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# Brillouin light scattering study of magnon branch crossover in thin iron films

P. Kabos,* W. D. Wilber, and C. E. Patton
*Department of Physics, Colorado State University, Fort Collins, Colorado 80523*

P. Grünberg
*Institut für Festkörperforschung der Kernforschungsanlage Jülich,*
*D-5170 Jülich, Federal Republic of Germany*

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Brillouin light scattering has been used to measure frequency versus wave number for the surface and exchange branches of the magnon dispersion manifold in thin iron films. For the thickest film studied (750 Å), multiple-exchange branches and the surface mode could be distinguished. For a thinner 348-Å film, the branch crossing and repulsion between the single-exchange branch and the surface branch were particularly well resolved. The measured dispersion branches and branch repulsion are in good agreement with the theory. For the thinnest film studied, 232 Å, the surface magnons associated with both sides of the film were observed, and the intensity ratio for the two peaks was measured versus wave number. The results are consistent with simple penetration depth considerations.

## I. INTRODUCTION

Several recent experimental and theoretical papers have been concerned with thermally excited surface and volume magnons in thin films.[1-7] From these investigations, the basic properties of magnetostatic surface magnons predicted by Damon and Eshbach[8] (DE) have been confirmed. An extension of the DE theory by Wolfram and DeWames[9,10] to include exchange as well as magnetostatic terms in the equation of motion and boundry conditions appropriate for thin films contained an intriguing result: crossover and branch repulsion between the surface branch and the various spin-wave branches which thread the surface branch in the usual dispersion diagram of magnon frequency versus wave number $k$. While some evidence for such crossover effects has been reported, based on ferromagnetic resonance[11] and light scattering,[4,5] these results were based on measurements of fields or frequencies for films of different sizes and thicknesses or by changing the in-plane wave-vector direction for fixed $k$. In this work, a high contrast multipass-tandem Fabry-Perot interferometer[12] has been used to measure the pertinent magnon frequencies versus *wave number,* in the range $4\times10^4 < k < 2.5\times10^5$ cm$^1$, for individual thin-film samples. In this way, direct evidence for branch crossover and repulsion between the surface and magnon and spin-wave branches of the dispersion manifold has been obtained.

## II. EXPERIMENT

The light scattering measurements were made on a series of polycrystalline iron films evaporated on sapphire substrates. Results described here are for three films, 750, 348, and 232 Å in thickness, as measured by optical interference techniques. These three samples were chosen because of the various possibilities for surface-branch and exchange-branch combinations. For 750 Å, the exchange shifted spin-wave branches are sufficiently low in frequency to yield several exchange branches in the spectra. For 348 Å, there is only one exchange branch which nicely bisects the surface branch; it is in this case that the branch repulsion is most accurately resolved. For 232 Å, the lowest-order exchange branch is displaced well above the surface branch so that the surface branch can be observed without crossover complications.

The geometry of the experimental light scattering arrangement is shown in Fig. 1. Data were obtained for backscattering, that is, backscattered light from the sample was collected about the incident light angle $\theta_i$, relative to the film normal. The static magnetic field was applied in-plane, and perpendicular to the light wave vector $\vec{k}_l$. The in-plane wave vector of the particular magnon contributing to the scattering, $\vec{k}_m$, is of magnitude

$$|\vec{k}_m| = 2k_l \sin\theta_i \ . \tag{1}$$

The basic objective of these experiments was to determine the pertinent magnon frequencies *versus* $k_m$ for propagation perpendicular to the in-plane field, and look for crossover and repulsion effects. This $k_m$ variation was accomplished by doing a series of scattering experiments for different values of $\theta_i$ ranging from 10° to 70°. Even though Brillouin scattering signals from iron are quite strong, generally speaking, these experiments turn out to be rather tedious when one is using very thin films, changing the scattering geometry, and attempting to follow subtle frequency shifts for the relatively weak, closely spaced individual magnon peaks.

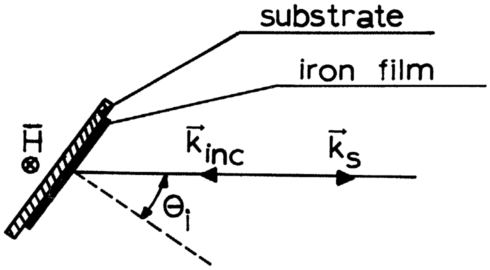

FIG. 1. Experimental light scattering geometry.

## III. RESULTS AND DISCUSSION

Figure 2 shows the experimental results of frequency versus wave number $k_m$ for the 750-Å film with an applied field of 2 kOe. The three lowest-order exchange branches, with frequencies which are essentially $k_m$ independent, are evident. The surface mode, indicated by the series of points which appear to cross the highest exchange branch, is also observed. The solid lines are intended merely as a guide to the eye in visualizing these branches. The frequency versus wave-number data in the region of crossover between the uppermost exchange branch and the surface branch show the expected repulsion between branches.

For this film, it is found that comparisons with theory fare very poorly, at least for material parameters appropriate for bulk iron. The dotted lines labeled "$S$" and "$E$" indicate the theoretical dispersion for the surface DE mode and the three lowest-order spin-wave exchange branches, assuming completely pinned or unpinned surface spins, and using a saturation induction $4\pi M_s$ of 21.2 kG, a spin-wave stiffness $D$ of $2.37\times10^{-9}$ Oe cm$^2$, and a $g$ factor of 2.09. While better fits could be obtained by adjusting the thickness, modifying the various material parameters, or introducing more complex surface boundary conditions, magnetization profiles through the thickness, etc., no such attempts were made. The main point here is that, even though the expected dispersion features are *qualitatively* observed, the actual film parameters are too complicated to accommodate agreement with simple theoretical models. Such complications appear to be connected with thick films. As described below, comparisons fare much better for the thinner iron films.

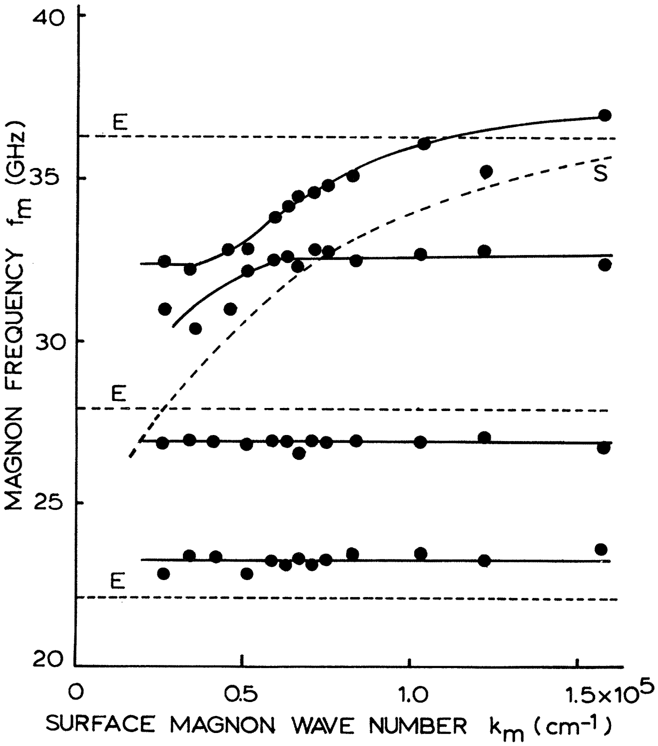

FIG. 2. Magnon dispersion data, frequency vs wave number, for the 750-Å iron film (solid circles and solid lines). The dotted lines labeled "$S$" and "$E$" indicate the theoretical dispersion curves for the Damon-Eshbach magnetostatic surface mode and the three lowest-order spin-wave exchange branches as described in text.

Figure 3 presents the results on frequency versus $k_m$ for the 348-Å film. Here, only one spin-wave branch threads the surface branch. The branch repulsion in the vicinity of crossover is clearly resolved. The solid lines in this figure also represent the simple theoretical predictions, the DE theory for the surface mode, and the first-order spin-wave mode frequency for the horizontal branch, with *no* pinning and the same parameters as given above. The dashed lines result from the magnetoexchange theory of Refs. 9 and 10. These curves match the data surprisingly well, with *no* adjustable parameters.

Finally, consider the results for the 232-Å film. The dispersion data were similar to the surface-mode results given above but with *no* exchange branches present, due to the thinner sample. Here, even the lowest-order exchange branch is shifted well above the surface branch. For such thin films, it is possible to see surface magnon peaks on *both* sides of the central Rayleigh peak in the Brillouin spectra.[1] Such a spectrum is shown in Fig. 4 for $k_m = 1.65\times10^5$ cm$^{-1}$. One generally associates the stronger peak with the surface mode supported by the film surface facing the light source, with the weaker peak attributed to the surface mode supported by the opposite surface at the film-substrate interface. The DE theory predicts that the rf magnetization associated with the surface mode decays exponentially as one moves into the film interior, with a decay length equal to $2\pi/k_m$, the propagation wavelength. One may perform a simple test of this result by measuring the strong peak-weak peak intensity ratio $R$ versus wave number $k_m$. Figure 5 shows the experimental results for $R$ vs $k_m$, along with the simple theoretical prediction, $R = \exp(-2k_m S)$, where $S$ is the film thickness. The results are in reasonably good agreement for $k_m > 1.0\times10^5$ cm$^{-1}$. For lower $k_m$ values, the ratio appears to be leveling off at a value well above unity. This could be associated with the problems of doing low-angle backscattering or a failure of the simple DE theory for $2\pi/k_m >> S$. The anomalous intensity ratios for very thin films, as discussed in Ref. 7, are not observed.

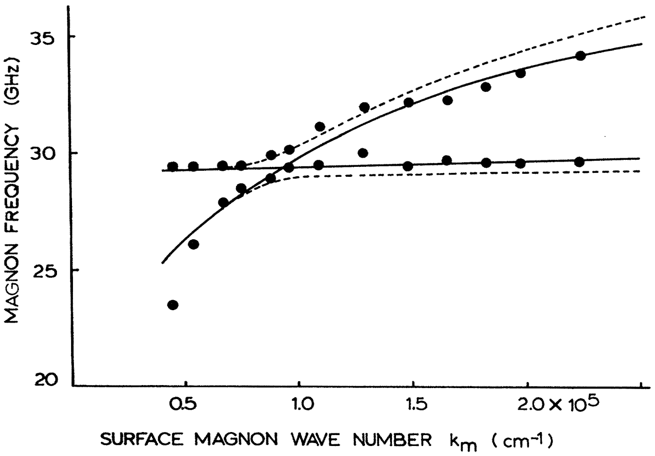

FIG. 3. Magnon dispersion data, frequency vs wave number, for the 343-Å film (solid circles). The solid lines indicate the simple predictions for the Damon-Eshbach surface mode and the exchange mode. The dashed lines indicate the predicted dispersion and repulsion from the dipole-exchange theory.

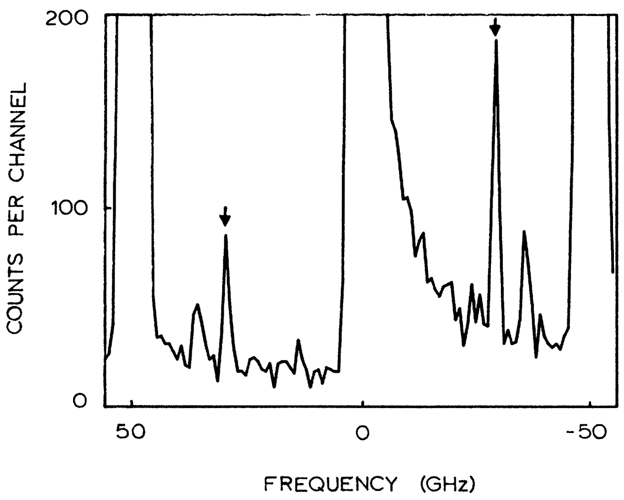

FIG. 4. Brillouin spectrum for the 232-Å iron film for an in-plane dc magnetic field of 2 kOe and an in-plane wave number (wave vector perpendicular to the field) of $1.65\times10^5$ cm$^{-1}$. The two arrows indicate the surface modes associated with the two film surfaces.

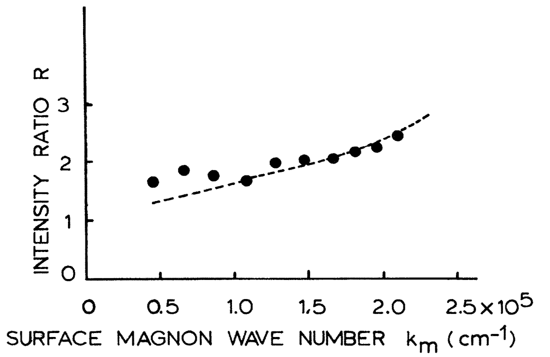

FIG. 5. Measured Stokes–anti-Stokes mode intensity ratio for the surface modes as shown in Fig. 4 vs wave number. The dotted line is from the simple exponential decay model.

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[*] On leave from Slovak Technical University, Bratislava, Czechoslovakia.

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