MAGNETIC RESONANCE BY HELICON–NUCLEAR-SPIN INTERACTION IN CONDUCTING PbTe*

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(Received 13 June 1966)

We wish to report what we believe to be the first experimental evidence of magnetic resonance in the bulk of a single-crystal conductor obtained with the rotating magnetic field of a helicon wave[1,2] interacting with nuclear spins. We observed the nuclear magnetic resonance (nmr) of Pb^{207} (spin $\frac{1}{2}$, positive nuclear moment) in a single crystal of p-type PbTe at 1.3°K (Fig. 1). The sample, of dimensions $3\times3.7\times12$ mm, has a conductivity of $10^{-5}\ \Omega$ cm. Magnetic resonance was detected with a standard Q meter.[3]

The usual dispersion law[2] between wave vector, k, and applied frequency, ω, can be extended in a straightforward manner to take the nuclear paramagnetic susceptibility into account:

$$k_\pm^2 = Ne\mu_0\frac{\omega}{B_0}\left(\pm1+\frac{i}{\omega_c\tau}\right)[1+(\chi'-i\chi'')\mp\epsilon(\chi'-i\chi'')],$$

where ± indicates the sense of rotation of the helicon field around the applied constant magnetic field B_0; N is the density of free carriers; e is the charge of free carriers, negative for electrons, positive for holes; ω_c is the cyclotron frequency; τ is the momentum relaxation time; χ' and χ'' are the usual dispersion and absorption components of nuclear magnetic susceptibility which exhibit resonant behavior at the nuclear Larmor frequency[4]; and $\epsilon=\gamma/|\gamma|$ is the sign of the nuclear gyromagnetic ratio γ. Nuclear moments are coupled with the propagating wave if the Larmor and the cyclotron precessions rotate in the same sense. The depth of penetration of the helicon wave is $(\omega_c\tau/\pi)\lambda$, where the wave length λ is 0.37 cm at 7.5 Mc/sec in the nmr field of 8450 G ($N=3\times10^{17}$ hole cm^{-3}). Many helicon dimensional resonances[5] were easily detected by sweeping the magnetic field, indicating an $\omega_c\tau$ value of at least 50 at 8450 G. One may then expect a depth of penetration of a few centimeters.

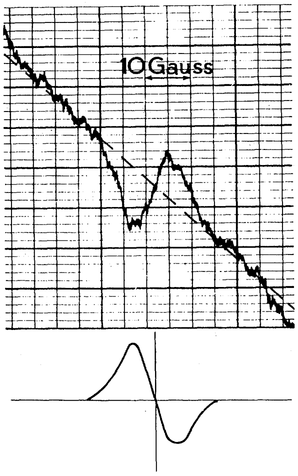

FIG. 1. Helicon nmr signal of Pb^{207} in a single crystal of conducting PbTe at 1.3°K (derivative of absorption signal by phase-sensitive detection). Top, actual recording: modulation frequency 318 cps, scanning speed 4 G per min. The linear variation of the base line (dashed line) is due to the derivative of the superimposed helicon dimensional resonance. Bottom, smoothed signal after subtraction of the linear helicon component.

It should be emphasized that the nmr signal (Fig. 1) is two orders of magnitude greater than one would expect if ordinary resonance occurred in the skin depth δ ($\delta\approx6\times10^{-3}$ cm). In the absence of helicons, the fraction η of the volume of the sample containing magnetic energy would be $\eta\approx\frac{1}{2}\delta S/V$, where S and V are total area and volume of the sample; in our experiment η would be approximately 1/25. However, the measured signal corresponds to $\eta\approx4$ instead of 1/25, showing that the helicon signal is even larger[6] than the signal of all the spins of the sample in the absence of propagation effects.

A dramatic exhibition of helicon–nuclear-spin interaction arises from the property of helicons to propagate with low attenuation along the applied magnetic field, whereas there is no propagation in a direction perpendicular to the field. We can then induce resonance with the sample out of the coil [Fig. 2(b)], the coil at the end of the sample being used only to couple the rf magnetic field into the crystal. When the magnetic field was along the large dimension [Fig. 2(b)], we obtained a signal slightly less intense than with arrangement of Fig. 2(a); on the contrary, when the magnetic field was in the orientation of Fig. 2(c), no signal was found.

The helicon–nuclear-spin interaction offers a means for detecting nmr in large single-crystal conducting samples, and provides all the

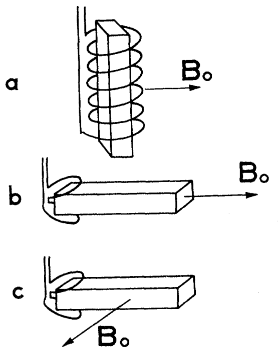

FIG. 2. Different arrangements of coil, sample, and field. (a) Sample in the coil. The signal obtained is shown in Fig. 1. (b) Sample out of the coil and magnetic field along the sample. The excited helicon wave propagates in the crystal and gives a signal. (c) Field at right angles to sample; the helicon wave cannot propagate along the crystal and no signal is obtained.

advantages of an experiment in the bulk. First, ordinary nmr, as performed within the skin depth of, for example, a powder, can be perturbed by surface effects. This is the case of PbTe, where the semiconducting properties change markedly on the surface. We have observed the signal from a PbTe powder as a complex pattern with 100-G linewidth; this is in contrast with the 4-G linewidth (Fig. 1) obtained in the bulk by the helicon nmr method. Second, the fact that the helicon propagation allows nmr to be observed in single crystals leads to the possibility of the observation of detailed anisotropic effects which manifest themselves as complex averages in the powder experiments. Unfortunately, this method is restricted to the cases where cyclotron and Larmor precessions have the same sense, that is, when carrier charge and nuclear gyromagnetic ratio have the same sign. It is also necessary that $\omega_c\tau \gg 1$ for helicon propagation. This requires high-purity samples, high magnetic fields, and low temperatures. In the case of metals, a field of typically 50 kG or more is required to eliminate the damping of the wave by the Doppler-shifted cyclotron absorption.[8] The case of indium seems to be the most promising one. Further theoretical and experimental study of the effect is in progress.

The samples were kindly provided by Mrs. H. Rodot. It is a pleasure to acknowledge discussions with Dr. A. Libchaber and Dr. A. Zylbersztejn. I am indebted to Dr. D. L. Carter for valuable comments concerning the manuscript. I would like to thank Professor I. Solomon for his constant interest in this work.

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*Work performed with the participation of Direction des Recherches et Moyens d'Essais.

[1] The idea is quite straightforward; to our knowledge the first mention of this experiment was made during the Seventh International Conference on the Physics of Semiconductors. 2. Symposium on Plasma Effects in Solids, Paris, 1964 (Academic Press, Inc., New York, Dunod, Paris, 1964).

[2] For a review article on helicon and plasma waves in solids see, for example, S. J. Buchsbaum, in Proceedings of the Seventh International Conference on the Physics of Semiconductors. 2. Symposium on Plasma Effects in Solids, Paris, 1964 (Academic Press, Inc., New York, Dunod, Paris, 1964), p. 3; R. Bowers, ibid. p. 19.

[3] See, for example, A. Abragam, Principles of Nuclear Magnetism (Oxford University Press, London, 1961), p. 75.

[4] Ibid., p. 49.

[5] Y. Kanai, Japan. J. Appl. Phys. 2, 137 (1963).

[6] It is a very difficult problem to take into account the boundary conditions[7] for a finite sample. Preliminary studies show that η is enhanced by the increase of rf field intensity in the interior of the sample due to the standing waves when $\omega_c\tau \gg 1$.

[7] R. G. Chambers and B. K. Jones, Proc. Roy. Soc. (London) A270, 417 (1962); C. R. Legendy, Phys. Rev. 135, A1713 (1964).

[8] E. A. Stern, Phys. Rev. Letters 10, 91 (1963); M. T. Taylor, J. R. Merrill, and R. Bowers, Phys. Letters 6, 159 (1963).