PHYSICAL REVIEW VOLUME 102, NUMBER 3 MAY 1, 1956

New Method for Measuring the Absolute Viscosity of Liquid Helium II†

HENRY H. KOLM* AND MELVIN A. HERLIN*
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received October 10, 1955)

A new type of static viscometer for use in liquid helium II has been developed in which the inner cylinder is suspended within a rigidly fixed, coaxial, outer cylinder by a servomechanically controlled magnetic bearing of the type used by Beams and others in vacuum ultracentrifuges. The inner cylinder is accelerated electromagnetically and the absolute viscosity of the medium is determined from the deceleration observed when it is permitted to coast freely. Bearing friction is negligible, and there is no inherent lower limit to the speed of the rotor. Reproducible viscosity values were obtained in gaseous helium. In liquid helium II damping proportional to $1/TS$ caused by thermomechanical flow, induced by eddy-current heating, was observed. This effect was reduced considerably by elaborate precautions to isolate the apparatus from ground vibrations; further improvement would require more favorable location of the apparatus. At higher speeds, the anomalous behavior reported elsewhere was again observed. The absolute viscosity was found to increase discontinuously to a higher value as the speed was increased. The observation is reproducible qualitatively, but, because of vibrations, not quantitatively. Attention is called to a possible analogy between this phenomenon and the observation of stable vorticity in water.

I. INTRODUCTION

THE temperature dependence of the viscosity of liquid helium II has been measured repeatedly by oscillating-disk techniques, but dynamic measurements of this nature yield only the product of an effective viscosity and an effective density. This density must be determined independently by other experiments; dynamic measurements are inherently incapable of showing whether observed anomalies in the kinematic viscosity reflect anomalies in the effective density of the fluid or in its absolute viscosity. The history of the problem has been reviewed recently by Daunt and Smith.[1]

The two effects could be separated by a capillary-flow measurement, but this technique is not applicable in helium II because of nonclassical, pressure-independent "superflow" which masks any viscous effects. Hollis-Hallet,[2] adapting a conventional constant-rotation viscometer for use in helium II, showed recently that it is extremely difficult to measure the very small torques involved in a static technique with sufficient accuracy to permit operation at the very low speeds at which a constant viscosity is observed. It appears, therefore, of considerable interest to search for a new static method of performing the measurement.

It was shown by Taylor[3] that, contrary to traditional belief,[2,4] stable laminar flow is possible in a viscometer in which the inner, rather than the outer, cylinder rotates. The geometry offers considerable advantages for operation in liquid helium. The torque required to drive a superconducting cylinder surrounded by a stationary, Pyrex outer cylinder by means of a rotating magnetic field can be measured with very great precision by well-known "slip-frequency" methods. Unfortunately, we found it impossible to construct suspension bearings which would support the rotating cylinder with sufficient constancy of (a) position and (b) bearing friction. The best available jewel bearings satisfied only the first requirement, while a magnetic bearing making use of the Meissner effect satisfied only the second. The only bearing known to fulfill both requirements to any degree desired is a servomechanically controlled bearing of the type used in vacuum ultracentrifuges by Beams and others.[5] We decided to attempt the adaptation of such a bearing for use in liquid helium II. The apparatus described represents the culmination of successive modifications and refinements.

The truly negligible "friction" of this magnetic bearing made it possible to perform the measurement by observing the rate of deceleration of a freely coasting rotor. The present experiment, although it resembles the constant-rotation experiment of Hollis-Hallet, in that it is also static, is analogous to the oscillating-disk measurements in one important respect: it measures energy dissipation in the fluid, rather than torque transmitted by it, and is sensitive therefore to thermomechanical flow like the oscillating-disk measurements, but unlike Hollis-Hallet's static experiment.

Sensitivity to thermomechanical flow is a decided disadvantage, particularly at temperatures below 1.5°K, as will be shown.

An advantage arises in this experiment from the fact that there is no inherent lower limit to the rotor speed at which measurements can be made, which was not true in previous experiments.

II. APPARATUS

Magnetic Bearing

The magnetic bearing operates as follows. A cylindrical iron rotor whose upper extremity terminates in a blunt

---

† This work was supported in part by the U. S. Army (Signal Corps), the U. S. Air Force (Office of Scientific Research, Air Research and Development Command), and the U. S. Navy (Office of Naval Research).

* Now at Lincoln Laboratory, Massachusetts Institute of Technology.

[1] J. G. Daunt and R. S. Smith, Revs. Modern Phys. 26, 172 (1954).

[2] A. C. Hollis-Hallet, Proc. Cambridge Phil. Soc. 49, 717 (1953).

[3] G. I. Taylor, Trans. Roy. Soc. (London) A223, 289 (1923).

[4] G. Kellström, Phil. Mag. (7) 23, 313 (1937).

[5] Beams, Ross, and Dillon, Rev. Sci. Instr. 22, 77 (1951).

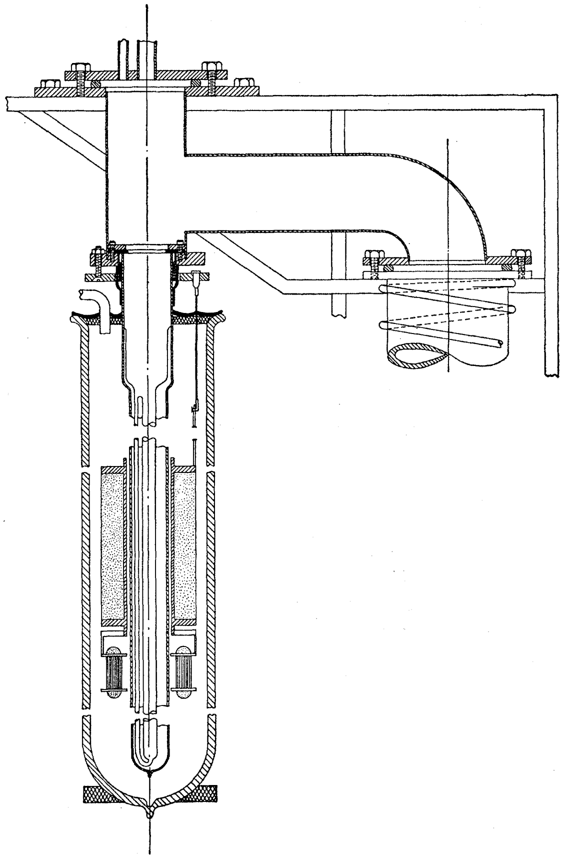

FIG. 1. Section through the Dewar system.

cone is suspended below the blunt conical tip of an iron core by the magnetic field produced by a solenoid surrounding the iron core. The horizontal position of the rotor is fixed by the divergence of the axially symmetric field, and its vertical position is stabilized by a servomechanism which controls the current in the solenoid and derives its input signal from a sensing coil mounted below the rotor. The sensing coil forms part of a tuned-grid, tuned-plate oscillator operating at about 8 Mc/sec and is sensitive to the proximity of iron. An error signal and its derivative signal are obtained from a cathode-follower detector, amplified separately, and then combined to form the grid input for the power triodes which control the solenoid current. Adjustment of the derivative signal is quite critical in view of the necessity for large control forces in the absence of mechanical damping, and in view of the necessity for control response over a very wide range of frequency. In liquid helium the adjustment must be made quickly and reliably with the aid of predetermined settings because the eddy-current heating caused by uncontrolled hunting will evaporate an entire filling of liquid helium in several seconds. All but the last stage of the control circuit is battery-powered and shielded. The solenoid comprises about 30 000 stack-wound turns of No. 26 Formex-insulated copper wire, and it proved expedient to protect it against accidental surges by means of a double spark gap.

Cryostat

Figure 1 represents a section through the Dewar system. The helium Dewar has an inside diameter of 0.75 inch and an enlarged reservoir section at the top. A filling tube passing down between the inner and outer walls makes the entire free cross section of the Dewar available for the viscometer. The solenoid surrounds the helium Dewar and is suspended by three stainless steel bicycle spokes anchored to the rim of the pumping tee; four vertical coils attached to its bottom end serve to produce a rotating magnetic field which drives the rotor. The outer liquid nitrogen Dewar has an inside diameter and a depth of 5 and 48 inches, respectively; its mouth is sealed by means of a Bakelite cap and a rubber mat so that it can be partially evacuated and then vented before taking a measurement in order to suppress ebulition of the nitrogen which would cause intolerable vibrations. In the present experiments, both Dewars were unsilvered.

As a further measure of noise suppression, the steel tripod stand which supports the cryostat is suspended on three laminated neoprene diaphragms covering apertures in a closed-pressure system of large volume. This "pneumatic spring" made it possible to suspend the 1500-pound cryostat with a natural period of 6 seconds and it reduced the amplitude of transmitted ground vibrations by three orders of magnitude. Suitable measures were taken to ensure mechanical decoupling of the 3-inch diameter vacuum pumping line.

The helium Dewar can be removed through the top of the 4-inch pumping tee by removing the seating ring (against which it is forced when evacuated) and the head plate. The head plate is provided with holes for manometer connections and helium transfer tube, as well as a central aperture through which the viscometer proper is inserted into the helium Dewar. The diffusion pump is Distillation Products MB-200.

Viscometer

The viscometer is housed in a Plexiglass tube which serves as the stationary outer cylinder fitting snugly inside the helium Dewar and extending upward through the head plate. A cutaway view of the viscometer is shown in Fig. 2, while Fig. 3 shows a cutaway view of the assembled apparatus. The iron core is supported by means of a pivot needle emerging in a suitably located slot and by a pivot bar passing diametrically through the plexiglass tube. A second needle protruding from the center of the upper face of the core is used to align the Dewar system with respect to the free-hanging core, and also to clamp the core to the Dewar system, which is accomplished by screwing a clamping capillary against the needle with the aid of a long, wire screw driver. In this way the accuracy of vertical adjustment can be checked and corrected even during a helium experiment. The conical tip at the bottom of the core is protected by a polystyrene cap which prevents accidental contact with the rotor.

The soft iron rotor, 0.5 inch in diameter and 3 inches long, is cylindrical to within 0.0001 inch. Twelve roughened lines of progressively decreasing length are spaced uniformly around its circumference at the bottom edge. These lines are barely visible in ordinary lighting but show up clearly in a narrow, collimated beam, appearing white against the black, polished surface; they serve to time the rotation. When at rest, the rotor is supported by a fixed polystyrene pedestal which also serves as the form for the twelve-turn sensing coil; the latter is connected to the control circuit by two leads of No. 32 copper wire which pass upward out of the cryostat through grooves in the wall of the Plexiglas tube. The relative operating position of the various individual parts is shown in Fig. 3.

III. EXPERIMENTAL PROCEDURE

All measurements in liquid helium II were performed during the hours between midnight and 6 A.M. when the level of ground vibrations is minimal. The following procedure was carried out. After precooling the cryostat with liquid nitrogen, liquid helium was transferred into the helium Dewar; vertical alignment was checked, and the pressure above the liquid helium was gradually reduced. Simultaneously, the pressure in the liquid nitrogen Dewar was lowered to about 10 cm Hg. The pneumatic suspension of the cryostat was trimmed to balance the loss of liquid nitrogen, and the outer Dewar was vented to the atmosphere. Ebulition in the nitrogen ceased instantly, and this quiescence could be relied upon to persist for 40 minutes. The helium bath was brought to some suitable pressure below the lambda point, measured by means of a McLeod gauge, and was maintained by manually adjusting the pumping rate with reference to an oil manometer. The rotor was raised to its operating position and a driving field was applied until it had reached a speed of approximately 1–2 rpm. The rotor was then permitted to coast freely, and after a period of several minutes (to ensure equilibrium motion of the fluid) its deceleration rate was timed by observing the reference marks moving through a masked, collimated light beam. At the completion of each revolution a Simplex time recorder was triggered which printed the time to the nearest 0.01 minute. After 30 minutes the peripheral velocity had decayed approximately from 0.1 to 0.05 cm/sec (about 1 to 0.5 rpm). The period of quiescence of the liquid nitrogen thus sufficed for one good measurement. Some measurements were continued until the level of liquid helium had dropped below the rotor. This procedure provided a very convenient means of comparing the relative effects of liquid and gaseous helium and of discerning any possible bearing effect.

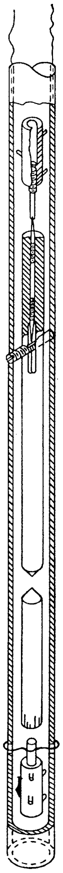

FIG. 2. Cutaway view of the viscometer.

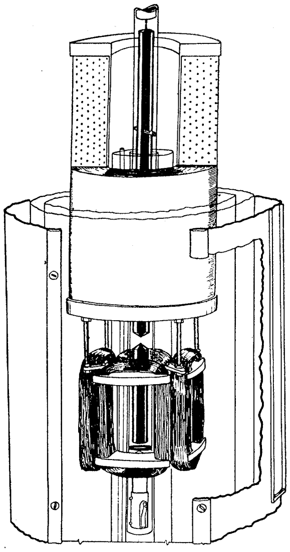

FIG. 3. Cutaway view of the assembled apparatus.

As an additional check, some measurements were made with a smaller rotor sealed into a Pyrex capsule filled with air at 1 mm Hg at room temperature. In the very good vacuum thus achieved at helium temperature, no deceleration whatever could be observed; any possible damping from the bearing was less than 0.1%

of the viscous damping by helium II just below the lambda point.

IV. ANALYSIS OF THE EXPERIMENT

The viscous retarding torque experienced by a cylindrical rotor rotating with angular velocity ω inside a stationary outer cylinder (neglecting end effects) is

$$\tau=\left[\frac{4\pi l r_1^2 r_2^2}{r_2^2-r_1^2}\right]\eta\omega=Q\eta\omega, \tag{1}$$

where r_1 and r_2 are the radii of inner and outer cylinders respectively, l is the length of the rotor, and η is the viscosity of the medium. The factor in brackets, designated by Q, is thus a geometric constant of the instrument.

If no other torque is acting on the "coasting" rotor, its instantaneous velocity is

$$\omega(t)=\omega_0 e^{-Q\eta t/I}=\omega_0 e^{-\beta t}, \tag{2}$$

where ω_0 represents the initial angular velocity at the origin of time, and I is the moment of inertia of the rotor. This exponential decay of velocity is characteristic of all systems involving only masses and viscous forces; the motion is finite in space though infinite in time.

Viscosity is measured by determining experimentally the logarithmic decay constant β. It is most convenient for this purpose to use θ, the angular displacement of the rotor, as the independent variable. By integrating Eq. (2), the motion can be described in linear form:

$$\omega=\omega_0-\beta\theta, \tag{3}$$

the angular displacement θ being measured with respect to the instant at which the initial velocity ω_0 prevailed. The decay constant β was obtained as the negative of the slope of the straight line representing the experimental values of $\omega(\theta)$. It should be noted that, unlike static measurements based on a direct-torque determination, the present experiment involves no lower limit of speed.

The decay constant β is the product of the viscosity η and an instrumental constant Q/I. A calculated value of the latter was in satisfactory agreement with an average value obtained from calibration runs in several gases of well-known viscosity at root temperature. The experimental value, which takes into account end effects, was used for interpretation of the helium II data.

V. DISCUSSION OF RESULTS

In all measurements the apparent viscosity is considerably higher than the results obtained by other authors suggested, and it fails to show any marked decrease with temperature. The viscosity indicated by our earliest measurements exceeded the accepted value by as much as a factor of five. A large part of the excess damping was found to be eddy-current damping caused by insufficient accuracy in alignment; the latter was eliminated entirely by improving the apparatus, as the absence of any measurable damping in vacuum at liquid helium temperatures indicated dramatically. Also, the correct value of viscosity (5 micropoises) was observed in gaseous helium at 2°K, which is even less viscous than liquid helium II at that temperature (20 μp). Nevertheless, even after the elimination of instrumental effects, the observed value of viscosity still exceeds the accepted value by a factor of two or more. The results shown in Fig. 4 are typical. Individual measurements show negligible scattering (0.5%), but variations of as much as 10% from run to run were common. The observed viscosity is 41 μp at 2.17°K (accepted value: 20 μp) and 44.4 μp at 1.97°K (accepted value: 12 μp). The measurement at 2.17°K was continued until the level of liquid helium had dropped below the rotor, and the new slope of the curve indicates the accepted value[6] of 5 μp for the viscosity of the vapor.

A satisfactory explanation for these discrepancies exists, and it suggests why all of the oscillating-disk measurements showed higher viscosity values below 1.5°K than the extrapolated static measurements of Hollis-Hallet indicated.

The presence of heat currents within the liquid helium II bath implies a counterflow of the superfluid and normal components. This thermomechanical flow connects the various heat sources (eddy-current heating in the rotor itself as well as radiation heating in all other parts of the apparatus) with the bath surface and results in the removal of energy (i.e., accelerated fluid) from the annular space between cylinders. This energy must be

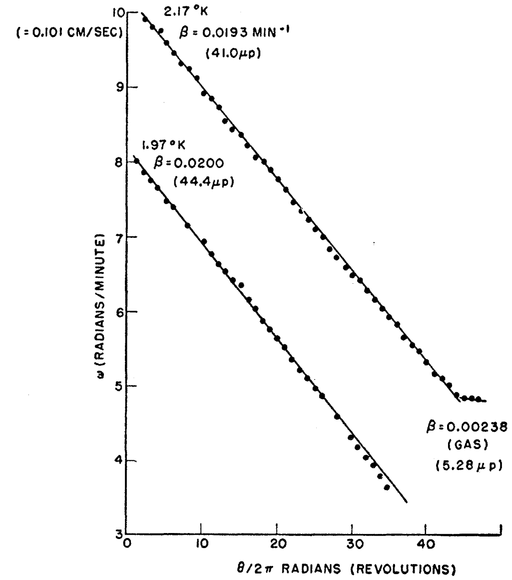

FIG. 4. The angular velocity ω of the rotor as a function of its angular displacement θ when coasting in liquid helium at 2.17°K (upper curve) and 1.97°K (lower curve); the upper curve is continued until the liquid level has dropped below the rotor.

---

[6] Becker, Misenta, and Schmeissner, Phys. Rev. **93**, 244 (1953).

supplied from the rotating cylinder. In Hollis-Hallet's experiment it is supplied by the driving mechanism and is not sensed in the torque measurement. In our experiment, the energy supplied by the coasting cylinder must result in a deceleration, and is measured therefore as a spurious viscosity. Oscillating-disk measurements are also energy-sensitive, rather than torque-sensitive, and a similar error is to be expected.

This effect may be treated quantitatively with the aid of an additional term in Eq. (1) for the retarding torque experienced by the cylindrical rotor:

$$\tau' = Q\eta\omega + \frac{dE/dt}{\omega}. \tag{4}$$

The value of dE/dt depends on an integral over the normal-fluid-flow field, caused by thermomechanical and viscous forces. In any case, it is proportional to ρ_n, the heat power input, and ω^2. The torque term derived from this effect is proportional to ω and is distinguishable from true viscous torque only by varying the heat input or normal fluid density. Expression (4) for the retarding torque may be written thus:

$$\tau' = (Q\eta + k)\omega, \tag{5}$$

from which it follows that the new logarithmic decrement consists of two terms:

$$\beta' = (Q\eta/I) + (k/I), \tag{6}$$

the first of which accounts for viscous damping, while the second represents the damping ascribable to thermomechanical flow of velocity v_n.

We are now in a position to determine the value of v_n which would account for the excess damping observed at 2.17°K (Fig. 4). We recall that the apparent viscosity of 41 μp is approximately twice the accepted value of 20 μp, which implies that the two terms in Eq. (6) are equal. We first calculate k/I, using the accepted value of ρ_n (0.133) at the temperature in question, and obtain: $k/I = 0.00807 v_n$; equating this quantity to $Q\eta/I$ (where η is the correct viscosity of 20 μp), we find that the excess damping is accounted for by flow through the annular space at a velocity of only $v_n = 1.76 \times 10^{-2}$ cm/sec.

If this flow of normal fluid is thermomechanical, we can calculate the corresponding heat-flow density using the well-known expression

$$\dot{Q} = T\rho S v_n = 6.47 \times 10^{-3} \text{ w/cm}^2, \tag{7}$$

where ρ represents the net density of the fluid (0.146) and S the entropy (0.3 cal/g-deg).

Multiplying the heat-flow density by the cross-sectional area of the annular space between cylinders, we obtain the rate of heat input to the rotor and to the surrounding walls which would account for the flow in question and, thus, for the observed excess damping:

Total heat input to rotor $= 4.62 \times 10^{-3}$ w. This value is quite plausible since it corresponds to about one-tenth of the total observed heat input to all parts of the apparatus.

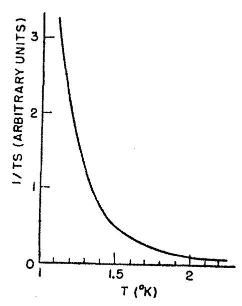

FIG. 5. The quantity $1/TS$ for liquid helium as a function of the absolute temperature T (reference 7).

It is now of interest to determine the effect this same heat input would have at the lower temperature of 1.97°K. Equation (7) indicates that the velocity of thermomechanical flow is proportional to $1/TS$ (at constant heat input), and the plot of this quantity (based on tabulated values of S given by Squire[7]) against temperature shown in Fig. 5 indicates the variation of the extraneous damping term with temperature. The extremely steep rise of this curve below 1.5°K might well account for the fact that oscillating-disk values reported in this temperature range[1] exceed the values obtained by extrapolation of the constant-rotation-viscometer results of Hollis-Hallet.

At the lower temperature of 1.97°K, the extraneous damping term is found to be larger by a factor of 1.69; i.e., $k_{1.97^\circ}/k_{2.17^\circ} = 1.69$; the excess "viscosity" has therefore increased to 20 μp$\times 1.69 = 33.8$ μp; adding to this extraneous damping the true viscosity at the lower temperature, we find that the apparent viscosity indicated by the second curve should be: 33.8 μp$+12$ μp$=45.8$ μp, which is in good agreement with the measured value of 44.4 μp.

It seems justifiable to conclude that the observed excess damping is caused by heat input to the rotor and to the surrounding walls, which in turn causes thermomechanical flow through the annular space surrounding the rotor. This heat input evidently remains quite constant during a run, but varies considerably from run to run. Observations indicate that it is caused predominantly by eddy-current heating in the rotor and core caused by corrections in the magnetic field applied by the servomechanism to counteract mechanical noise. This noise can be observed continuously by an oscilloscope display of the correction signal (in this respect the magnetic bearing serves as an excellent seismograph with flat frequency response); it consists primarily of very energetic ground vibrations of such magnitude that the free surface in a bottle of alcohol placed on the concrete laboratory floor can be seen to tremble continuously; vibrations produced by the vacuum pumps are quite negligible in comparison. Noise isolation is inherently difficult in liquid-helium experiments since

---

[7] C. F. Squire, *Low Temperature Physics* (McGraw-Hill Book Company, Inc., New York, 1953).

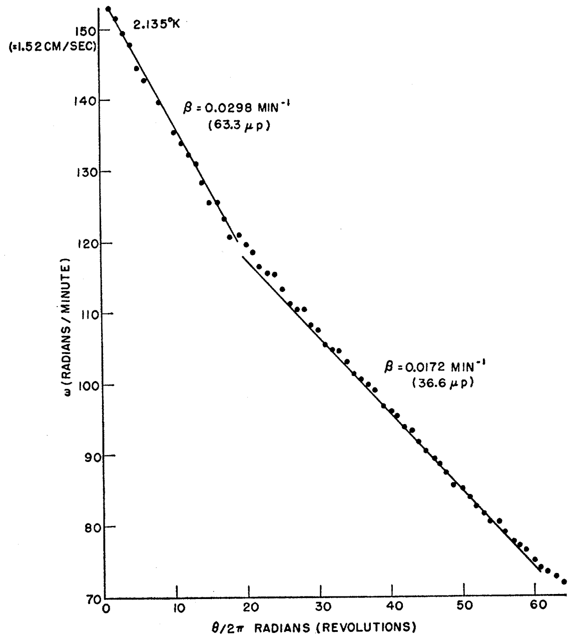

FIG. 6. The angular velocity ω of the rotor as a function of its angular displacement θ when coasting in liquid helium at 2.135°K, showing the discontinuous change in damping at about 120 radians/minute.

the apparatus is mounted of necessity on the end of a very effective "tuning fork," the inner envelope of the helium Dewar. For reasons of thermal isolation this envelope can only be supported by the ring seal at its upper extremity. The elaborate pneumatic suspension described above reduces the vibration level at the cryostat by three orders of magnitude, but this level is evidently still excessive.

Since the object of the present investigation was not only to measure the absolute viscosity but also to observe the nature of nonlinear effects, a number of measurements were made at speeds considerably higher than 0.1 cm/sec, the speed above which Hollis-Hallet[2] observed departures from linear behavior. The measurement represented by the curve in Fig. 6 is typical of the behavior observed. Although excessive scattering precludes a quantitative analysis, it was generally found that departures from the straight line representing the motion at low speeds do not occur below about 1 cm/sec. When departures do occur, they take the form of a discontinuous increase in slope rather than a gradual curvature of the line. It appears as though liquid helium II were capable of exhibiting at least two distinct values of classical viscosity. This is in agreement with the observation reported by Hollis-Hallet[8] that the logarithmic damping of an oscillating disk (proportional to the product of viscosity and density) increases as the speed of the motion (amplitude or frequency) is increased beyond a certain point, and then saturates at some new value as the speed is further increased. The fact that this anomaly has now been observed in two independent static measurements which are insensitive to variations in effective density, the static measurements of Hollis-Hallet[2] and the present investigation, proves, as suggested by Hollis-Hallet, that it cannot be explained exclusively in terms of "mutual-friction" forces of any form, but must be caused at least in part by momentum transfer effects.

Before any undetermined, nonclassical property of helium II is invoked, the problem of flow between two rotating cylinders should first be investigated within the framework of classical hydrodynamics. The problem was examined theoretically and experimentally by Taylor[3] in 1923 who showed that stable and reproducible vortex patterns can be observed in water between two rotating cylinders. It is conceivable that an analogous, but microscopic, form of stable vorticity becomes significant in the case of helium II and accounts for some of the observed anomalies.

VI. SUGGESTED MODIFICATIONS OF THE EXPERIMENT

The apparatus has been perfected to the extent that all damping caused by the magnetic bearing has been eliminated. The excess damping which is still observed results from heat input to the rotor and to its surroundings, attributable mostly to eddy-current heating induced by mechanical vibrations. The next logical step toward improvement of the method is a systematic investigation of the feasibility of reducing this major source of heat input by two methods: (1) further reduction of the vibration level by moving the apparatus to a more suitable location, and (2) substitution of a ferrite rotor. It was found that commercially available ferrite materials are not nearly homogeneous enough to permit adequate dynamic balance; the development of suitable ferrites must await a more widespread need for such material.

Various other sources of heat input should also be investigated. The most important among these is radiation from the surroundings (the Dewars could be partially silvered) and from the light source used for the observation. The intensity of the light source could probably be reduced considerably if special optical provisions were made to refine the method of viewing. It should be emphasized, however, that radiation heating is still negligible compared to the effect of eddy currents.

Should it prove impossible to reduce the heat input to the rotor sufficiently, our technique could still be used by installing the magnetic bearing in a suitable chamber at the top of the cryostat (above the head plate) and suspending the viscometer rotor from a suitable glass rod attached to a "dummy" iron rotor operating in this chamber. Clearances around this dummy rotor could be made sufficiently large to reduce the added viscous

---

[8] A. C. Hollis-Hallet, Proc. Roy. Soc. (London) **A210**, 404 (1952).

damping to a small value, one which can be allowed for in interpreting the results.

It would be considerably more profitable, however, to retain the present form of the apparatus. The fact that no mechanical connection to the rotor is required provides certain advantages. It would be possible, for instance, to seal the rotor into a pressure chamber so as to make measurements at pressures above the vapor-pressure line; measurements could also be made in He^3, for example, by filling the chamber and sealing it at room temperature.

Note added in proof.—The question has arisen as to why we made no attempt to circumvent the difficulty of thermomechanical flow by making measurements above the λ point. This would have required the use of a double helium bath and radiation shielding to reduce convection flow to a tolerable level. Such extensive modifications of the apparatus seemed beyond the scope of the present work, which was intended to resolve some difficulties concerning the anomalous behavior of helium II. The viscosity of helium I has been measured satisfactorily by various other methods.

PHYSICAL REVIEW VOLUME 102, NUMBER 3 MAY 1, 1956

Photoconductivity in Manganese-Doped Germanium

R. NEWMAN, H. H. WOODBURY, AND W. W. TYLER
General Electric Research Laboratory, Schenectady, New York

(Received December 12, 1955)

Impurity photoconduction has been observed in *n*- and *p*-type Mn-doped germanium at low temperatures. The spectra are consistent with the published ionization energy values determined from conductivity data High-resistivity *n*-type samples show high intrinsic photosensitivity and long response times at low temperatures. In such samples the intrinsic photocurrent could be quenched by a factor of $\sim 10^4$ with light in the 0.3 to 0.7 ev range. Intrinsic photoconductivity was found to vary more rapidly than linearly with light intensity over a limited range.

INTRODUCTION

A PREVIOUS publication has described some of the electrical properties of Mn-doped germanium.[1] In this paper we shall describe some of the electro-optical properties with particular reference to photoconductivity. In earlier papers[2–7] measurements of the photoconductivity spectra, photoconductive yield, quenching of photoconductivity, and optical absorption of injected carriers for germanium doped with the elements Au, Fe, Ni, and Co have been reported. The behavior of Mn-doped germanium is qualitatively similar to these other cases. However, a number of the effects which were just barely measurable for the other materials are quite pronounced and readily measurable for Mn-doped germanium. For this reason a somewhat extended report of this work is presented.

EXPERIMENTAL

The method of crystal preparation has been described in earlier publications as have the details of the optical measurements.[1–7]

RESULTS AND DISCUSSION

A. Photoconductive Spectra

It has been found that Mn introduces two acceptor centers in germanium, one located 0.37 ev below the conduction band (upper level) and one located 0.16 ev above the valence band (lower level).[1] By suitable control of the ratio of ordinary donors and Mn acceptors, samples can be prepared for which the Fermi level is "locked-in" at either one level or the other at low temperatures.[1] In Fig. 1 are shown typical photoconductive spectra for *n*- and *p*-type samples of Mn-doped germanium for which the Fermi level is "locked-in" at the upper and lower Mn levels, respectively. These spectra can be divided into two regions in the usual way. At photon energies in excess of about 0.7 ev the response is due to intrinsic photoconductivity. Below about 0.7 ev the response is impurity photoconductivity which presumably results from the photoexcitation of carriers from the Mn centers.[6] The shapes of the two curves of impurity response in Fig. 1 are similar to those found for other double acceptor impurities. The impurity response for *p*-type samples shows a more or less flat plateau terminated at the low-energy side by a sharp drop in response at an energy approximately that found by electrical-conductivity methods. The *n*-type samples show no well-defined low-energy threshold but rather a monotonic decrease

---

[1] H. H. Woodbury and W. W. Tyler, Phys. Rev. **100**, 659 (1955).
[2] R. Newman, Phys. Rev. **94**, 278 (1954).
[3] R. Newman and W. W. Tyler, Phys. Rev. **96**, 882 (1954); W. W. Tyler and H. H. Woodbury, Phys. Rev. **96**, 874 (1954).
[4] Tyler, Newman, and Woodbury, Phys. Rev. **97**, 669 (1955).
[5] Tyler, Newman, and Woodbury, Phys. Rev. **98**, 461 (1955).
[6] W. W. Tyler and R. Newman, Phys. Rev. **98**, 961 (1955).
[7] R. Newman, Phys. Rev. **96**, 1188 (1954).