Magnetophonons and Transport Theories

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THE magnetophonon effect, a relatively unexplored phenomenon observed in quantum magnetoresistance studies of semiconductors, is increasing in prominence as shown by the publication of two articles on this subject within one week (R. L. Peterson, *Phys. Rev. Lett.*, **28**, 431; 1972; L. Eaves *et al.*, *J. Phys. C (London)*, **5** L19; 1972). First predicted in 1961 by two Russian theoreticians, Gurevich and Firsov, and subsequently observed in 1963, the magnetophonon effect arises from the resonant scattering of electrons by optical phonons between the quantum states which are formed by the cyclotron motion of the electrons in a magnetic field. Unlike the acoustic phonons which are also present within the crystal, the optical phonons which can interact with electrons have a single well-defined frequency, ω_L . The cyclotron states are, of course, each separated by a quantum of energy $\hbar\omega_c$ where ω_c is the cyclotron frequency, and as a result of the single frequency of the interacting phonons the phonon scattering is strongest whenever the phonon energy is equal to the spacing between any two cyclotron states. The magnetoresistance therefore shows a series of peaks at magnetic fields given by $\omega_L = M\omega_c$ where M is an integer.

There are three chief applications of the magnetophonon experiment. First, it may be used as a proving ground for the various theories of quantum transport in a magnetic field. Second, the cyclotron effective mass of the charge carriers, $m^* = qB_M/\omega_c$, may be calculated directly from the magnetic field positions, B_M , of the magnetoresistance peaks, provided that the phonon frequency is known accurately from other experiments. In this respect the magnetophonon effect may be thought of as a simple form of the cyclotron resonance experiment in which the internally generated phonons replace microwave or infrared photons produced externally. The effective mass, which can be measured in either a magnetophonon or a cyclotron resonance experiment, is an extremely important parameter in describing the flow of electrical current in solids and is needed to obtain a detailed understanding of the operation of devices based on semiconducting materials.

The third application arises as a result of the disappearance of the normal magnetophonon effect at temperatures much below that of liquid nitrogen because of the small probability of thermal excitation of the optical phonons required to cause magnetophonon transitions between the quantum states. Even at very low temperatures, however, magnetophonon peaks can be made to reappear in the magnetoresistance curve by applying moderate or strong electric fields to the sample, so that the carriers are heated sufficiently out of equilibrium with the crystal lattice to begin to emit significant numbers of the high-energy monochromatic phonons. The magnetophonon effect may therefore be used to study the properties of these non-equilibrium or "hot" electrons, and several new processes for energy relaxation have been identified by this means (see, for example, R. A. Stradling *et al.*, *Proc. Tenth Intern. Conf. on Physics of Semiconductors*, 369; Boston, 1970). Because several semiconductor devices (such as Gunn oscillators) operate with "hot" electron distribution, this type of fundamental observation is of considerable importance.

Peterson is concerned with the application of quantum transport theories to describe magnetophonon phenomena. The theory becomes particularly difficult to develop for the experimental configuration in which the magnetic field is applied parallel to the direction of the electrical current, as the strongest scattering occurs with the magnetic field applied perpendicular to the current direction. With the magnetic field parallel to the current, resonant scattering processes are second order and are "indirect" as, from geometrical arguments, the traditions involved must change the carrier energy along the magnetic field as well as the cyclotron energy. Thus the experimental results are more complex and difficult to interpret in several important respects. With the purest samples and at the highest temperatures, a doubling occurs in the number of magnetophonon extrema that can be observed. This observation has previously been interpreted as arising from the increasing importance at higher temperatures of indirect scattering processes involving two optical phonons, as compared with processes involving a single phonon and an impurity scattering event. But Peterson reinterprets the experimental data in terms of "pseudo-resonances", involving coincidences between the scattering of carriers in different cyclotron states which happen to have the same momentum along the magnetic field.

In the second article, Eaves and colleagues present some experimental results for the semiconducting compound CdSe, from which the conduction band effective masses in this anisotropic material are derived. At the same time these results test those quantum transport theories involving the concept of a polaron (the quasi-particle involving an electron surrounded by a cloud of virtual phonons) in a magnetic field. Results are also reported with the magnetic field parallel to the direction of the current, which will serve to check further the theory for this experimental configuration.

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Magnetism and ³He

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SOLID ³He has a unique position in the theory of magnetism because the large amount of zero-point motion of the atoms leads to an exchange coupling between the nuclear spins which is similar to the exchange coupling between electrons in magnetic insulators. For various reasons ³He is expected to be a particularly simple system. The spin of the nucleus is one half, whereas most magnetic ions have larger spin, the magnetic dipole interaction between the nuclei is very weak compared with the exchange interaction, and the nearest neighbour exchange could possibly be much stronger than any other exchange.

The exchange energy is the result of two (or more) atoms changing places by tunnelling past each other. Because of the difficulty of this process it should occur much more readily for nearest neighbours than for further neighbours. Also the process becomes more difficult when the density gets larger, as there is less room for the atoms to pass one another, so the exchange energy

decreases rapidly as the density increases. The sensitivity of the entropy of the spin system to density can be observed by measuring the pressure as a function of temperature for a fixed volume of the sample, using temperatures from 0.02 K to 0.08 K, far above the antiferromagnetic ordering temperature of a few millidegrees. These measurements have been carried out in the presence of a large magnetic field, and a recent article by L. I. Zane (*Phys. Rev. Lett.*, **28**, 420; 1972) contains an analysis of some of these results.

If only nearest neighbour exchange were important a detailed fit to the experimental results should be obtained. The spin one-half Heisenberg model with nearest neighbour exchange has been studied in considerable detail, and more terms of the high temperature perturbation series for the thermodynamic properties of the spin system have been calculated than should be needed. In fact the fit is poor, and it seems that other exchanges must occur. Theoretical estimates have suggested that three-atom exchange should be the next most important process. Whereas two-atom exchange favours antiparallel spins, three-atom exchange favours parallel spins. The most important conclusion of Zane's article is that the fit to the experimental results can be greatly improved by including a three-atom exchange term whose strength is about 5 per cent of the strength of the two-atom exchange. The opposite sign of the exchange constant associated with such a term is said to be the most important feature for improving the fit. This should raise the temperature of the transition to the antiferromagnetic state.

As more detailed experimental results become available this kind of analysis can be carried further. It can only be successful if more complicated exchange processes occur with considerably lower probability than the simpler processes. Four particle exchange must be represented by a spin Hamiltonian which includes quartic terms, whereas two and three particle exchange is represented by terms quadratic in the spin variables.

NP 0532 (Edward Phillips) Giant Pulses

OPTICAL pulses from the pulsar in the Crab Nebula are more regular in their behaviour than might be expected from a study of the radio pulses. This result is reported in the current issue of *Astrophysical Journal Letters* by P. Horowitz of Harvard University and C. Papaliolis and N. P. Carleton of the Smithsonian Astrophysical Observatory and Harvard University, who were inspired by the variability that the Crab

pulsar (NP 0532) shows at radio frequencies to carry out a long term study of the variability in the optical spectrum (172, L51; 1972).

In the radio spectrum, for example, the Crab pulsar occasionally emits pulses which can be up to three orders of magnitude stronger than the average and which occur several times per hour. It was these giant pulses that led to the detection of the Crab pulsar.

To begin with, they report a two-hour sequence of observations in which a photomultiplier was used to measure the optical emission during successive peaks of the pulse train, the output of the photomultiplier being recorded digitally on tape. An analysis of the tape showed that the photomultiplier counts fit a Poisson distribution, and there was no indication of the occurrence of giant pulses, even though previous observations suggest that several giant pulses would have occurred in the radio emission during

the duration of the observing period.

To demonstrate the overall constancy of the optical pulses, the Harvard group obtained an average light curve showing the main pulse and the interpulse based on observations during ten nights during the 1969-70 observing season, and a second average light curve from observations during 1970-71. Subtraction of the two curves showed that there is no detectable difference between the two curves, and the Harvard group report that the same result has been obtained from observations during the most recent observing season. This amazing stability in the long term also extends to shorter time scales—the Harvard group have compared long runs of data obtained in November and December last year, and again find no significant discrepancies between the curves. Their conclusion is that the optical light curve of the Crab pulsar looks the same whether averaged over one night or several years.

Cooperation in Astronomy at Meudon

from a Correspondent

THE inaugural meeting of the Astronomy and Astrophysics Division of the European Physical Society, attended by about 150 scientists from twelve countries, was held at Meudon, France, on February 3-5. The occasion also marked the official opening of the new Department of Fundamental Astrophysics at the Meudon Observatory.

During the session devoted to radio astronomy, H. van der Laan (Leiden Observatory) reviewed some studies of extragalactic objects made with the Westerbork array, which began observations in 1970. The high sensitivity of this telescope means that maps of extended sources can be obtained in which the radio contours are determined down to lower surface brightness than in previous maps. In many cases the maps show that double sources are joined to their parent object by faint "bridges", which often display much higher polarization than the rest of the source. Some oddly-shaped sources in clusters of galaxies (3C 465, for example) were interpreted by van der Laan as "galactic wakes", resulting from continuous or repeated ejection of radio-emitting plasma by galaxies moving at $\gtrsim 1,000 \text{ km s}^{-1}$ through the intergalactic gas. Radio emission has been detected from all Shapley-Ames galaxies brighter than the tenth magnitude.

Radio maps of nearby spiral galaxies (such as M51 and NGC 4268) have yielded some new insights into the origin of spiral structure which lend support to the "density wave" theory developed by C. L. Lin of MIT and his associates. Moreover, some obser-

vations of NGC 4268 suggest that the formation of spiral arms might be initiated by the ejection from the nucleus of two oppositely directed jets of gas in the plane of the galaxy. As the jets move outward they sweep up gas from the spinning disk, causing a density enhancement along a spiral track. This interpretation is based on continuum observations at 1,400 MHz, and it will be tested when 21 cm line studies (which are planned for the near future) map the velocity distribution of the gas in NGC 4268.

P. G. Mezger (University of Bonn) reviewed recent radio studies of interstellar gas in our galaxy. The gas is denser and cooler in spiral arms, so star formation will be concentrated in these regions. Mezger also discussed the evidence (from both hydrogen and molecular line observations) for an expanding ring of gas near the galactic centre.

Some problems of the final stages of stellar evolution and the formation of pulsars were discussed by B. Paczynski (Institute of Astronomy, Warsaw). If supernovae are triggered by the explosive ignition of carbon, calculations suggest that the star would be completely disrupted, leaving no remnant behind. Therefore if a neutron star is to be left behind, some process is needed for making the explosion less efficient. Paczynski suggested that, if the core were convective, cooling by the URCA process would be more effective than had been assumed previously. This would delay carbon ignition until the core had evolved to a denser and more tightly-bound configuration.

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