the usual pathological "monsters" associated with the free-electron model. A cross section of the second zone surface, taken perpendicular to [001], is shown in Fig. 2.

According to the theory of the magnetoacoustic effect,[4] the oscillations for a propagation direction $\vec{q}$ and field direction $\vec{H}$ measure the extremal dimensions in the direction $\vec{q}\times\vec{H}$ of the cross sections of the Fermi surface perpendicular to $\vec{H}$. For the configuration corresponding to Fig. 1, one would thus expect an extremal momentum in the second zone corresponding to the indicated dimension. This has the value

$$k_{\text{theory}} = 5.5\times10^{7}\ \text{cm}^{-1},$$

which must be considered to be quite reasonable agreement with the larger of the two experimental values. Presumably the smaller dimension corresponds to an extremal dimension for one of the higher zone surfaces. It thus appears that the free-electron model might have even greater application than previously envisioned.

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## SCATTERING OF PHONONS BY SPINS AT LOW TEMPERATURES

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One method of studying the interaction of spins and phonons is to investigate the lattice thermal conductivity of crystals containing paramagnetic ions. If a paramagnetic ion has a low-lying excited level at an energy $kT'$ above the ground state, then one might expect that, at temperatures of the order of $T'$, the phonons will induce transitions to the higher state and will themselves be scattered. This will give rise to an extra thermal resistivity. Some experiments have already been reported[1,2] in which this effect was thought to have been observed. These showed that the low-temperature heat conductivity of mixed crystals of $ZnSO_4$ and $FeSO_4$ was much smaller than that of pure $ZnSO_4$. The decrease was much more than could be ascribed to ordinary impurity scattering. Nevertheless, these experiments were unsatisfactory in that the energy levels of the paramagnetic ion were determined by the internal field of the crystal and could not be changed to any appreciable extent by the application of an external magnetic field.

In the present experiments the heat conductivity of holmium ethyl sulfate has been measured and for this material the application of a magnetic field parallel to the hexagonal axis of the crystal has a marked effect on the thermal conductivity. Due to the magnetic anisotropy of the crystal there is hardly any effect when the field is perpendicular to the hexagonal axis.

Figure 1 shows the field dependence of the relative change in the thermal resistance $\Delta W/W_0$, where $W_0$ is the thermal resistance in zero field, at a series of temperatures in the liquid helium region. At the lower temperatures $\Delta W/W_0$ has a

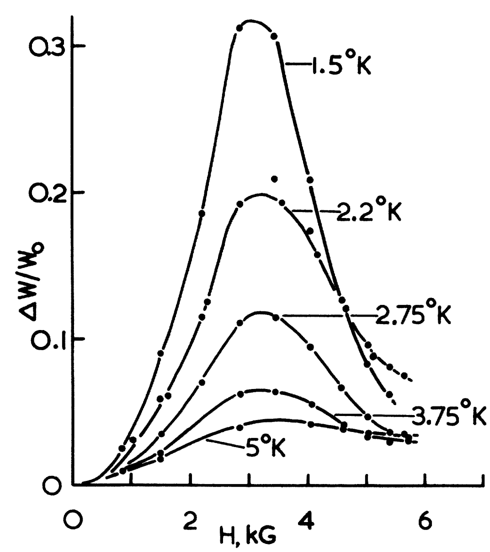


FIG. 1. The relative change in the thermal resistance, $\Delta W/W_0$, of holmium ethyl sulfate, as a function of the magnetic field, $H$, parallel to the hexagonal axis of the crystal.

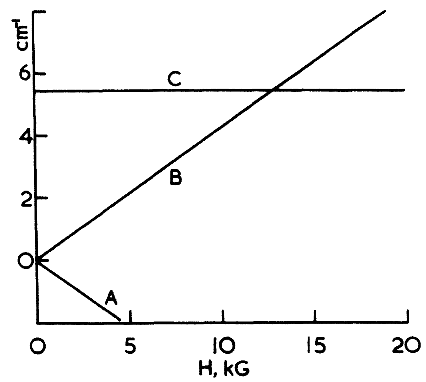


FIG. 2. The energy levels of holmium ethyl sulfate as a function of magnetic field parallel to the hexagonal axis of the crystal.

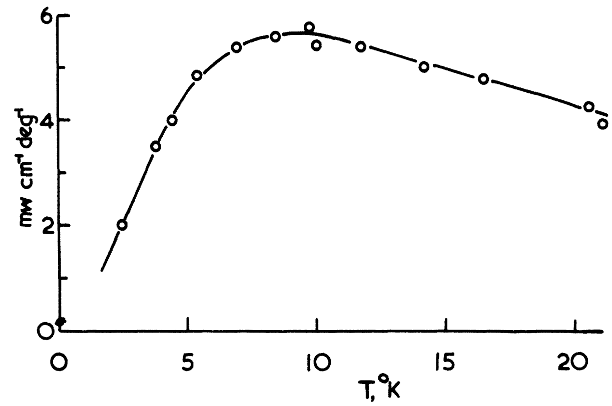


FIG. 3. The temperature dependence of the thermal conductivity of holmium ethyl sulfate.

very sharp maximum. A simple explanation for this effect can be given if one considers a paramagnetic ion whose lowest state consists of a simple doublet which can be split by a magnetic field. As the field is increased the separation of this doublet increases and when this becomes of the order of $kT$ there will be the maximum probability of interaction with the phonons—the specimen will be, as it were, "tuned in" to the phonons. At higher fields the separation of the doublet increases further, beyond $kT$, and so the probability of phonon interaction becomes less. In this way the maximum in the thermal resistance may be explained.

Holmium ethyl sulfate is a convenient material to work with because it has a very large effective value of $g$—15.4—and so splittings of the order of $kT$ can be made in quite moderate fields. There is a complication, however, because above the ground-state doublet there is a singlet state which is only ~5.5 $cm^{-1}$ away[3] (Fig. 2). Thus besides transitions between states $A$ and $B$, which are of the type which we have already discussed, there is also the possibility of transitions between states $B$ and $C$. These will change both the line shape of the $\Delta W/W_0$ vs $H$ curve and also the field at which the maximum resistivity is obtained.

In addition to this, transitions to state $C$ will be possible in zero field and this will also give rise to an extra thermal resistivity. It will indeed be noted that the thermal conductivity of the crystal (Fig. 3) is only a few mw $cm^{-1}$ $deg^{-1}$—about the same value as that of glass—and it is thought that this is due to zero-field transitions of this nature.

These experiments show for the first time in a direct manner the interaction of thermal phonons with the spin system and it would appear that such measurements are a useful method for the investigation of spin-lattice interactions.

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