contribution. We can only make the following suppositions.

Since the projection of moments on the basal plane is not 0 [this follows from the fact of the presence of reflection (111)], the class of symmetry of such a crystal according to Dzyaloshinsky[6] allows for the existence of ferromagnetism.

A quantitative solution of this problem may be obtained through a neutron-diffraction study by means of a single-crystal of $NiCO_3$.

In the present studies, which were carried out at different temperatures, such as T_{He} and T_{H_2}, a determination was made of the earlier unknown transition point of $NiCO_3$ into the antiferromagnetic state. By extrapolating the reflection intensities (111) and (100) for various temperatures of the Brillouin curve we obtain $T_N \sim 25°K$.

I wish to express my deep gratitude to Academician P. L. Kapitza for his constant attention to this study.

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Some Experiments on Magnetic Inelastic Scattering of Neutrons

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Thermal excitations in magnetic substances give rise to inelastic scattering of neutrons. The characteristic scattering surface which results gives detailed information about the nature of the excitations and may be studied by two different experimental techniques. The techniques are described and shown to give consistent results. Special attention is paid to the temperature behaviour of spin waves in magnetite. When approaching the Curie temperature, the lifetime and the energy of the spin waves are found to decrease. The temperature region in which the decrease shows up depends on the wavelength of the spin waves.

The angular and energy distribution of neutrons scattered inelastically by magnetic spin waves are determined by the conservation laws of momentum and energy:

$$\boldsymbol{k}_f-\boldsymbol{k}_i+2\pi\boldsymbol{\tau}+\boldsymbol{q}=0 \qquad (1)$$

$$\frac{\hbar^2}{2m}(k_f^2-k_i^2)-\hbar\omega=0 \qquad (2)$$

m is the neutron mass, $\boldsymbol{k}_i$ and $\boldsymbol{k}_f$ are the wavevectors of the incoming and outgoing neutrons respectively and $\boldsymbol{\tau}$ is a reciprocal lattice vector of the crystal. The spin wave energy $\hbar\omega$ is connected with the corresponding momentum $\hbar q$ through a dispersion relation

$$\omega=Dq^n \qquad (3)$$

where $n=1$ for an antiferromagnet and 2 for ferri- and ferromagnets. D is the effective exchange coupling.

From the equations above it is readily shown that the locus of $\boldsymbol{k}_f$, the scattering surface, is a sphere (This is only an approximation in the case of an antiferromagnet). The scattering surface has its centre displaced from the reciprocal lattice point through a small distance, but is otherwise a conformal mapping of a constant energy surface for

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spin waves.

In some recent experiments at Saclay, France, the existence of the scattering surfaces for ferrimagnetic spin waves has been clearly established[1]. These experiments make use of a cold moderator source[2], thus a factor 10 was gained in the neutron flux. The energies of scattered neutrons were analyzed by time of flight technique, typical curves are shown in Fig. 1. A single crystal of magnetite, Fe_3O_4, was kept fixed in a beam of monochromatic neutrons and the neutron spectrum was recorded in a direction which cuts through the centre of the scattering surface. The two peaks in the diagram thus correspond to points which are located diametrically opposite to each other on the constant energy surfaces of magnons. It is clearly seen from Fig. 1 that the diameter of the constant energy curves increases as the temperature is raised. This corresponds to a decrease of the constant D in eqn. (3), a question which has been much discussed by theorists lately[3]. The increase of the diameter, as seen in Fig. 1, has earlier been observed in diffraction experiments[4]. In the latter experiments one measures the angular width of the diffuse spot of scattered neutrons, this width is directly related to the diameter. The two experimental methods gave qualitatively consistent results for the increase of the diameter, as seen in Fig. 2. The two curves correspond to different spin wave energies.

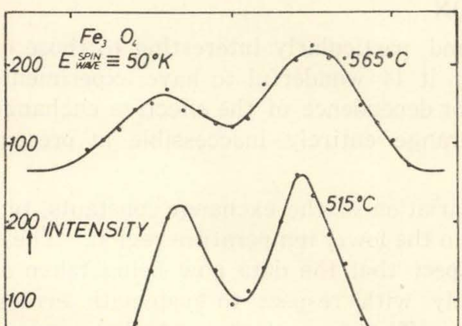

Fig. 1. Neutron spectra observed after inelastic magnetic scattering in Fe_3O_4.

The curves of Fig. 2 show that spin waves of different energies behave differently. The different shapes of the two curves imply that D in eqn. (3) depends, not only on T, but also on q. Antiferromagnetic substances behave in the same way; this has been demonstrated in experiments using the diffraction technique[5].

An additional phenomenon is revealed by Fig. 1. It is seen from the curve on the top that the neutron line is broadened at sufficiently high temperatures. If the linewidth at room temperature is arbitrarily taken to represent the resolution function, the "true" linewidth for spin waves behaves as shown in Fig. 3. Also shown in this figure is the corresponding curve for the magnon lifetime. We have derived the lifetime simply by dividing the linewidth by $\hbar$. We want to emphasize, however, that the quantitative values of Fig. 3 may be subject to systematic errors.

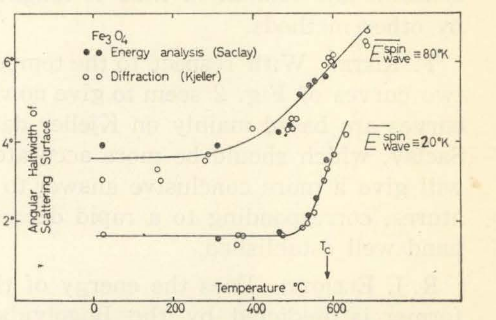

Fig. 2. Temperature variation of the diameter (or angular width) of constant energy surfaces of spin waves with consistent sets of data from two different methods.

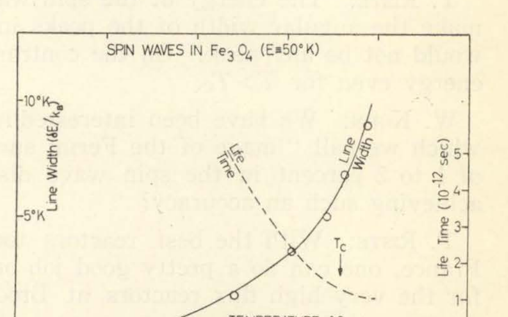

Fig. 3. Temperature variation of linewidth and lifetime of magnons.

Another phenomenon which has been studied is that of fluctuations in the z-components of the spins. Within the accuracy of the experiments the onset of these longitudinal fluctuations coincides with the decrease of the exchange coupling D for the corresponding excitation energy[6]. The curves presented here also show that the line broadening falls within the same temperature range. In the case of magnetite, for which most of our data were taken, the perturbation of the spin waves does on the average coincide with the decrease of the magnetization. There is, however, a marked difference between excitations of different energies, the low energy ones remaining unperturbed almost up to the Curie temperature.

The author wants to express his deep gratitude to his coworkers on these experiments. At Kjeller they were K. Blinowski, J. Janik and A. Wanic from the Institute of Nuclear Studies, Poland. Those at Saclay were D. Cribier and B. Jacrot.

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DISCUSSION

C. KITTEL: This is most remarkable work and particularly interesting to those of us who are concerned with theory of magnons; it is wonderful to have experiments giving directly the temperature and wave-vector dependence of the effective exchange constant and relaxation time of magnons in a range entirely inaccessible at present by other methods.

T. RISTE: With respect to the temperature variation of the exchange constants, our two curves of Fig. 2 seem to give no variation in the lower temperature region. These curves are based mainly on Kjeller data. I expect that the data now being taken at Saclay, which should be more accurate especially with respect to systematic errors, will give a more conclusive answer to this point. The steep slopes at higher temperatures, corresponding to a rapid decrease of the exchange constants, are on the other hand well established.

R. J. ELLIOTT: Does the energy of the spin wave go to zero at T_C or not? The former is predicted by the Bogolyubov and Englert theories which renormalize the spin wave energies by the magnetization, while the latter would be some conformation of Keffer and Loudon's theory which at low T gives a renormalization with the average energy.

T. RISTE: The energy of the spin waves does not go to zero at T_C. This would make the angular width of the peaks in the neutron pattern go to infinity, i.e., there would not be any peak. On the contrary, the spin waves are seen to exist with finite energy even for $T > T_C$.

W. KOHN: We have been interested in a certain effect in metallic spin wave spectra which we call "image of the Fermi surface". To observe it will require a precision of 1 to 2 percent in the spin wave dispersion relations. What are the prospects of achieving such an accuracy?

T. RISTE: With the best reactors today, such as NRU in Canada and EL-3 in France, one can do a pretty good job on it. I believe, however, that one has to wait for the very high flux reactors at Brookhaven and Oak Ridge before obtaining the accuracy that you require.

W. C. MARSHALL: We might also add that, because of the high absorption cross section, it is unlikely that such an experiment be performed on Gd—the material for which the calculations were made.