de Haas-van Alphen effect

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Abstract

Theory of the de Haas-van Alphen effect is briefly explained as well as its relation to the fermi surface. Two different tecniques to measure it are discussed. Also we discussed how the fermi surface can be obtained from the knowledge of the periods of the quantum oscillations

Introduction

The fermi surface is related to many impartant physical properties. Information about the transport coefficients can be obtained from a knowledge of the shape of the fermi surface. Also equilibrium and optical properties can be learned from it. It is also important when testing new band structures calculations. Therefore it becomes important to be able to measure experimentally properties of the fermi surface [1].

One of the techniques used the most in obtaining information about the fermi surface is based on the "de Haas-van Alphen" effect. The effect was discovered in 1930 by de Haas-van Alphen when he observed oscilllation in M/H where M is the magnetization and H is the applied magnetic field to a sample of bistmuth. Later Onsanger related the frecuency of the oscillation to the cross sectional area of the fermi surface in a plane normal to the magnetig field. The main point is that the period of oscillation due to a change in 1/H where H is the magnetic field applied will be [1]:

$$\Delta(1/H) = 2\pi e/\hbar c A_e$$

where A_e is any extremal cross-sectianal area of normal to H. Therefore from the knowledge of the frequency of the quantum oscillation we can obtain information about the fermi surface and its shape. Many obsevation have been made of this oscillatory dependence in the susceptibility as well as in other physical quantities such as the conductivity. In fact the quantum oscilation are observed in many physical phenomenom.

These quantum oscillation can only be explained from a pure quantum mechanical point of view, and no classical or semiclassical theory would explain them. Basically the effect has its origin in the quantization of closed electronics orbits in a magnetic field [1] [5].

Observing the de Haas-van Alphen effect.

Torque Method

The de Haas-van Alphen effect has been observed using several tecniques, but there are two that have been widely exploited. One of them is based on the fact that a magnetized material in a magnetic field will experience a torque. This torque will be proportianal to the magnetic moment itself. Therefore measuring the oscillation in angular position of a sample of a metal as a function of the magnetic field will give information about oscillation in the magnetic field. This method is widely discussed in Shoenberg and the idea is as follow: the torque on the crystal will be related to the cross sectional area of the fermi surface, the parallel component of the magnetization, and the angle specifying the direction of the magnetic field H. The relation is given by [2]:

$$T = (-1/F) dF/d\Theta M_{||} HV$$

where $M_{||}$ is the parallel component of the magnetization, Θ is the angle specifying the direction of the magnetic field and F is a quantitie related to the fermi surface in the

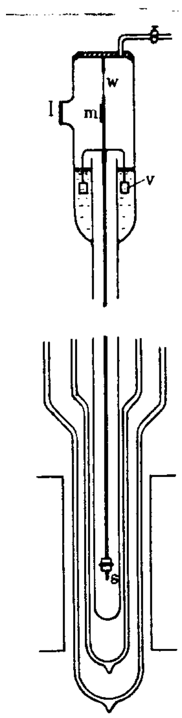

Figure 1: Apparatus to measure torque

following way $F = (c\hbar/2\pi e)A_e$ This torque can be measured using simple equipment. In figure 1 we have diagram of the aparatus used/cite2. The torque acting on the sample s will twist the mirror m slightly against the torsional restrain of the wire w, therefore the reflected image of an iluminated slit formed by the lens l. There is damping to the vibration comimg from the vanes V in figure 1. Under favorable condition, tipical values for the torque will be araund 10 dyne cm, and it turns out that this is easily measurable with a good presition, usually around 1 percent and this performance can be considerable improved with more sophisticated equipment, usually novel methods of angle sensing has been used combined with others new tecniques. Originally the torque method was essentially a low field since a vertical axis of suspension requires a horizontal magnetic field and this cannot usually exceed $3/x10^3G$, but with the development of superconducting magnets, rather higher fields have become possible. This is an important consideration since limitation to low fields implies that only small extremal areas of a complicated fermi surface can be observed. It is important to notice that the actual performance depends very much on the electronic noise and drift and how it is reduced. Some data obtained using this method is shown in figure 2.

Modulation Tecniques

The field modulation tecnique is a simple aproach for dHvA studies. This tecnique measures the voltage induced in a pickup coil surrounding the sample when a field is applied. This tecniques is used for shorter periods where large fields are required, usually

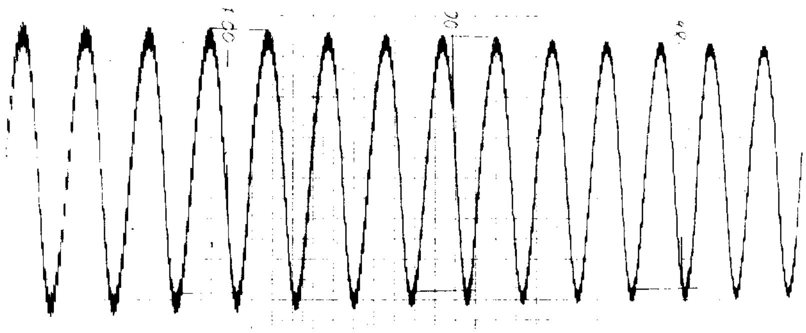

Figure 2: Torque dHvA oscillations in Au at 1.2 K. The torque is plotted versus the inverse of the field

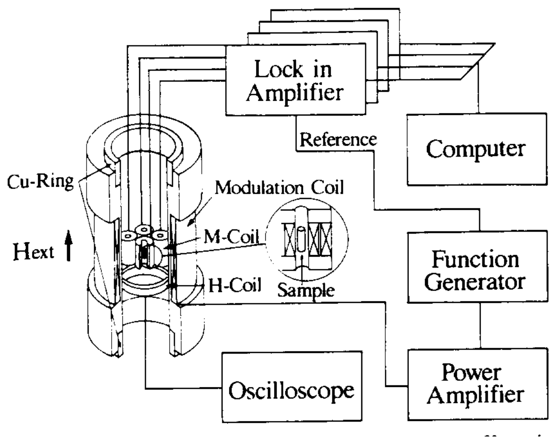

Figure 3: Apparatus used to measure the dHvA oscillation using the modulation technique

of the ortder of 10 T at a temperature of 1 K. With this tecnique we can observe the effect satisfactorily for those short periods [3]. To obtain the high fields, superconducting solenoids are used creating a high field H_o. The samples are typically single-crystal wires in a small pickup coil. A periodic variation in the field is achieved by superimposing a small sinousoidal periodic field $H_1 cos(\omega t)$to the field H_o. Doing a taylor series about the average field, we can get an expression for the magnetization that will include derivatives of the magnetization with respect to the field evaluated at H_0.

$$M(t) = M(H_0) + H_1 cos(\omega t)(dM/dH)_{H_o} + 1/2[H_1 cos(\omega t)]^2(d^2M/dH^2)_{H_o} + ...$$

Now the derivative of the magnetization with respect to time will give the emf induced in the pickup coil.

$$-dM/dt = +\omega H_1(dM/dH)_{H_o} sin(\omega t) + 1/2\omega H_1^2(d^2H/dH^2)_{H_o} sin(2\omega t) + ...$$

The oscillation of the magnetization associated with the de Haas-van Alphen effect imply a non zero value for the second derivative d^2H/dH^2 in the Taylor expantion which

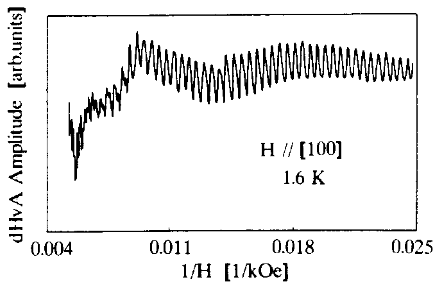

Figure 4: Oscillatory AC susceptibility of PrSb

oscillates as a function of the applied field H_o and is also the coefficient of the second harmonic in the Tailor expantion [3]. This is basically has information of the period as a funtion of the inverse of the applied field Now if we employ a phase sensitive detection at frecuency 2ω, (where ω is the natural frecuency of the modulating field) we can observe the effect and reduce the signal to noise ratio.. Ussually the modulating amplitude is chosen to be compared with the period of the oscillation. Recently field of the order of 28 T, were produced using hybrid magnets [4]. The apparatus is shown in figure 3, An AC field of up to 30 mT is generated in the modulation coil using a high power amplifier. The time derivate of the magnetization is detected from the coils and the induced voltages are measured. The temperature for this experiment was of 4.4 K. In figure 4 we can see some of the results from these experiment.

Measuring the Fermi Surface.

Once the de Haas-van Alphen effect has ben detected and the frecuency has been measured, we can obtain information about the fermi surface using equation 1. When we change the magnetic field direction we can get different extremal areas, these extremal areas are mapped out. This will be enough to reconstruct the actual shape of the fermi surface. This is a complex task, in many cases it is easier to guess at what the surface is from some theoritical aproximation to the band estructure, and improving the guess when comparing it witn the data. For instance for gold for quite a wide range of field directions Shoenberg observed that the magnetic moment has a period of 2 x10-19 gauss -1, and this correspond to a extremal area of 4.8x10-6 cm -2, and this value is in agreement with the experimental value of the fermi wave vector [5].

Conclusions.

We can see that besides being an interesting phenomenon by itself due to the fact that it is a pure quantum phenomenon, the de-Haas-van Alphen effect provides information in an effective way about the fermi surface and therefore about many important quantities of the crystal. The tecniques to measure it are in general simple and easy to set up and good presition can be obtained.

References

[1] Neil W, Ashcroft, N. D. Mermin, *Solid State Physics*, Sounders Co. 1976

[2] D. Shoenberg, *Magnetics oscillations in metals*, Cambrige University Press, 1984

[3] J. R. Hook, H. E. Hall, *Solid State Physics* 2nd ed, John Wiley and Sons, 1991

[4] G Kido et al, *Physica B*, bf 177 (1992) 46-48

[5] Charles Kittel, *Introduction to Solid State Physics* 7th John Wiley and Sons, 1996.