The authors gratefully acknowledge the technical assistance of A. H. Studna. Special thanks are due to J. H. Armstrong who provided the quartz-crystal oscillator.

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MEASUREMENT OF THE MAGNON DISPERSION RELATION OF IRON*

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(Received 16 June 1965)

This note reports that the magnon dispersion curve for iron deviates considerably from the quadratic law, $\hbar\omega = Dq^2$, even for relatively small wave vectors q, indicating a long-range magnetic interaction in this metal.

The measurements were done by utilizing the diffraction method[1] in conjunction with polarized neutrons. The angular width of the magnon scattering surface was determined as a function of the angle $\Delta\varphi$ by which the crystal is misset from the elastic Bragg peak (110). (See Fig. 1.)

Correction for the instrumental resolution was made by folding the resolution function (measured by scanning the Bragg peak) into an ideal rectangular profile. A least-squares fit of the profile so obtained to the observed profile was made with the width as the varied parameter. The use of polarized neutrons in the present experiment allows one to distinguish unambiguously the magnon scattering from other scattering contributions, as has already been described in some detail.[2] The main part of the data were collected on a single crystal of iron containing 4 at.% silicon, kindly provided by Dr. H. J. Williams and Dr. A. J. Williams of Bell Telephone Laboratories.

The energy of a magnon with wave vector $\vec{q}$ may be written as a function of the exchange interactions $J(\vec{r})$,

$$\hbar\omega = 2S\sum_{\vec{r}} J(\vec{r})(1-e^{i\vec{q}\cdot\vec{r}}), \tag{1}$$

assuming zero energy gap. For a body-centered lattice with $\vec{q}$ along the [100] direction, this expression reduces to the following simple form if only the nearest neighbor interaction J_1 is effective:

$$\hbar\omega = 16J_1S[1-\cos(\tfrac{1}{2}qa)]. \tag{2}$$

And for small q values,

$$\hbar\omega = 2J_1Sq^2a^2\left(1-\frac{q^2a^2}{24}+\frac{q^4a^4}{5760}+\cdots\right). \tag{3}$$

Small-angle scattering measurements by Lowde and Umakantha and other workers at Harwell[3] yield the result $\hbar\omega = Dq^2$, with $D = 286$ meV Å^2. This method corresponds to the special case of the diffraction technique with zero misset angle at the (000) reflection and effectively samples the dispersion curve for exceedingly small q values ($qa/2\pi < 0.025$), so that the higher terms in Eq. (3) are truly negligible.

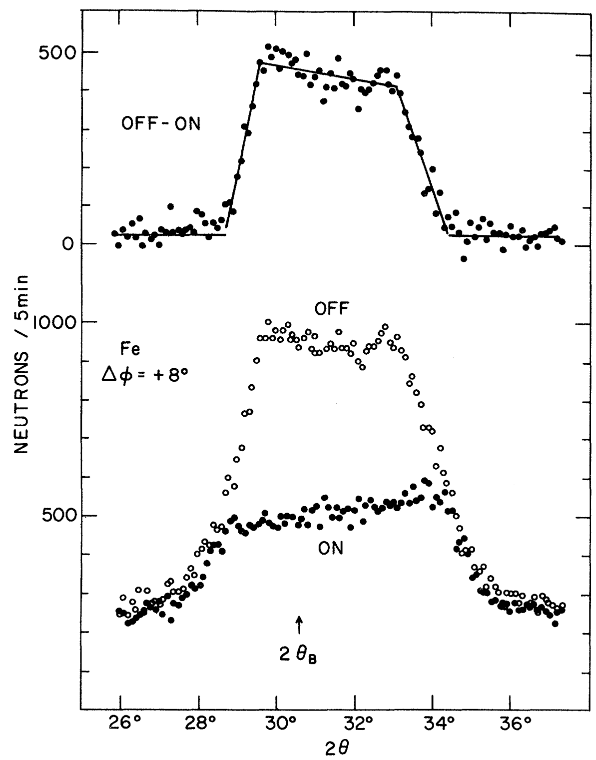

FIG. 1. The sharp cutoffs due to a magnon scattering surface when the neutron detector is scanned through a range of scattering angles for a given angle of crystal misset, $\Delta\varphi$. The difference of the two spin states, signified here as rf neutron flipper on or off, contains magnon contributions only.

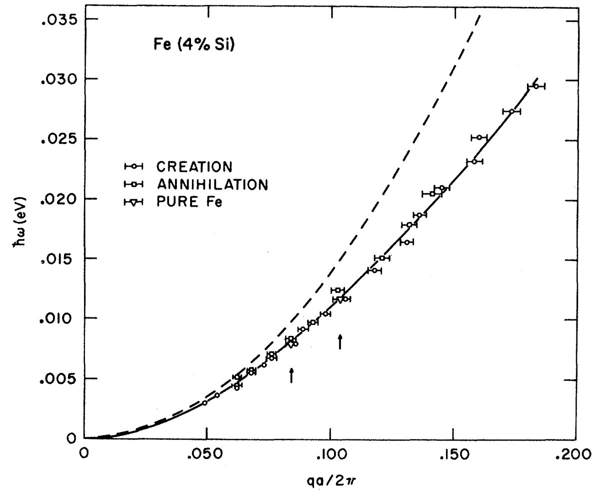

FIG. 2. Magnon dispersion relation for iron, containing 4% Si. The arrows call attention to the two points measured for pure iron. The dashed curve is the function $\hbar\omega = 286q^2$, while the smooth curve is a least-squares fit through the experimental points as explained in the text.

We have collected extensive data at room temperature up to a positive misset angle, $\Delta\varphi = +24°$, as well as for several negative $\Delta\varphi$'s. ($\Delta\varphi > 0$ corresponds to the creation of magnons, while $\Delta\varphi < 0$ corresponds to magnon annihilation.) The neutron wavelength was 1.07 Å.

If one utilizes the fact that sharp cutoffs in scans of the scattering surface are observed (see Fig. 1) and assumes that the dispersion curve is continuous, it is then possible by successive approximations to deduce the dispersion relation from the measurements of the width of the scattering surface as a function of the misset angle. This procedure, the details of which will be published elsewhere,[4] has been successfully applied to magnetite,[4] a material for which the dispersion relation has been well established experimentally[5] as well as theoretically.[6] Figure 2 shows the dispersion curve as measured for iron. Since these data do not extend to very low values of q, only an upper limit of 1 meV may be placed on the value of the energy gap. However, the results of the previous experiments[3] as well as calculated estimates have led us to take the energy gap to be zero in the analysis of our data.

If an expansion of the energy in powers of q^2 is assumed,

$$\hbar\omega = Dq^2(1-\beta q^2+\gamma q^4+\cdots), \tag{4}$$

then least-square fits to the data show that there is considerable improvement by taking two terms instead of only one and even some further improvement by including three terms. The smooth curve drawn through the experimental points in Fig. 2 has for its parameters

$$D = 266 \text{ meV Å}^2,$$
$$\beta = 3.2 \text{ Å}^2,$$
$$\gamma = 8.4 \text{ Å}^4. \tag{5}$$

This value of D is in good agreement with the D value reported by the Harwell group.[3] If only the nearest-neighbor interaction were effective [Eq. (3)], then at the value $qa/2\pi = 0.18$, the q^4 term should make a contribution of only 3.7% to the energy and higher terms would be negligible. However, at this relatively small value of q, our results [Eqs. (4) and (5)] indicate that the negative q^4 term contributes 51% to the energy and the positive q^6 term, 21%. It thus seems safe to conclude that the long-range interaction in iron contributes significantly to the magnon energies.

Our data also contain information on the form factor associated with the spin waves via the observed intensities. As seen in the upper plot in Fig. 1, the magnon intensity falls off slightly, but significantly, with increasing 2θ. This behavior is even more pronounced in the data for larger misset angles. This angular dependence is approximately what one expects for a $3d$-type form factor. Thus in the range of q values for which data are presented here, we are dealing with fluctuations whose spin density is comparable to that of $3d$ unpaired electrons.

A few measurements on a single crystal of pure iron were also made; however, the inclusion of small misoriented crystallites inherent in the nature of the growth process precluded the possibility of taking all the data from this crystal. The results shown in Fig. 2 for the two points that were measured are in excellent agreement with the iron-silicon data. Also drawn for comparison purposes is the quadratic law with the value $D = 286$ meV Å^2.

The exact values of β and γ are subject to change as further data at higher energies are included. Measurements are currently underway to extend the data into this region. It is also planned to determine the entire dispersion curve by direct energy analysis utilizing polarized neutrons.

We are very grateful to Dr. T. Riste, Dr. M. Blume, and Dr. R. D. Lowde for many stimulating discussions, and to Dr. H. J. Williams and Dr. A. J. Williams for the loan of an excellent single crystal.

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*Work performed under the auspices of the U. S. Atomic Energy Commission.

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OBSERVATION OF ELECTRON SPIN RESONANCE IN COPPER*

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(Received 16 June 1965)

We have observed electron spin resonance in single-crystal copper at a frequency of 9400 Mc/sec, over a temperature range from 1.4 to 60°K, utilizing the "selective-transmission" technique.[1-4] In this method there is a dc magnetic field and a perpendicular rf magnetic field in the usual manner, and the electrons absorb power from an rf field at their resonant frequency during the time they are in the skin depth. However, if the spin relaxation time is longer than the electron collision time, some of the electrons diffusing over to the other side of the sample will still be in a nonequilibrium state. That is, there will be a net precessing magnetization at the Larmor frequency. This precessing magnetization will set up eddy currents and radiate power. It is this "transmitted" power that is measured as a function of frequency (or dc magnetic field). Under suitable experimental conditions this power can be made larger than the power transmitted via the normal skin-effect damping and spurious leakages and, hence, can be a very sensitive unambiguous test for electron spin resonance.

The samples were 2.5 cm in diameter, 0.0038 (I), 0.0127 (II), and 0.0441 (III) cm thick and formed part of the common wall between a pair