The relation between C and α, the coefficient of expansion, follows from the Maxwell equation

$$(\partial S/\partial P)_T = (\partial V/\partial T)_P = -\alpha V. \quad (5)$$

This definition of α is at constant pressure, which at equilibrium is at $P = 0$. The entropy, using Eq. (1), is given by the equation

$$S = \int_0^T \frac{C(T')}{T'} dT' = NM^*\left(\frac{\pi}{3}\right)^{2/3} \frac{k^2}{\hbar^2}\left(\frac{V}{N}\right)^{2/3} T, \quad (6)$$

where we have neglected any possible variation of M^* with temperature, which would give corrections of order T^2 and higher.

At low pressures and low temperature, the pressure can be written

$$P = \beta \frac{V_0 - V}{V_0}. \quad (7)$$

The parameter β as determined in the calculations of Brueckner and Gammel is 18.9 atmospheres; the experimental value obtained from the velocity of sound[3,4] is 27.5 atmospheres which we adopt as more accurate. Using Eqs. (5), (6), and (7), we thus obtain the result at $V = V_0$

$$\alpha = T\left(\frac{\pi}{3}\right)^{2/3} \frac{N^{1/3}}{\beta}\left[\frac{\partial}{\partial V}(M^* V^{2/3})\right]_{V=V_0}. \quad (8)$$

Using Eq. (3), we find

$$\alpha = T\left(\frac{\pi}{3}\right)^{2/3} \frac{k^2 M}{\hbar^2} \frac{2}{3\beta}\left[1.84 - \frac{3}{2}(2.25)\right]. \quad (9)$$

The second term in the square bracket in Eq. (9) arises from the density variation of the effective mass. If it is neglected, then the coefficient of expansion is positive and the liquid would contract when cooled near 0°K. The density variation of the effective mass is sufficiently rapid, however, to change the sign of α. Inserting the numerical values of β and V_0, we find

$$\alpha = -0.076\ T\,(\text{deg K})^{-1}, \quad (10)$$

where T is measured in degrees Kelvin.

The result of Eq. (10) can be expected to hold only very close to 0°K, where the specific heat follows the simple linear law of Eq. (1) and Eq. (2). This probably limits the validity of Eq. (10) to temperatures below 0.2°K. At $T=0.2$°K, we find that α is $-0.0152\,(\text{deg K})^{-1}$ corresponding to a decrease in volume from 0°K of 0.15%, i.e., the liquid contracts as it is heated.

This anomaly in the coefficient of expansion can be attributed to the dominant effects of the Fermi statistics at very low temperatures. When the liquid is cooled, the tendency of the He^3 atoms to form a state of momentum order, the degenerate Fermi gas, is inhibited by the effects of the strong forces. The repulsion is enhanced by the action of the exclusion principle in the degenerate state, while the attraction becomes less effective in the presence of high zero-point energy and short wavelengths. These two effects are less pronounced if the liquid density is decreased; consequently the liquid expands to "make room" for the atoms as they drop down into the state of momentum order.

---

*Supported in part by grants from the National Science Foundation.

[1]K. A. Brueckner and J. L. Gammel, Phys. Rev. 109, 1040 (1958).

[2]Lee, Reppy, and Fairbank, Bull. Am. Phys. Soc. Ser. II, 3, 339 (1958).

[3]H. Flicker and K. R. Atkins, Symposium on Solid and Liquid Helium Three, 1957 (Ohio State University Press, Columbus, 1958), p. 11.

[4]Laquer, Sydoriak, and Roberts, Symposium on Solid and Liquid Helium Three, 1957 (Ohio State University Press, Columbus, 1958), p. 15.

ALIGNMENT OF METASTABLE HELIUM ATOMS BY UNPOLARIZED RESONANCE RADIATION*

P. A. Franken and F. D. Colegrove
Harrison M. Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan
(Received October 8, 1958)

This is a preliminary report of experiments in which helium atoms in the $^3S_1$ metastable state have been aligned by the action of unpolarized optical resonance radiation. The techniques and theory of this effect exhibit many similarities to "optical pumping" experiments,[1] but there are important dissimilarities. The alignment has been detected by resonance methods; the observed line widths are of the order of a milligauss with a raw signal-to-noise ratio of ~100:1. Our simplest experimental arrangement will be described, followed by an outline of the theory.

Pure helium at a pressure of 2 mm Hg is contained in a 12-in. long, $1\frac{1}{2}$-in. diameter, cylindrical, Pyrex tube fitted with an aluminum disk electrode at each end. Within this tube helium atoms are continuously excited to the $^3S_1$ metastable state by a discharge maintained with a few milliamperes of either dc or rf current. Light from a bright helium lamp[2] is passed

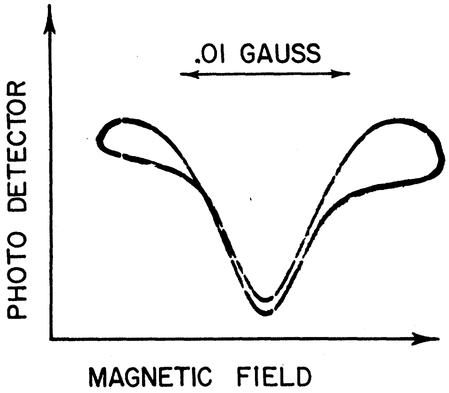

FIG. 1. CRO trace of the metastable helium resonance at 1.3 Mc/sec as seen in the earth's magnetic field. The field was modulated at 60 cycles/sec. The amplifier bandwidth was ~5 kc/sec. The signal-to-noise ratio was ~10^2 in the original photograph. The line width is due almost entirely to the inhomogeneity of the earth's magnetic field in the laboratory.

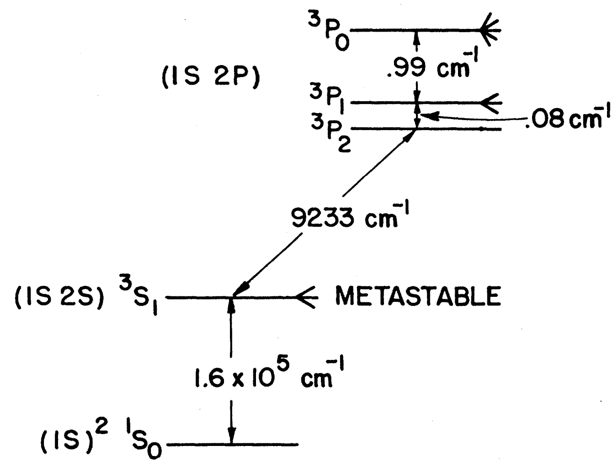

FIG. 2. Relevant features of the helium energy level diagram (not to scale).

through the discharge tube along the direction of the earth's magnetic field. This light is received by a Kodak PbS "Ektron" detector, the output of which is amplified and displayed on a CRO. A radio-frequency magnetic field is produced at right angles to the earth's field by means of several turns of wire wrapped arount the discharge tube and driven by a General Radio Unit Oscillator. Helmholtz coils are used to modulate the earth's field synchronously with the horizontal trace of the CRO.

The resonance shown in Fig. 1 was obtained with this apparatus. The resonance frequency was 1.5 Mc/sec corresponding to a "g-value" of 2.8 Mc/gauss. A signal of the same sense and roughly the same magnitude is observed when the optical resonance radiation is passed through the discharge tube at 90° with respect to the earth's field.

The features of the helium energy level diagram relevant to this experiment are shown in Fig. 2. By "resonance radiation" is meant that light emitted in transitions from the set of closely spaced ($1S2P$) ^3P levels to the $^3S_1$ metastable levels. The light originating from the $^3P_2$, $^3P_1$, and $^3P_0$ states will be denoted as D_2, D_1, and D_0 radiation, respectively. In a typical helium arc the D_2 and D_1 radiation are totally unresolved, but completely separate from the D_0 radiation. Thus the D_2 and D_1 radiations have equal intensity and, from consideration of the statistical weights, should be greater than the D_0 light. Let it then be assumed that the intensities of the D_2, D_1, and D_0 radiations are in the ratio of $1:1:K$.

A beam of this radiation is now projected through the dilute sea of metastable helium atoms which are continuously produced in the discharge tube. Let the rates at which the $m=1$, $m=0$, and $m=-1$ states of $^3S_1$ absorb this resonance radiation be denoted by R_1, R_0, and R_{-1}, respectively. If the light is projected collinearly with the magnetic field, it can be shown[3] that $R_1:R_0:R_{-1}=5+K:6:5+K$. Since the ^3P states are thoroughly mixed by collisions in the discharge tube, they will reradiate back to the $^3S_1$ levels without preference. (In the absence of this mixing, as in a free space experiment, the following conclusions are affected by a few percent.) Let the populations of the $m=1$, $m=0$, $m=-1$ levels of $^3S_1$ be denoted by n_1, n_0, and n_{-1}, respectively. If relaxation effects are neglected, it follows that the steady state populations will be $6:5+K:6$. Thus there is an alignment in the $^3S_1$ states provided K differs from unity.

This alignment can be diminished by an rf magnetic field at the resonance frequency determined by the $^3S_1$ splitting. An inspection of the values of R_1, R_0, and R_{-1} reveals that more resonance radiation would now be absorbed by the metastable atoms, which accounts for the sign of the resonance signal shown in Fig. 1.

If the resonance radiation is projected at right angles to the magnetic field, $R_1:R_0:R_{-1}=(11+K):(10+2K):(11+K)$. This leads, in the absence of relaxation effects, to an alignment specified by $n_1:n_0:n_{-1}=(10+2K):(11+K):(10+2K)$. The resonant rf field will diminish this alignment which again produces an increased absorption of the resonance radiation. Thus the same sense of signal is observed as when the light was collinear with the magnetic field.

It is easily shown that no alignment can be produced when the light beam makes an angle of $\cos^{-1}(\frac{1}{3})^{1/2} \cong 55°$ with the field axis. This follows from a consideration of the sum rules[3] and is independent of the values for the transition matrix elements. This prediction has been verified with the described experimental arrangement.

The effect of relaxation processes is to decrease the alignment and hence the resonance signal. We believe the relaxation time is of the order of one millisecond for our systems and is due to a quenching of the metastable states by impurities, including electrons, that are present in the discharge. Thus the resonance should exhibit a width of $\sim 10^{-4}$ gauss in a perfectly homogeneous magnetic field. We have observed line widths of $\sim 6 \times 10^{-3}$ gauss, which is consistent with the measured inhomogenieties of the earth's magnetic field presented by the Randall Laboratories. We have moved the apparatus into an adjacent parking area and observed line widths of $\sim 10^{-3}$ gauss, which appears consistent with the inhomogenieties of that area.

The helium pressure in the discharge tube may be varied over a range of about 10^2. The design of the discharge tube is not critical to the experiment. We have used dc excitation and rf excitation applied either to the electrodes or externally to the glass envelope.

The analysis outlined above assumed a dilute sea of metastable atoms—specifically, one in which the optical mean free path for the resonance radiation was large compared to the dimensions of the discharge tube. The dense-sea case is very complicated and gives rise to novel experimental effects such as a total inversion of the resonance line. The discussion of these effects is elaborate and will be presented in later papers together with a detailed discussion of the simple effects and their applications.

---

*This work was supported in part by the Faculty Research Fund of the Horace H. Rackham School of Graduate Studies of The University of Michigan, and the U. S. Atomic Energy Commission.

[1] See, for example, A. Kastler, J. Opt. Soc. Am. 47, 460 (1957), and H. G. Dehmelt, Phys. Rev. 105, 1487 (1957).

[2] The Osram Helium Spectroscopic Lamp with rf excitation has been used for much of this work. However, it exhibits the disadvantage of low-frequency noise. We have recently developed helium lamps with superior noise characteristics which will be described in a later paper.

[3] E. U. Condon and G. Shortley, The Theory of Atomic Spectra (Cambridge University Press, Cambridge, 1957), Chap. 3.

FAR INFRARED ENERGY GAP MEASUREMENTS IN BULK SUPERCONDUCTORS*

P. L. Richards† and M. Tinkham
Department of Physics,
University of California,
Berkeley, California
(Received October 13, 1958)

Several measurements[1] of the surface resistance of superconductors have been made at microwave frequencies with photon energies comparable with kT_c. In these experiments the surface resistance has generally approached zero for temperatures much less than T_c, showing that the photons used were not energetic enough to excite electrons across the absolute zero energy gap of $\sim 3.5\ kT_c$.[2,3] Using far infrared techniques, we have measured the onset of absorption in superconducting tin and lead for $T \ll T_c$ over the quantum energy ranges of $(1 \text{ to } 13)kT_c$ for lead and $(2 \text{ to } 18)kT_c$ for tin, corresponding to a wavelength range of ~0.15 to 2 mm. For both lead and tin these energy ranges span the transition from essentially lossless reflection to absorption indistinguishable from that of the metal in the normal state.

The output of a far infrared grating monochromator was conveyed through a brass light pipe to a cast nonresonant superconducting cavity immersed in liquid helium at 1.55°K. After making many reflections to build up the metallic absorption to a measurable amount, the radiation was absorbed in a carbon resistance bolometer mounted on a wall of the cavity. The power (P_S) reaching the bolometer when the cavity was superconducting was compared to that (P_N) when it was held normal by a magnetic field. The percentage change of the bolometer signal $[(P_S - P_N)/P_N]$ for tin and lead is plotted against photon energy in units of kT_c in Fig. 1.

For quantum energies below the energy gap these curves show the difference between the nearly perfect reflection of the superconducting state and the frequency-dependent reflection of the normal state. At quantum energies high enough to excite electrons across the energy