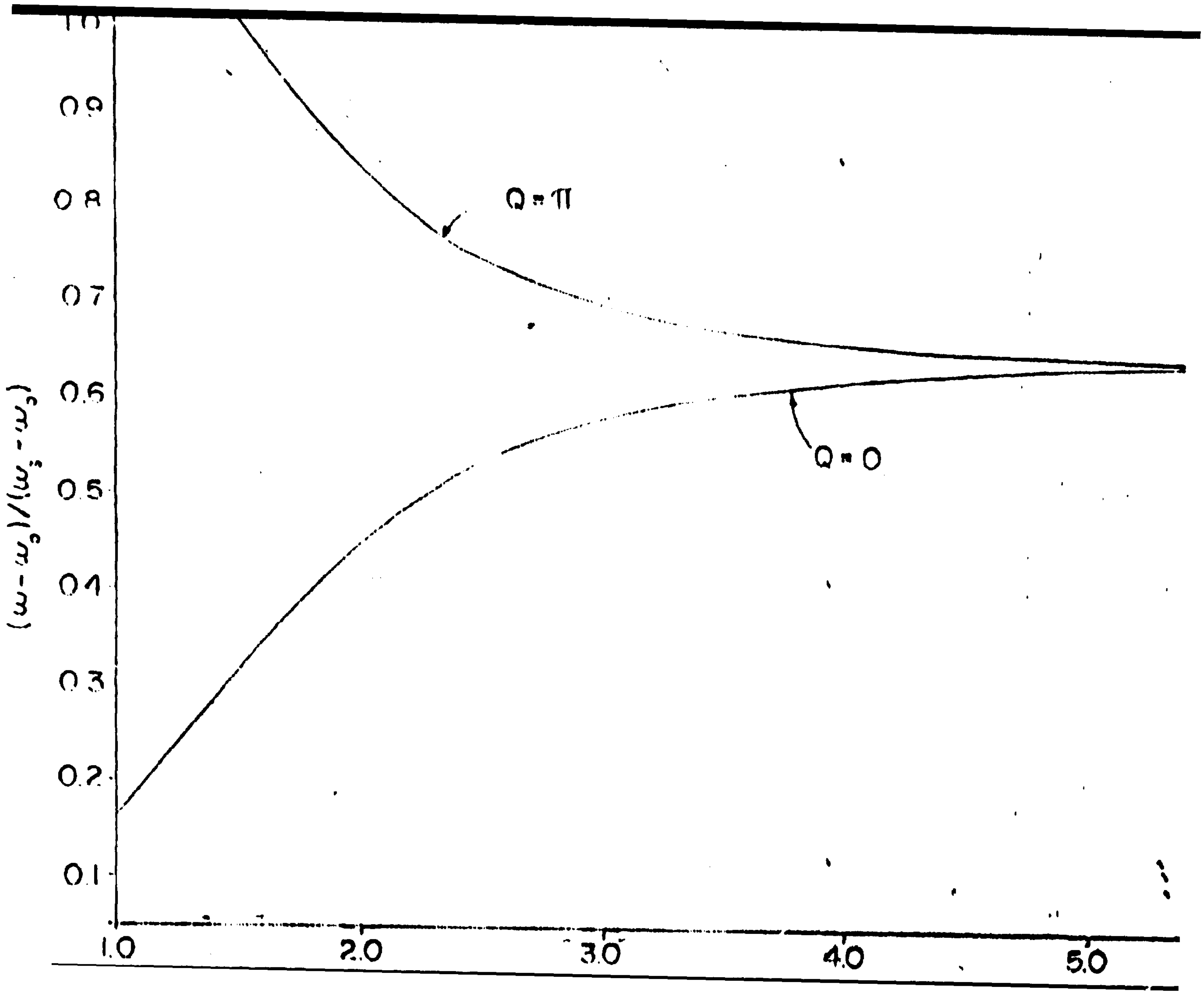
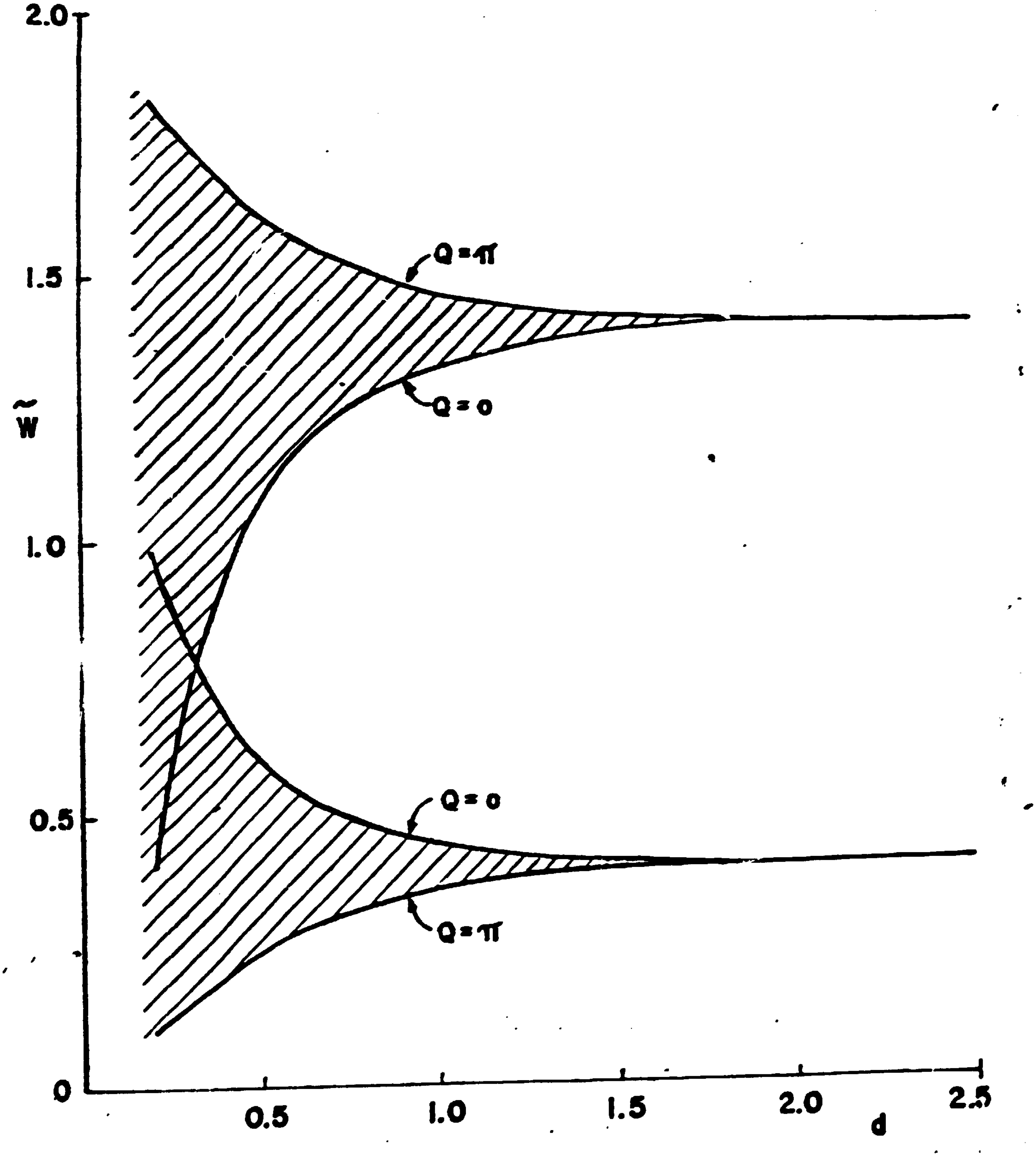


FIGURE 1



1.0
0.5
0.0
10
20


1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
1.0
2.0
3.0
4.0
5.0
Q = π
Q = 0



2.0
1.5
1.0
0.5
0
W̃
0.5
1.0
1.5
2.0
2.5
d
Q = π
Q = o
Q = o
Q = π