FIG. 1. Oscilloscope pictures of resonance absorption in lithium vs magnetic field. *Left*: Electron spin resonance. Zero field at the center of the sweep. The four peaks arise from a small phase shift between the horizontal and vertical axes. Sweep amplitude about 40 gauss. *Right*: Li[7] nuclear resonance at about 10 000 gauss. Sweep amplitude approximately 3 gauss.

alternating field inducing transitions, γ is the gyromagnetic ratio of an electron, and χ'' is the imaginary or "loss" part of the complex magnetic susceptibility. This same equation is satisfied by a line of any shape which is sufficiently narrow, and by a broad line of the type discussed by Garstens.[3]

The measurement of χ_p, which involves an absolute intensity measurement, appears difficult at first glance. Such experiments have been done by Hutchison and Pastor.[4] The essential and new feature of our experiment is the elimination of most of the usual difficulties by comparing the absorption of the electron resonance in lithium with that of the nuclear resonance in Li[7] in the same sample and at the same frequency (17 Mc/sec). (See Fig. 1.) In order to observe the resonances of the electrons or nuclei we merely change H from 6 gauss to 10 000 gauss, leaving all circuits unchanged. We can measure the ratio of the areas under the absorption curve. With the use of Eq. (1) we can relate this ratio to the ratio of the electron and nuclear static susceptibilities. Knowledge of the nuclear susceptibility, the ratio of the absorption areas, and the gyromagnetic ratio of electron and nucleus is all that is needed to determine the electron susceptibility, since circuit parameters and the amount of sample cancel out in the ratio. The nuclear susceptibility can, of course, be calculated to a high degree of precision from the Langevin formula.

The value of spin susceptibility we obtain for lithium is $2.0\pm0.3\times10^{-6}$ cgs volume units. The theoretical spin value of Pines[5] is 1.87×10^{-6}, while the free-electron (Pauli) value is 1.17×10^{-6}. The experimental value of Rao and Sarithri[6] measured by conventional means is 1.35×10^{-6}, and includes, of course, a diamagnetic part associated with orbital electron motion and ion cores. Starr and Kaufmann[7] find 1.95×10^{-6}, also by conventional means. Pines' theoretical value clearly agrees much more closely with experiment than does the free-electron value.

A fuller account of this research will be published at a later date, together with a discussion of the inherent limitations in accuracy. It is worth while pointing out here, however, that the reaction of the lithium to form nonmetallic compounds is not likely to effect accuracy to first order, since the nuclear resonance in the metals is displaced several gauss from that in a nonmetal[8]

(Knight shift), with the result that we measure only the ratio of electron absorption to that of metal nuclei. There is, of course, no electron resonance in the nonmetal. In support of these statements, we have not found a sample dependence in our work.

We suggest that there are other systems in which a simultaneous nuclear and electron resonance can be found (e.g., the metal ammonia solutions and free radicals) where the comparison will make possible an improved determination of electron susceptibilities and may be used to determine the concentration of electron absorbing centers.

We are continuing the work on lithium and sodium. We hope that improvement of the signal-to-noise ratio will give adequate precision for reliable values of the diamagnetism.

We wish to express our appreciation to Dr. Pines for numerous interesting conversations. We have had many stimulating discussions with other members of our resonance group, particularly with Dr. Richard E. Norberg.

[1] D. Bohm and D. Pines, Phys. Rev. 92, 609 (1953); D. Pines *ibid*. 92, 626 (1953).
[2] F. Bloch, Phys. Rev. 70, 460 (1946).
[3] M. A. Garstens, Phys. Rev. 93, 1228 (1954).
[4] C. A. Hutchison and R. C. Pastor, Revs. Modern Phys. 25, 285 (1953).
[5] D. Pines, following letter [Phys. Rev. 95, 1090 (1954)].
[6] S. R. Rao and K. Sarithri, Proc. Indian Acad. Sci. 6, 207 (1942).
[7] C. Starr and A. R. Kaufmann, Phys. Rev. 59, 476 (1941).
[8] W. D. Knight, Phys. Rev. 76, 1259 (1949).

Paramagnetic Susceptibility of Conduction Electrons*

DAVID PINES
*Department of Physics, University of Illinois,
Urbana, Illinois*

WE here report the results of a calculation of the effect of electron-electron interactions on the paramagnetic susceptibility of conduction electrons in metals using the collective description of electron interactions.[1] We have computed the paramagnetic susceptibility χ_p at $0°K$, using the method of Sampson and Seitz,[2] which requires a knowledge of the way in which the energy of the electronic system changes as the population of electrons of spin up and spin down varies. Our calculation for χ_p differs from that of SS in that we use the expressions for the correlation energy developed in IV, rather than the earlier Wigner expression.

As shown in IV, the average energy per electron may be written as

$$E=E_0+E_F+E_{\text{exch}}+E_{\text{corr}}^{\text{l.r.}}+E_{\text{corr}}^{\text{s.r.}}, \quad (1)$$

where E_0 is the binding energy due to the periodic field of the lattice, E_F the average Fermi energy, E_{exch} the exchange energy per electron, $E_{\text{corr}}^{\text{l.r.}}$ represents the effect of the long-range Coulomb correlations on the electronic energy and is given in IV, and $E_{\text{corr}}^{\text{s.r.}}$ represents the reduction in energy due to short-range Coulomb correlations between electrons of antiparallel spin. An approximate expression for $E_{\text{corr}}^{\text{s.r.}}$ is

$$E_{\text{corr}}^{\text{s.r.}} = -0.0764\{0.333-0.819 \ln\beta+(\beta^2/12)\} \text{ ry}, \quad (2)$$

where $\beta = (k_c/k_0)$ is the inverse electron screening length measured in units of the maximum electron wave vector. The effect of electron correlations on χ_p may be readily computed provided we assume that the effective screening length for electron-electron interactions, k_c^{-1}, is not altered by a shift in the spin populations. Physically, this assumption appears quite reasonable, since the screening length is determined primarily by the long-range correlations, which are in turn relatively insensitive to the electron spin alignment. A more detailed investigation verifies the validity of this approximation.

Our results may be put in the form, $\chi_p = -(2n\gamma^2/\alpha)$, where γ is a Bohr magneton, n the density of conduction electrons, and α is given by

$$\alpha = (20/9)E_F + (8/9)E_{\text{exch}} + \alpha_{\text{l.r.}} + \alpha_{\text{s.r.}}, \quad (3)$$

the latter terms representing the effect of long-range and short-range electronic correlations on χ_p. Table I gives the various contributions to α for the alkali metals, together with values of χ_p obtained using (3), and, for comparison, those obtained in the free-electron approximation and those calculated by SS. We see that the Coulomb correlations tend to compensate exchange, but that the resultant susceptibility is always rather higher than the free-electron value. We estimate the accuracy of our theoretical values for χ_p as about 20 percent. A direct measurement of χ_p for lithium has been carried out recently by Schumacher, Carver, and Slichter.[3] We see that our theoretical calculation of

TABLE I. χ_p for the alkali metals. Units: Rows (c)—(g), ry; Rows (h), (i), and (j), cgs volume units$\times 10^6$.

Metal	Li	Na	K	Rb	Cs
(a) $(m^*/m)^a$	1.45	0.98	0.93	0.89	0.83
(b) β	0.73	0.68	0.73	0.73	0.73
(c) $(20/9)E_F$	0.326	0.319	0.221	0.207	0.191
(d) $(8/9)E_{\text{exch}}$	−0.253	−0.206	−0.167	−0.157	−0.146
(e) $\alpha_{\text{l.r.}}$	0.023	0.015	0.014	0.014	0.013
(f) $\alpha_{\text{s.r.}}$	0.108	0.111	0.109	0.109	0.108
(g) α	0.204	0.239	0.177	0.173	0.166
(h) χ_p	1.87	0.85	0.61	0.53	0.44
(i) χ_p^{free}	1.17	0.64	0.48	0.44	0.38
(j) $\chi_p(\text{SS})$	2.92	1.21			

a These values of the effective mass are due to Harvey Brooks (private communication).

1.87×10^{-6} cgs volume units is in substantially better agreement with their experimental result of $2.0 \pm 0.3 \times 10^{-6}$ cgs volume units than the free-electron value or that of SS.

Details of the foregoing calculation will be described in a forthcoming paper on the effects of electronic correlations on metallic phenomena. The writer would like to thank Dr. R. E. Norberg and Dr. C. P. Slichter for stimulating his interest in the magnetic properties of the alkali metals, and Mrs. M. C. Huse for her invaluable assistance in carrying out numerical calculations.

[1] D. Bohm and D. Pines, Phys. Rev. 92, 609 (1953); D. Pines, Phys. Rev. 92, 626 (1953), hereafter referred to as IV.
[2] J. B. Sampson and F. Seitz, Phys. Rev. 58, 633 (1940), hereafter referred to as SS.
[3] Schumacher, Carver, and Slichter, preceding letter [Phys. Rev. 95, 000 (1954)].
[4] See A. H. Wilson, The Theory of Metals (Cambridge University Press, London, 1953), p. 175.
[5] S. R. Rao and K. Sarithri, Proc. Indian Acad. Sci. 6, 207 (1942).

Self-Powered Semiconductor Amplifier

C. G. B. Garrett and W. H. Brattain

Bell Telephone Laboratories, Murray Hill, New Jersey

DURING the course of experiments on the electrical properties of germanium-electrolyte systems, it became apparent that the surface of a sample of n-type germanium passing anodic current acts as a multiplying collector for holes.[1] Using this principle, it becomes possible to construct a germanium-electrolyte amplifying device which incorporates its own power supply. In this device, a slice of n-type germanium, having an indium-alloyed emitter on one surface, has its other surface exposed to a suitable electrolyte. Another electrode, having a half-cell potential higher (more noble) than that of germanium, is also placed in the electrolyte. Connections are made to the indium, to a goldbonded contact to the germanium, and to the other electrode (Fig. 1).
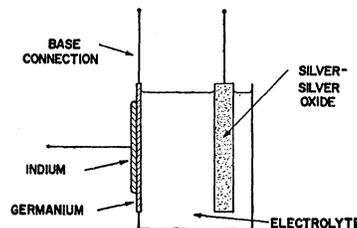

FIG. 1. The self-powered semiconductor amplifier.