to the transition between the bound states $n=0$, $l=1$ and $n=1$, $l=1$. The transitions between the bound states $n=0$, $l=0$ and $n=1$, $l=0$, 2 is approximately $0.05\hbar\omega_c$ above this in energy. We ascribe the two observed lines to these two types of transitions and the splitting to this difference in their transition energies. The calculated separation of $0.05\hbar\omega_c$ is in excellent agreement with the observed value $0.055\hbar\omega_c$.[3] The relative increases in intensity of the satellite line at higher temperatures is due to an increase in the number of carriers in the excited donor states and in the conduction band.

We have also determined the conduction-band effective mass. Figure 3 shows the results of a series

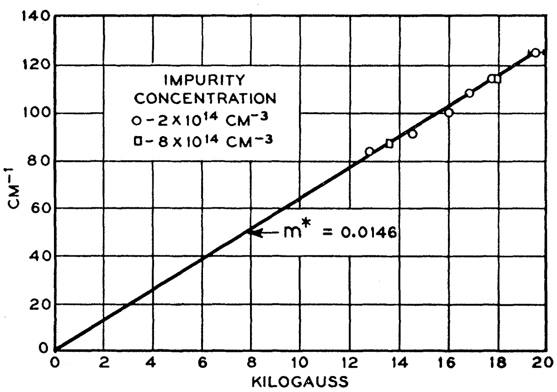

FIG. 3. The resonant frequency for bound electrons plotted against the corresponding magnetic field.

of measurements taken from 70 to 120 microns on two samples of different impurity concentration, the resonant field corresponding to the low-field line. From the slope of this curve we obtain a mass of $0.0146m_0$ for the main transition between donor states. Using the value of the line splitting, we find the effective mass to be $(0.0155\pm0.005)m_0$. This is considerably higher than the value $(0.013\pm0.001)m_0$ obtained from microwave measurements[4] but presumably not beyond the possible error in measurement because of the small value of ω_T. Our results when combined with previous infrared cyclotron resonance measurements[5] taken at room temperature show a smooth variation of effective mass with magnetic field extending down essentially to the bottom of the conduction band at zero field.

The authors wish to acknowledge valuable discussion with J. K. Galt.

[1] Yafet, Keyes, and Adams, J. Phys. Chem. Solids **1**, 137 (1956).

[2] M. H. Johnson and B. A. Lippmann, Phys. Rev. **76**, 828 (1949).

[3] Here ω_c is the angular frequency for resonance in the conduction band. The experimentally observed splitting is determined from the ratio of the magnetic fields for the two lines.

[4] Dresselhaus, Kip, Kittel, and Wagoner, Phys. Rev. **98**, 556 (1955).

[5] Keyes, Zwerdling, Foner, Kolm, and Lax, Phys. Rev. **104**, 1804 (1956); Burstein, Picus, and Gebbie, Phys. Rev. **103**, 825 (1956).

Paramagnetic Resonance of Nickel Fluosilicate under High Hydrostatic Pressure*

W. M. WALSH, JR.,† AND N. BLOEMBERGEN
Gordon McKay Laboratory, Harvard University, Cambridge, Massachusetts
(Received June 3, 1957)

A SINGLE crystal sample of $NiSiF_6\cdot6H_2O$ has been examined by para-magnetic resonance techniques while exposed to hydrostatic pressures up to 10 000 kg/cm² at room temperature. For details of crystal structure and spin Hamiltonian the reader is referred to the literature.[1–4] Analysis of our data taken with the static magnetic field along the trigonal axis leads to the curve of zero-field splitting, D, *versus* pressure shown in Fig. 1, where $\partial D/\partial P=0.834\times10^{-4}$ $cm^{-1}/(kg/cm^2)$ at $T=300°K$. The sign of D is not determined by paramagnetic resonance but is known to be negative at atmospheric pressure.[3] That D goes to zero is indicated by the crossing of two transitions at 6200 kg/cm² where a pronounced minimum in the line width of the superposed resonances occurs. The interesting question of exchange narrowing *versus* broadening in this pressure region will be investigated more fully.[5,6] The values of D near 10 000 kg/cm² are assumed to be positive because of the monotonic, linear character of the data up to 6200 kg/cm². The g factor was found to be $g_{\parallel}=2.34\pm0.02$ at all pressures.

Since it is known that D is produced by the trigonal component of the crystalline electric field in conjunction with spin-orbit coupling, we infer that this crystalline field component varies monotonically with P, changing sign at $P=6200$ kg/cm².

This change in the crystalline field is presumably due to anisotropy of the elastic constants of the crystal. Measurements of D *versus* temperature support this view, D decreasing in magnitude with temperature to a constant value of -0.12 cm⁻¹ at $T=20°K$.[3,4,7] Bagguley *et al.*[4] ascribe this to anisotropic thermal expansion. Attempts will be made to measure the anisotropy of

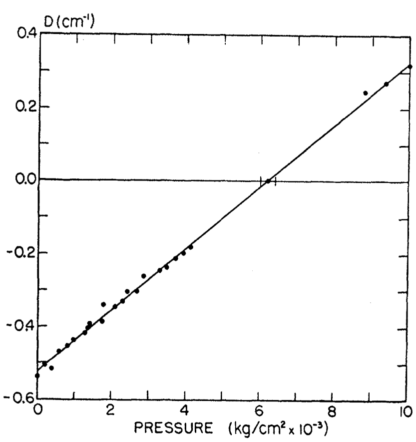

FIG. 1. Pressure dependence of the zero-field splitting in $NiSiF_6\cdot6H_2O$ at 300°K.

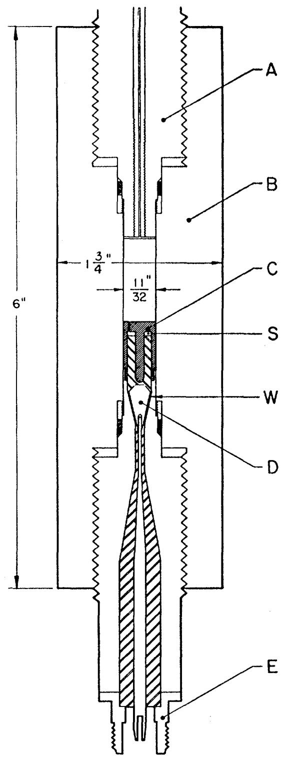

FIG. 2. High-pressure bomb and microwave transmission plug. *A*—pressure feed plug; *B*—BeCu bomb; *C*—microwave cavity; *D*—sealing cone; *E*—type *N* connector; *S*—sample position; *W*—synthetic mica washer.

both the compressibility and the thermal expansion in order to test these explanations quantitatively.

Since this is, to our knowledge, the first electron spin resonance experiment performed under high pressure, a description of the microwave coupling into the high-pressure region is given. Details of the high-pressure generating and measuring equipment are available in the literature.[8,9] The complete assembly shown in Fig. 2 consists of a nonmagnetic, BeCu cylinder with a pressure feed plug threaded into one end with a Bridgman sealing system[6] and a microwave transmission plug similarly connected at the other end. The plugs are also hardened BeCu. The microwave connection starts at a standard, 50-ohm, connector followed by a constant, 50-ohm, impedance line which tapers to 0.100 in. o.d. The line then tapers up to 0.250 in. o.d. with a BeCu cone serving as the center conductor. The cone seats on a synthetic mica ($KMg_3AlSi_3O_{10}F_2$) washer. This cone and washer assembly constitute the pressure seal for the coaxial line. The brass microwave resonant cavity is press fitted on the end of this open circuited transmission line. The cavity is coaxial, with a center stub $\sim n/4$ long (T.E.M. mode). The coupling to the transmission line is capacitive and is adjusted by changing the gap between the center stub and the cone. This type of coupling concentrates the microwave electric field in the coupling region and thus permits rather large paramagnetic samples to be placed at the shorted end of the cavity without prohibitive dielectric losses. The remaining volume of the cavity and the transmission line are filled with Teflon. The loaded Q of the cavity, monitored by sampling the reflected microwave power, is about 500. The cavity is immersed in the pressure transmission fluid, petroleum ether, thus requiring no mechanical strength of the cavity and ensuring that the paramagnetic sample is subject to purely hydrostatic pressure.

We gratefully acknowledge the assistance of Dr. G. B. Benedek of this laboratory in the design of the high-pressure system. We also wish to thank Dr. J. W. Meyer of Lincoln Laboratory for the crystal of $NiSiF_6 \cdot 6H_2O$ used in the experiment.

* Supported by a Joint Services contract.
† General Electric Company Fellow.

[1] K. D. Bowers and J. Owen, Repts. Progr. Phys. **18**, 304 (1955).
[2] Holden, Kittel, and Yager, Phys. Rev. **75**, 1443 (1949).
[3] R. P. Penrose and K. W. H. Stevens, Proc. Phys. Soc. (London) **A63**, 29 (1950).
[4] Bagguley, Bleaney, Griffiths, Penrose, and Plumpton, Proc. Phys. Soc. (London) **61**, 551 (1948).
[5] J. F. Ollom and J. G. Van Vleck, Physica **17**, 205 (1951).
[6] A. Abragam and K. Kambe, Phys. Rev. **91**, 894 (1953).
[7] J. W. Meyer, thesis, University of Wisconsin, 1955 (unpublished).
[8] P. W. Bridgman, *The Physics of High Pressure* (G. Bell & Son, Ltd., London, 1952).
[9] Kushida, Benedek, and Bloembergen, Phys. Rev. **104**, 1364 (1956).

The Convergatron, a Neutron Amplifier

LYLE B. BORST
New York University, University Heights, New York
(Received June 10, 1957)

NEUTRON sources for power production or research may be divided into three categories: (a) divergent chain reactions, (b) accelerators, and (c) accelerators with amplifying targets (a convergent chain reaction). Accelerators have limited neutron output, whereas inadequate control of the divergent chain reaction may lead to a destructive excursion.

By introducing a series array of neutron-amplifier stages, it is possible to operate an arbitrarily large neutron source as a subcritical system without fear of destructive excursion by means of a small controllable primary source.

The Convergatron is a neutron amplifier consisting of three zones per stage: fissionable fuel zone (with or without moderator), a thermal neutron barrier, and a neutron moderator zone. If arranged in a series sequence the polar properties permit neutron flow from fuel through the barrier and moderator to the next fuel zone. Neutrons moving in the reverse direction are moderated and absorbed by the thermal neutron barrier so that flow is inhibited.

If each Convergatron stage has characteristics approaching a critical multiplying system, the neutron