COLLAPSE OF THE SMALL-ANGLE MAGNON SCATTERING IN Fe AS A FUNCTION OF MAGNETIC FIELD

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ABSTRACT

The dependence of the spin wave energy on the magnetization $\vec{M}$ and the applied magnetic field $\vec{H}$ in Fe (and other ferromagnets) has not been very well investigated with neutrons. According to the Holstein-Primakoff dispersion relation, the contributions of the Zeeman energy $g\mu_B H$ and the dipole-dipole interactions $4\pi g\mu_B M \sin^2\theta_q$ do not simply add linearly to the exchange energy Dq^2. However, in order to see these contributions, one must observe the very low energy (.01 - .1 mev) spin waves. One of the predictions of this dispersion relation is that the scattering of neutrons by spin waves near the origin should disappear as the magnetic field is increased. This is a consequence of the kinematics of the scattering process. Using our double-Si crystal technique for small angle scattering we have experimentally observed this collapse at a field of about 8 kG in Fe at room temperature as predicted by theory. We have also measured the scattering due to these very low energy spin waves at temperatures up to .7 T_c and compared the data on an absolute scale with the theoretical cross section. The agreement is reasonably good.

INTRODUCTION

The Holstein-Primakoff dispersion relation for very long wavelength spin waves in uniaxial ferromagnets is[1]

$$\hbar\omega = \left[(g\mu_B H + Dq^2)(g\mu_B H + Dq^2 + 4\pi\, g\mu_B M \sin^2\theta_q)\right]^{\frac{1}{2}} , \qquad (1)$$

where $\vec{H}$ is the effective magnetic field and is the sum of the anisotropy field and the applied field, $\vec{q}$ is the wavevector of the spin wave, D is the spin wave stiffness coefficient, $\vec{M}$ is the magnetization and θ_q is the angle between the $\vec{M}$ and $\vec{q}$. For a neutron scattering vector $\vec{\varkappa} = \vec{q}$, this dispersion relation requires that the scattering be confined very close to the origin in order to satisfy energy conservation.[2] The locus of scattered neutron wavevectors $\vec{k}$ which satisfy the kinematics is given by two closed scattering surfaces, one for the annihilation and one for the creation of spin waves. Annihilation surfaces calculated using Eq. (1) for various applied magnetic fields are shown in Fig. 1.

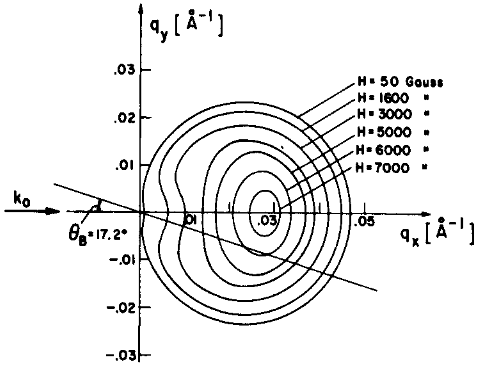

Fig. 1. Annihilation portion of the spin wave scattering surfaces in iron at room temperature.

The magnetization M and the stiffness coefficient D were set equal to 1707 gauss and 260 mev Å^2 respectively, which are appropriate for Fe at room temperature. The creation surfaces are essentially identical and are mirror reflections of the annihilation surfaces about the $q_y - q_z$ plane. The incident neutron wavevector $\vec{k}_o$ is directed along the q_x-axis. The direction of the applied field and the magnetization have been taken to be along the q_y-axis in this case. Since the wavevector $\vec{q}$ terminating on any one of these surfaces is very small, the Zeeman $(g\mu_B H)$ and the dipole-dipole $(4\pi g\mu_B M \sin^2\theta_q)$ contributions are important, and in fact are comparable to the exchange energy Dq^2. For example in Fe at room temperature, for a wavevector $q = .02\text{Å}^{-1}$, $Dq^2 = 0.1$ mev, while $4\pi g\mu_B M = 0.25$ mev. Thus the shape of these scattering surfaces is quite sensitive to the form of the dispersion relation. These surfaces become smaller and smaller as the applied field is incresed until they collapse to a point. This occurs in Fe at about 8 kG. Thus, at fields above 8 kG, the spin wave scattering near the origin should disappear.

EXPERIMENTAL TECHNIQUES AND RESULTS

The small angle scattering method used in these experiments has been described previously.[3] Briefly, it consists of two silicon crystals oriented in the parallel position with the Fe single crystal placed between them. The first Si crystal is the monochromator and the second is the analyzer. Data is taken as a function of the analyzer crystal angle φ. The intensity observed at a given setting φ is proportional to the integral of the spin wave cross-section over the intersection of the scattering surface with a vertical plane oriented at an an angle $\theta_B (= 17.5^\circ)$ away from $\vec{k}_0$ as shown in Fig. 1. This "plane of integration" moves in a direction parallel to its normal as a function of φ.

The Fe sample used in these experiments consists of two single crystal pieces cut in the shape of rectangular parallelepipeds (1.7 cm × 0.79 cm × 0.61 cm) placed in juxtaposition with (110), ($\bar{1}12$) and ($1\bar{1}1$) planes parallel to the faces. The sample could therefore be placed directly between the poles of an electromagnet with the field directed along any one of three major axes. Incident neutrons of wavelength 1.84Å were used. Even with this long wavelength it was necessary to insure that no reciprocal lattice point was on the sphere of reflection which could lead to an apparent small angle scattering via multiple scattering. This was done by measuring the transmission of the sample as it was rotated through angles of ± 10°. Since the sample is so large, a Bragg reflection causes a significant decrease in the transmission. The Fe crystal was then oriented at an angle corresponding to a flat region of the transmission, which generally corresponded to a setting in which the magnetic field was within 4° of being perpendicular to the incident beam (in the horizontal plane). This setting was then checked by geometrical construction to be free of Bragg scattering.

Results obtained with the applied magnetic field along the ⟨110⟩ direction are shown in Fig. 2.

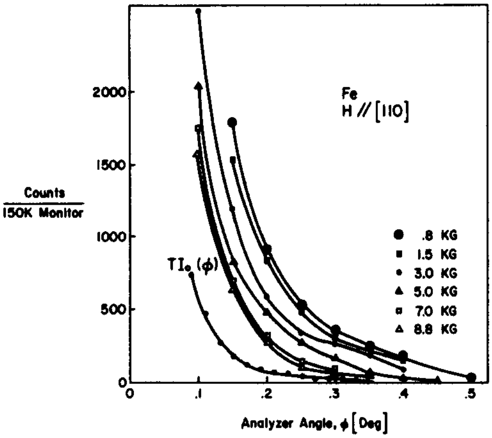

Fig. 2. Small angle scattering in iron for various applied magnetic fields.

The curve labeled $TI_o(\varphi)$ is the rocking curve of the analyzer with the sample removed multipled by the sample transmission T. It is seen that the scattering surface is indeed contracting as a function of magnetic field. At a given angle the scattered intensity is also decreasing as is predicted by the theoretical expression for the spin wave scattering cross-section.[4] The same type of data obtained with the magnetic field along the ⟨111⟩ direction, only taken at fixed analyzer angle as a function of magnetic field is shown in Fig. 3.

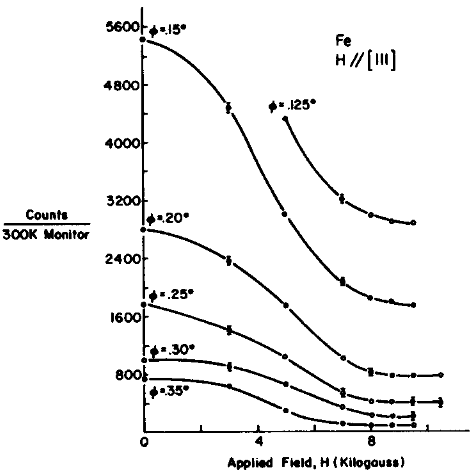

Fig. 3. Field dependence of the small angle scattering in Fe at various analyzer settings φ.

It is seen from both of these results that the scattered intensity becomes almost independent of field at about 8 kG. We interpret this as the disappearance of spin wave scattering. The origin of the residual scattering (above the rocking curve with the sample removed) is not yet known. Several possibilities exist among which is the scattering from imperfections and the crystallographic and magnetic disturbances surrounding them.

The experimental difficulties involved in making the measurements reported here are apparent: As the field is increased the scattering occurs at smaller and smaller angles and its intensity progressively decreases. In order to be sure that the scattering above the "saturation curve" (residual scattering at 9.7 kG) is in fact only due to spin waves we have made measurements at elevated temperatures. The intensity becomes larger and occurs over a progressively larger range of angles as the temperature is raised. We have assumed that the saturation curve at room temperature should be subtracted from all of the data in order to get the spin wave scattering. The result of this procedure is shown in Fig. 4.

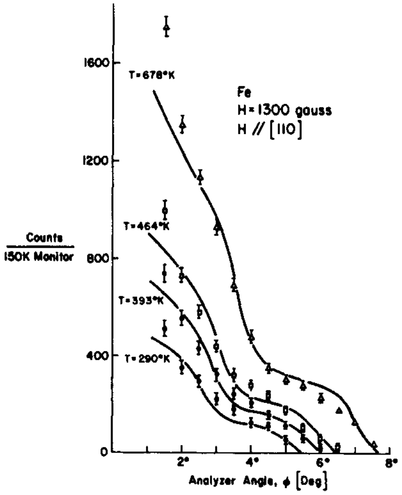

Fig. 4. Small angle scattering in Fe at various temperatures.

The solid lines are the results of a numerical integration over the scattering surface using the spin wave cross-section given by Elliott and Lowde and folding the result with the experimental resolution function. These theoretical curves are plotted on an absolute scale where the only adjustable parameter is D which was determined by the cut-off angle. The agreement is really remarkable.

CONCLUSIONS

These measurements have demonstrated the importance of the Zeeman and dipole-dipole terms in the dispersion relation for very low energy spin waves. It has been demonstrated that the scattered intensity agrees on an absolute scale with theory and that the spin wave scattering near the origin does in fact disappear with magnetic field as predicted by the Holstein-Primakoff dispersion relation and kinematics.

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