resistance of one specimen continued to rise at temperatures as low as 0.4°K, and, in fact, seemed to be approaching infinity at absolute zero. These authors concluded that the minimum is not due to spurious causes such as gas absorption or unavoidable disturbances caused by the current and potential leads to the specimens.

The only other published measurements on gold appear to be those of Meissner.[4] Here, measurements on gold monocrystals (impurities $\sim 10^{-3}$ percent) showed no minimum down to 1.3°K, a temperature well below the minimum temperature found necessary by the Leiden investigators.

If the effect reported by the Leiden group should prove to be real (i.e., not due to impurities or some similar cause), then it appears that a rather fundamental violation of the basic quantum theory of solids has appeared. Thus, a monovalent substance like gold, where the Fermi surface in the first zone is presumably nearly spherical and far from a zone boundary, approaches the ideal Bloch model closely—the conduction electrons are nearly "free." Presumably, one would then have to go a step further than the present theory of solids and consider the possibility of electron interaction—a mechanism which has sometimes been suggested as responsible for superconductivity.

It seems more plausible to suppose that the effect is of a secondary nature, and in some way connected with the crystallite boundaries in the polycrystalline material. Thus, Meissner's single crystals do not show the effect even though the impurity content of his material was about ten times as large as that used by de Haas and collaborators. It may, of course, be that in the process of growing single crystals, Meissner automatically purified his material—such a process has been used for refining, the impurities being "flushed" to one end of the crystal, and this end then rejected.

It might, therefore, be of interest to re-examine this matter, making use of both single crystal and polycrystalline specimens fabricated from the same material and each having the same impurity content.

[1] de Haas, de Boer, and van den Berg, Physica **1**, 1115 (1934).
[2] W. J. de Haas and G. J. van den Berg, Physica **4**, 683 (1937).
[3] de Haas, Casimir, and van den Berg, Physica **5**, 225 (1938).
[4] W. Meissner, Zeits. f. Physik **38**, 647 (1926).

Magnetic Effects of a Rotating Superconductor*

W. F. Love, R. F. Blunt, and P. B. Alers
The Rice Institute, Houston, Texas

June 8, 1949

It was discovered by Meissner[1] that when a substance goes superconducting in a small magnetic field, the magnetic induction vector $B=0$. What is often observed is a Meissner effect varying anywhere from no effect at all to the complete effect, and this seems to depend on the degree of impurity, geometrical shape, and whether or not the specimen is a single crystal.[2] We have studied the frozen-in magnetic flux of superconducting tin whose total impurity is 0.012 percent. The tin was melted in a vacuum furnace and allowed to cool slowly after the manner of forming a single crystal. Ultrasonic pulses at 10 megacycles per second showed no evidence of flaws. The specimen was in the shape of a cylinder with well-rounded edges, approximately an ellipsoid, and mounted in Textolite such that it could be rotated about its long axis. The rotor of tin was enclosed in a lead shield so that with the lead superconducting, the magnetic field around the tin was not changed by external effects. With the lead housing superconducting, the magnetic field between the lead wall and the normal conducting tin rotor was about 0.01 gauss and remained unchanged (± 0.00005 gauss) with variation in the angular position of the tin rotor. Cooling further, the magnetic field detector, which was placed between the tin rotor and the lead housing, showed the Meissner effect as the tin rotor became superconducting and flux was pushed out of it.

The superconducting tin rotor showed a very pronounced frozen-in flux (incomplete Meissner effect) in that the magnetic field at the detector now varied sinusoidally with the angular position of the rotor. The frozen-in flux threaded through the superconducting tin in an orientation determined by the magnetic field within the lead housing. That is to say, the magnetic moment locked into the superconducting tin was independent of the angular orientation of the rotor with respect to the lead housing when the transition temperature was passed. Thus, there was no special path of impurities or structure flaws through the tin rotor for the frozen flux to choose. The frozen magnetic flux showed no observable relaxation effects over a period of five minutes.

A Meissner effect has been observed when the specimen has been cooled while rotating at 5000 revolutions per minute. On the stopping rotation the specimen showed no frozen flux. The magnetic field was observed to penetrate the rotor (reverse Meissner effect) when the temperature was then raised through the transition point. Magnetic fields were detected by the "magnetic airborne detector," AN-ASQ-3, kindly supplied by the Office of Naval Research.

We may conclude that when a solid ellipsoid of pure tin goes superconducting it may do two things with the magnetic flux which existed within its body. It may eject part of the flux, corresponding to the Meissner effect, by setting up macroscopic currents described by the theory of F. and H. London,[3] and this current does not move with the rotor as it is turned but stays fixed with respect to the external field. The remainder exhibits the intermediate state proposed by Gorter and Casimir[4] wherein magnetic flux is crowded into small regions where the critical field is exceeded, and this flux is supported by annular superconducting currents which we have observed to stay fixed with respect to the rotor. The earlier experiments by Onnes and Tuyn[5] support these conclusions. The authors acknowledge with pleasure the directing guidance of Professor C. F. Squire and the many helpful discussions with Professor W. V. Houston.

* Research supported by the ONR, Contract N6onr-224.

[1] W. Meissner and R. Ochsenfeld, Naturwiss. **21**, 787 (1933).
[2] K. Mendelssohn, Proc. Roy. Soc. **A155**, 558 (1936).
[3] F. and H. London, Proc. Roy. Soc. **A149**, 71 (1935).
[4] C. J. Gorter and H. Casimir, Physica **1**, 305 (1934).
[5] H. K. Onnes and W. Tuyn, Leiden Comm. Suppl. No. 50a.

The Viscosity and Thermal Conductivity of Mixtures of He^3 and He^4

K. S. Singwi and L. S. Kothari
Department of Physics, University of Delhi, India

May 31, 1949

Recently Ter Haar and Wergeland,[1] using Tisza's phenomenological picture of the viscosity of He^4, have estimated the influence of an admixture of He^3 to the He^4 liquid. Their expression for the increase in viscosity due to a fraction x of He^3 in He^4 liquid is

$$\Delta\eta = x(\eta_3{}^{\text{kin}} - \eta_4{}^{\text{kin}}) \approx x\eta_3{}^{\text{kin}}. \tag{1}$$

In deducing (1) the kinetic viscosity of He^4 is neglected in comparison to that of He^3, and also the dynamic viscosity of both He^3 and He^4 is assumed to be the same.

In calculating η^{kin} from the well-known expression

$$\eta^{\text{kin}} = \tfrac{1}{3}\rho\bar{c}\Lambda,$$

these authors have assumed that the mean free path Λ is equal to $m/\sqrt{2}\pi d^2$. This, however, is not justified, since in a degenerate Fermi-Dirac gas the mean free path Λ increases with decreasing temperature because the number of possible collisions is greatly reduced because of the exclusion principle. Indeed, at a temperature T, the possible transitions are limited to the states of the "Maxwell tail" beyond the maximum zero point energy $E_m = (h^2/2M)(3\rho/8\pi M)^{\frac{2}{3}}$: In velocity space such cells roughly fill a spherical cell of radius $v_m = (2E_m/M)^{\frac{1}{2}}$ and thickness

$\Delta v = \Delta E/P_m \sim kT/(2ME_m)^{\frac{1}{2}}$. The mean free path Λ is given by

$$\Lambda \approx \frac{M}{\rho S(\Delta v/v_m)^2} \approx \frac{M}{\rho}\frac{1}{S}\left(\frac{E_m}{kT}\right)^2, \tag{2}$$

where S is the collision cross section.

In a degenerate Fermi-Dirac gas, the coefficients of viscosity η and heat conductivity χ may be written in the familiar form

$$\eta = \alpha_\eta \tfrac{1}{3}\rho\bar{v}\Lambda_\eta, \tag{3a}$$

$$\chi = \alpha_\chi \tfrac{1}{3}\rho\bar{v}C_v\Lambda_\chi. \tag{3b}$$

where α's are the numerical factors and $\bar{v}$ is the mean velocity of the particles. The specific heat C_v per unit mass is given by

$$C_v = \pi^2/2(k^2T/ME_m). \tag{4}$$

Using (2) and (4) in (3) we have

$$\eta_3 = \alpha_\eta \frac{1}{3}\frac{h^5}{2^{5/2}M_3^2}\left(\frac{3\rho_4}{8\pi M_4}\right)^{5/3}\frac{1}{S}\frac{1}{(kT)^2}, \tag{5a}$$

$$\chi_3 = \alpha_\chi \frac{\pi^2}{12}\frac{h^3}{M_3^2}\left(\frac{3\rho_4}{8\pi M_4}\right)\frac{1}{ST}, \tag{5b}$$

where we have taken $\rho_3/M_3 = \rho_4/M_4$.[1]

In the following rough calculation we have assumed $S = \pi d^2$, where $d = 2.9\times 10^{-8}$ cm, and have taken α to be equal to unity.* We shall also assume $\rho_4 = 0.145$ g/cc, since the density of He^4 does not change appreciably over the whole range of temperatures for which He^3 constitutes a degenerate gas (the degeneracy parameter $A = 10T^{-\frac{3}{2}}$). In Table I we have given (1) the changes in viscosity for $x = 0.01$ and (2) $x\chi_3$.

TABLE I. Calculated values for the change in viscosity for $x = 0.01$ and for the product $x\chi$

T in °K	1.6	1.8	2.0	2.1	2.2	2.4	3	4
η_4 in μp^2	0.18	0.35	0.80	1.5	15	22	25	28
Ter Haar $\Delta\eta/\eta_4$	0.35	0.18	0.079	0.042	0.0042	0.0029	0.0025	0.0022
Our value $\Delta\eta/\eta_4$	6.4	2.6	0.92	0.44	0.040	0.023	0.013	0.0065
$x\chi_3$ in c.g.s.	58.8	52.3	47.1	44.8	42.8	39.2	31.4	23.5

The values as computed by us are higher than those given by Ter Haar and Wergeland, as is expected. The values are, however, uncertain on account of our lack of exact knowledge of α and S.

It may be noted that the maximum value of heat conductivity of He^4, as determined experimentally, is nearly 300 cal. cm^{-1} deg.$^{-1}$ sec.$^{-1}$ at 2°K; whereas this value for pure He^3, at the same temperature, as computed by us is 4710 c.g.s. units.

Our thanks are due to Professor D. S. Kothari and Professor R. C. Majumdar for their kind interest in this work.

[1] D. Ter Haar and H. Wergeland, Phys. Rev. **75**, 886 (1949).
[2] W. H. Keesom, *Helium*, p. 271.
* In an exact calculation the numerical coefficients α and the collision cross section S will have to be evaluated rigorously. We shall do so in a future paper.

Polarization of Mesons Produced at Threshold in Gamma-Nucleon Collisions

DANIEL B. FEER
The Institute for Advanced Study, Princeton, New Jersey
May 27, 1949

WENTZEL[1] has proposed using the anisotropy in the angular distribution of μ-mesons resulting from the decay of a polarized beam of integral spin mesons to determine the spin of the π-meson. Such a beam can be produced near threshold in nucleon-nucleon collisions; however, as pointed out by Wentzel, precession in strong magnetic fields, which will occur during the π-meson lifetime, which varies by about 10^{-8} sec. will blur the polarization effect, and hence the experiment cannot be performed directly inside a cyclotron tank.

The polarization of mesons produced in gamma-nucleon collisions, as from the gamma-ray beam from a synchrotron, has accordingly been examined. The ratio of the cross sections for production of longitudinal and transverse mesons has been calculated at exact threshold, taken to be mc^2 ($m = \pi$-meson mass) since terms of order m^2/M^2 (M = nucleon mass) are neglected. This quantity has the values shown in Table I. 0 denotes complete transverse polarization, ∞ complete longitudinal polarization. The complete polarization will be reduced by terms of order m^2/M^2, which will be a small effect.

TABLE I.

Field	Coupling	Cross section ratio
Vector	Vector	0
Vector	Tensor	0.4
Pseudovector	Pseudovector	∞
Pseudovector	Dual-tensor	0

These results, and, in particular, the difference between vector and pseudovector fields, can be simply understood as follows. There are four processes which can produce this effect: a direct interaction coupling the four particles involved, and three others involving the creation of virtual mesons or nucleons and the absorption of the photon. For example, for vector-type coupling, the direct interaction term is of the form,

$$u_n^* o u_p \mathbf{A}\cdot\mathbf{V}, \tag{1}$$

the u's being the nucleon wave function, $\mathbf{A}$ the transverse vector potential, and $\mathbf{V}$ the meson wave function. For a vector field o is the unit operator, and for a pseudoscalar field it is γ_5. Since near threshold, $\gamma_5 = v/c = m/M$, the contribution of the term (1) to the cross section is smaller by m^2/M^2 for pseudovector fields than for vector fields. Thus, while this term will produce transversely polarized mesons of both types, it will not be appreciable for the pseudovector field. A similar investigation of other terms shows that they give mainly longitudinal polarization, which dominates for the pseudovector field.

The corresponding analysis for the vector field with tensor coupling, together with the fact that one must average over the unknown polarization of the incident gamma-rays, verifies the result that only this case does not give complete polarization.

The anomalous magnetic moment of the nucleon will enter only in the one process which involves the photon-nucleon interaction. This term is of the form

$$\lambda(m/M)(e\hbar/mc)u_n^*\beta\boldsymbol{\sigma}\cdot\mathbf{H}u_p;$$

since the photon's momentum is mc, the factor m/M means that this contribution will never be a dominant one.

In an actual experimental situation, one must consider both the internal motion of the bombarded nuclei and the fact that a continuous gamma-ray beam producing mesons with a wide range of kinetic energies is actually used. For mesons with a kinetic energy up to about 20 Mev, the values of v/c involved are of the order m/M; new terms introduced into the matrix elements will be of this order and lead to terms in the cross section of order m^2/M^2, which have been consistently neglected.

It is thus possible to produce near threshold a beam of polarized integral-spin mesons by the synchrotron gamma-ray beam. Since there appear to arise no new depolarizing effects other than those discussed by Wentzel, and since the experiment can be performed outside the tank, thereby eliminating the effect of magnetic fields on Wentzel's experiment, it seems that such an experiment might give useful information on the π-meson spin.

I wish to thank Dr. Oppenheimer for suggesting this problem, and the Institute for Advanced Study for a grant-in-aid-of-research from the AEC.

[1] G. Wentzel, Phys. Rev. **75**, 1810 (1949).