Magnetoexchange Branch Repulsion in Thin Single-Crystal Disks of Yttrium Iron Garnet*

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We have made a ferromagnetic-resonance study of thin single-crystal yttrium iron garnet disks in perpendicular resonance and compared the experimental results with existing theory. For small transverse wave vectors good agreement is observed between theory and experiment for both pinned and unpinned films.

With the recent development of chemical vapor-deposition techniques capable of growing good quality single-crystal yttrium iron garnet (YIG) films,[1] the opportunity exists to study standing spin waves with magnetostatic energies comparable to the exchange contribution. To date, few experimental studies have been reported of such systems[2] whereas there exists a rather large theoretical literature.[3,4]

This is the first experimental demonstration of interacting magnetoexchange branches where a dramatic repulsion is observed between even branches and an interference between even and odd branches. When a film shows more than one magnetoexchange branch, the initial slope of the dispersion relation agrees with that predicted for the pinned surface spin case. When only one branch is present, the initial slope of the dispersion relation agrees with that predicted for the unpinned surface spin case.

The theoretical work of Sparks and that of Wolfram and De Wames agree with experimental data for the lowest-order magnetoexchange or magnetostatic branch for small transverse wave vectors (k_ρ). For higher-order magnetoexchange branches the agreement appears poor and for large transverse wave vectors even the magnetostatic branch is inadequately described by present theories.

Data were taken at 9.12 or 23.8 GHz, room temperature, and with the static magnetic field perpendicular to the film plane. The samples were disk shaped with dimensions given in Table I. Samples with the same letter designation were etched from a common film. Disks were deposited on (100) gadolinium gallium garnet (GGG) substrates, with the exception of sample D-10 which was deposited on a (110) GGG substrate. The lattice mismatch between GGG (12.383 Å) and YIG (12.376 Å) induces a strain in the YIG films which

TABLE I. Experimentally determined initial slopes of dispersion relation. Theoretical values are 0.25 (unpinned), 0.203 (pinned $n=1$), 0.023 (pinned $n=3$), and 0.008 (pinned $n=5$).

Film	Thickness (μm)	Radius (μm)	Initial Slope -1st Branch	Initial Slope -2nd Branch	Initial Slope -3rd Branch
A-20	0.48	508	0.27 ± 0.01		
A-10	0.48	254	0.235 ± 0.005	Branches Not Present	
A- 5	0.48	127	0.255 ± 0.005		
B-20	0.37	508	0.22 ± 0.015		
B-10	0.37	254	0.21 ± 0.01	Modes Overlap	
B- 5	0.37	127	0.203 ± 0.005		
C-20	1.15	508	0.203 ± 0.005	0.08 ± 0.01	
C-10	1.15	254	0.206 ± 0.005	0.10 ± 0.01	
C- 5	1.15	127	0.120 ± 0.005	0.10 ± 0.01	0.08 ± 0.02
D-10	0.90	254	0.216 ± 0.01	0.07 ± 0.01	0.04 ± 0.01

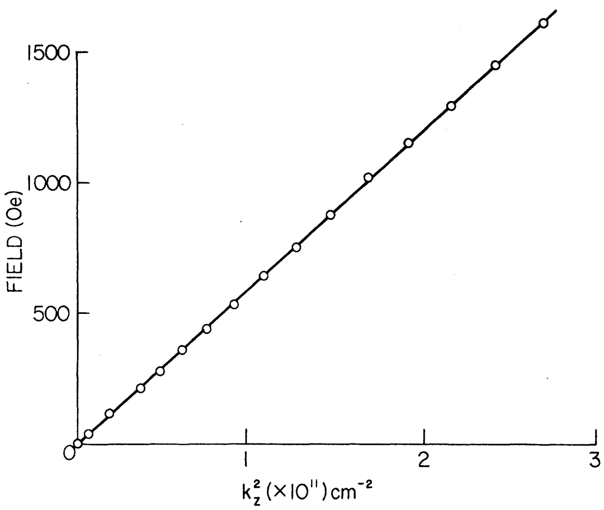

FIG. 1. Normalized branch position versus the square of the wave vector normal to the film plane for film C-20. The circles represent the experimental data. The circle at $k_z^2 = 0.5\times10^{11}$ cm^{-2} is the first observable odd branch. Data were taken at room temperature, X band, and perpendicular configuration.

produces a baseline shift of the spin-wave spectra in perpendicular resonance.[5] This strain may also be responsible for the larger value of the exchange constant measured for these films compared to those reported in bulk samples.[6]

Figure 1 is a plot of the resonance field versus the square of the wave vector normal to the film surface (k_z^2). The straight-line behavior even for small wave vectors indicates that, for these films, there is little if any inhomogeneity in the demagnetizing field.[7] The exchange constant obtained from the data in Fig. 1 is

$$D/4\pi = (3.40 \pm 0.15)\times10^{-12} \text{ cm}^2.$$

This was found by assuming spin pinning on both large surfaces and $4\pi M = 1750$ G. The exchange constant for YIG reported by LeCraw and Walker[6] is about 13% lower than the value observed above. The difference may arise from lattice-induced strain in our samples or from the presence of a thin (~0.04 μm) surface layer.

Note the appearance of odd spin waves above $k_z^2 = 0.36\times10^{11}$ cm^{-2} in Fig. 1. For a film with symmetric pinning on the large surfaces, one would not expect to excite spin waves with odd symmetry. For the pinned films studied, both even and odd modes are excited. For thick films such as C-20, the odd modes are weaker than the even modes until $k_z > 2.4\times10^5$ cm^{-1}. But for thin films such as B-20, the odd modes are comparable in intensity for all values of k_z. Although the occurrence of these odd modes is suggestive of an asymmetric inhomogeneity in the demagnetization field, this is not the only model which accounts for nonzero intensities of the odd modes. The odd mode intensities are also consistent with a model in which the spins become asymetrically quasipinned for large k_z.[8]

There is a deviation from a quadratic dispersion for the lower order branches. Such deviations are however too small to show in Fig. 1; and, perhaps more importantly, the deviations are in the opposite direction to those expected for Portis-type pinning. The origin of this nonquadratic behavior is not understood at this time. Such small shifts (less than 5 G) could possibly arise from shape and structural defects in the samples.

The dispersion relation for perpendicular resonance with pinned surface spins is[4]

$$\frac{\omega}{\gamma} = H_a - 4\pi M + H_\lambda - H_c + MDk_z^2 + \frac{8Mk_\rho S}{n^2\pi^2} \qquad (1)$$

and with unpinned surface spins,

$$\omega/\gamma = H_a - 4\pi M + H_\lambda - H_c + \pi M k_\rho S, \qquad (2)$$

where ω is the resonance frequency, γ is the gyromagnetic ratio, H_a is the applied field, $4\pi M$ is the shape demagnetizing field, S is the film thickness, H_c is the cubic anisotropy field, and H_λ is the stress field. The above dispersion relation was obtained by considering an infinite film in Cartesian coordinates. For finite circular films of radius r the allowed k_ρ values must satisfy

$$J_0(k_\rho r) = 0 \qquad (3)$$

with $J_0(k_\rho r)$ being the zero-order Bessel function. For films having pinned surface spins the allowed values of k_z are as usual

$$k_z = n\pi/S, \quad n = 1, 2, 3, \cdots.$$

From Eq. (1), the initial slope of $\tilde{H}_a$ versus $k_\rho S$ for films having pinned surface spins is

$$\Delta\tilde{H}_a/\Delta k_\rho S = -2/n^2\pi^2. \qquad (4)$$

For films having unpinned surface spins, only the modes having $k_z = 2k_\rho/S$ for $k_\rho S \ll \pi$ are observed. The initial slope for this condition is

$$\Delta\tilde{H}_a/\Delta k_\rho S = -\tfrac{1}{4}. \qquad (5)$$

In the above equations, H_a is defined by

$$4\pi M\tilde{H}_a = H_a - \omega/\gamma + H_\lambda - H_c - 4\pi M + n^2\pi^2 DM/S^2$$

with $n = 0$ or 1 for unpinned or pinned, respec-

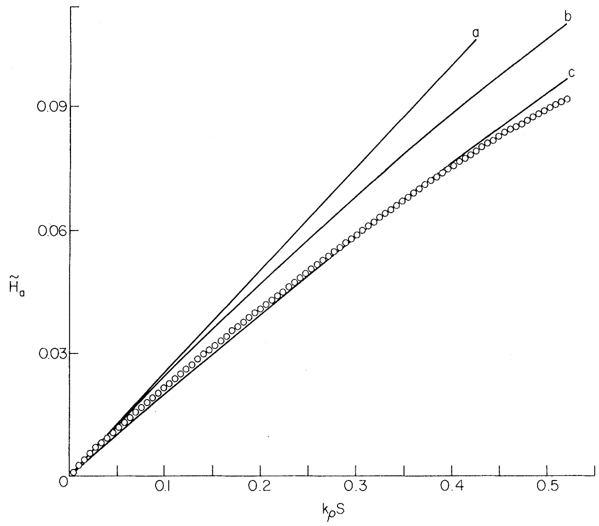

FIG. 2. Mode positions of the magnetostatic branch of film A-20. Curve a, Eq. (5); b, Eq. (6); c, Eq. (7). The data were taken at room temperature, X band, and perpendicular configuration.

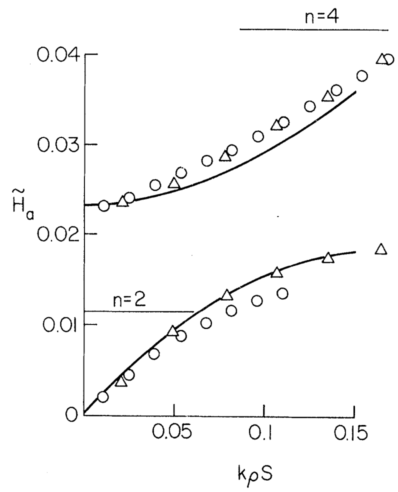

FIG. 3. Mode positions of the $n=1$ and $n=3$ magnetoexchange branches of film C-20 (circles) and C-10 (triangles). The data were taken at X band and K band, room temperature, and perpendicular configuration.

tively.

The values of the initial slope observed for the films investigated are listed in Table I. The slopes for these films agree well with Eqs. (4) and (5) for the first branch. Films having unpinned surface spins (A series) show one strong magnetostatic branch whose initial slope agrees with Eq. (4). The slope of the second magnetoexchange branch for the pinned case does not agree with the theoretical result of 0.02. The discrepancy appears to get even worse for the higher branches. The reasons for the discrepancies in the initial slopes as measured here and predicted by theory for the first branch of film C-5 and the higher branches of all films is the same and will be discussed after the unpinned case.

Data for the unpinned film A-20 are shown in Fig. 2. The straight line representing Eq. (5) is seen to fit the data in the limit $k_\rho S \to 0$. The result of Sparks,

$$\tilde{H}_a = -\tfrac{1}{2}[1-(1-e^{-k_\rho S})/k_\rho S] \tag{6}$$

for the unpinned case and

$$\tilde{H}_a = -(4k_\rho S/\pi^3)\tan^{-1}(\pi^3/8k_\rho S) \tag{7}$$

for the pinned case with repulsion neglected, are also shown for comparison. The initial slope of the data equals 0.25; but, for $k_\rho S>0.1$, the slope is even less than theory predicts for the pinned case. The infinite-film results for unpinned surface spins, given by De Wames and Wolfram, are well represented by curve b, deviations being less than 2% over this range of $k_\rho S$. A very weak higher-order branch (intensity $\approx 10^{-4}$ times that of the main branch) is present at $\tilde{H}_a = 0.096$. It seems unlikely that a repulsion from this weak higher-order branch could account for the deviation from the theoretical curve, since the magnetostatic mode spacing is changing quite slowly immediately preceding this higher-order branch and since some overlap of the two branches is observed.

Figure 3 is a plot of $\tilde{H}_a$ versus $k_\rho S$ for films C-20 and C-10. The repulsion of the even branches is quite dramatic and shows why the initial slope of film C-5 appears to be so small. For film C-5 the first two modes from which the initial slope is measured are at $k_\rho S = 0.029$ and 0.05. From the data for C-20 and C-10 one can see that such values of $k_\rho S$ are far removed from the linear portion of the dispersion relation and the measurement does not yield the initial slope for the film C-5.

The disappearance of standing spin waves for $k_\rho S > 0.13$ in the first branch for film C-20 arises from the finite linewidth of the modes. The continuation of this curve for C-10 to higher $k_\rho S$ values supports this contention. The disappearance of spin waves beyond $\tilde{H}_a > 0.04$ for the $n=3$ branch is much more abrupt and appears to happen as this branch passes through the weak $n=4$ branch.[9]

The solid lines in Fig. 3 represent the numerical evaluation of the eigenvalue problem as discussed in Ref. 4. In this calculation, $D/4\pi = 3.87 \times 10^{-12}$ cm^2 was used to give a good fit to the data. This was necessary because of the previously discussed nonquadratic behavior for the lower order branches. From Fig. 3 the agreement between theory and experiment is seen to be quite good. The initial slope of the dispersion relation obtained by numerical evaluation is still 0.02 for the $n=3$ branch, but the linear portion of the dispersion extends only out to $k_\rho S < 0.01$. Thus the data for the higher order branches do not really represent a measurement of the initial slope. Just as in the case of the $n=1$ branch of film C-5, the measurements are being made on a portion of the dispersion curve that is nonlinear because of repulsion between branches.

The present study demonstrates several important aspects of spin waves in finite films whose thickness is less than 1.2 μm. (1) Films having a magnetostatic branch do not indicate a strong repulsion between branches and have initial slopes of about 0.25. These data agree with the predictions of the theory for films having unpinned surface spins.[4] (2) In the case of unpinned surface spins, the discrepancy between experiment and theory for $k_\rho S > 0.1$ is not understood at present. (3) Inhomogeneities in the demagnetizing fields are small. (4) Films that have several strong magnetoexchange branches obey a quadratic dispersion relation, show strong repulsion between even branches, and have initial slopes for the first branch of about 0.20. All of these data are in agreement with the theory of Wolfram and De Wames and verify their contention that branch repulsion cannot be neglected.

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[8]By quasipinned we mean that neither the value nor the slope of the rotating microwave magnetization is zero at the large surface.

[9]More recent data confirm this contention. Modes are observed after the $n=3$ branch passes through the $n=4$ branch.

0^+ Excited States in the Actinides*

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We present a calculation of 0^+ excited states in the actinides for a pairing-force theory of the type suggested by Griffin, Jackson, and Volkov. Contrary to previous results, we find that such a theory does not explain low-lying 0^+ excited states in the actinides any better than does a conventional pairing-force theory.

It has recently been proposed[1,2] that the low-lying 0^+ excited states seen in the actinides can be explained in terms of a modified pairing-force theory. The basic idea of this modified theory is to label single-particle states as oblate or prolate and to assume that the pairing-force matrix elements between an oblate and prolate state are considerably weaker than the matrix elements between two prolate states or two oblate states. The purpose of this Letter is to point out some serious objections to such an explanation for the low-lying 0^+ excited states in the actinides.

There are two distinct issues involved in the notion of prolate-oblate pairing, and we should distinguish between them at the outset. (1) Should the constant-G pairing-force model be replaced by a model in which the pairing-interaction matrix elements G_{ij} depend on the oblateness or prolateness of levels i and j? (2) If this replacement is made, does it explain the low-lying 0^+ excited states in the actinides? In this Letter, we assume that this replacement should be made, and carry out calculations in the framework of the modified theory in order to answer the second