[8]E. Varoquaux, J. Phys. (Paris) Colloq. 39, C6-1605 (1978).
[9]T. A. Alvesalo, T. Haavasoja, M. T. Manninen, and A. T. Soinne, Phys. Rev. Lett. 44, 1076 (1980).
[10]D. Bloyet, E. Varoquaux, C. Vibet, O. Avenel, P. Berglund, and R. Combescot, Phys. Rev. Lett. 42, 1158 (1979).
[11]K. Maki and Y. R. Lin-Liu, private communication. A similar approach has also been taken by J. A. Sauls and J. W. Serene, with similar conclusions.
[12]H. Ebisawa and R. Combescot, to be published.
[13]V. E. Koch and P. Wölfle, private communication.

Measurement of Anisotropy in the Dielectric Constant of ^{3}He-A

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The first observation of anisotropy in the dielectric constant of superfluid ^{3}He-A is reported. The measurement is made using parallel-plate capacitors immersed in ^{3}He. A magnetic field is used to orient the anisotropy axis $\hat{l}$. At T_{AB} and 29 bars, the anisotropy is only $\epsilon_{\hat{l}\perp\vec{E}} - \epsilon_{\hat{l}\parallel\vec{E}} = 5\times 10^{-11}$.

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The magnetic dipolar interaction between ^{3}He nuclei is responsible for much of the complex behavior[1] of superfluid ^{3}He-A. Delrieu[2] first suggested that a similar interaction should exist between electric dipole moments induced by an applied electric field in the superfluid, and predicted that the magnitude of the electric dipole interaction energy F_E could be simply calculated from the known magnetic dipolar interaction energy by multiplying by $(\alpha E/\mu)^2$, where αE is the induced electric moment and μ is the nuclear magnetic moment. Thus it was expected that an electric field should tend to orient the ^{3}He-A orbital anisotropy axis $\hat{l}$ with an energy given by $F_E \simeq (2\times 10^{-12}\ \text{erg/cm V}^2)(1 - T/T_c)(\vec{E}\cdot\hat{l})^2$. This is equivalent to an anisotropy in the dielectric-constant tensor given by $\Delta\epsilon_{ij} = -4\pi\, \partial^2 F_E/\partial E_i \partial E_j$, so that $\epsilon_{\hat{l}\perp\vec{E}} - \epsilon_{\hat{l}\parallel\vec{E}} \simeq 10^{-6}(1 - T/T_c)$.

The simple theory outlined above treats the ^{3}He atoms as point dipoles. Although this is an excellent approximation for the magnetic dipoles (of nuclear size), Maki[3] pointed out that the nonzero atomic size reduces the electric dipole interactions by a factor of about 3. A much larger reduction in the dielectric anisotropy results from Fermi-liquid effects. Crudely speaking, one expects that the magnetic dipole interaction should be screened by a factor $(1+F_0^a)^2$ (two factors because two quasiparticles are involved in the interaction), and the electric dipole interaction should be screened by $(1+F_0^s)^2$, where F_0^s and F_0^a are the $l=0$ symmetric and antisymmetric Landau Fermi-liquid parameters. Thus the original estimate of the anisotropy should be reduced by $(1+F_0^a)^2/(1+F_0^s)^2$, which is about 10^{-5} at high pressures. Fomin, Pethick, and Serene[4] consider these Fermi-liquid corrections more thoroughly, by using wave-vector–dependent Landau parameters to properly include screening effects for the very short interquasiparticle spacings which are most important in the r^{-3} dipole interactions. Including Maki's correction, they conclude that the simple estimate should be reduced by a factor $\langle R^2\rangle \simeq 10^{-4}$ in the A phase so that $\epsilon_{\hat{l}\perp\vec{E}} - \epsilon_{\hat{l}\parallel\vec{E}} \simeq 10^{-10}(1 - T/T_c)$.

Several experimental groups have looked for this effect without success. The first attempt[5] made use of NMR measurements in an applied electric field. Zero-sound propagation has also been used as a probe of $\hat{l}$ in an applied electric field,[6] establishing an upper bound of $\langle R^2\rangle < 10^{-3}$ at 30 bars. NMR has been used as a probe of the B-phase texture in an applied electric field,[7] showing $\langle R^2\rangle < 10^{-3}$ at 10 bars and $< 4\times 10^{-4}$ at 32 bars. These limits are consistent with the theory of Fomin, Pethick, and Serene and with the value we have measured.

The present experimental method observes the superfluid electric-dipole orienting energy by detecting the A-phase dielectric constant with parallel-plate capacitors in an ac bridge circuit, and varying the direction of $\hat{l}$ in the capacitor gaps by means of a magnetic field. The technique is illustrated schematically in Fig. 1. The two capacitors C_1 and C_2 are both immersed in the superfluid, but are oriented at right angles to each other in a magnetic field $\vec{B}$ which can be rotated. The $\hat{l}$ textures produced by the magnetic

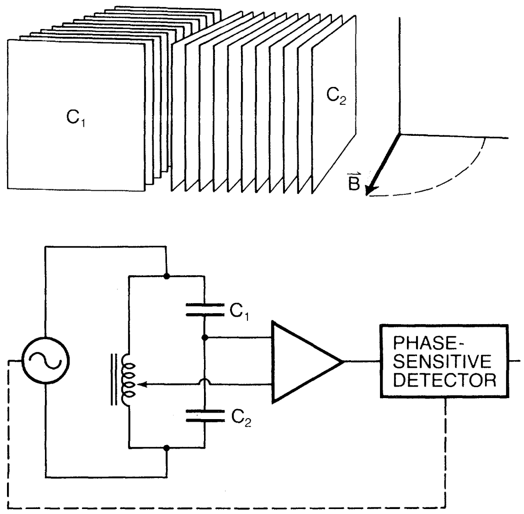

FIG. 1. Schematic of the apparatus. See text for discussion.

field in parallel-plate geometry have been studied by Fetter.[8] When $\vec{B}$ lies in the plane of the capacitor, as for C_2 in Fig. 1(a), a uniform texture with $\hat{l}$ perpendicular to the walls satisfies the boundary condition at the walls and minimizes the magnetic dipole, susceptibility anisotropy, and gradient energies, so that $\hat{l}\parallel\vec{E}$. When $\vec{B}$ is perpendicular to the plane of the capacitors, as for C_1 in Fig. 1(a), the magnetic dipole interaction orients $\hat{l}\perp\vec{B}$ in the central region, so that $\hat{l}\perp\vec{E}$ except very near the walls. Thus in the configuration of Fig. 1(a), C_1 is proportional to $\epsilon_\perp$ while C_2 is proportional to $\epsilon_\parallel$. Changing the direction of $\vec{B}$ by 90° reverses the situation, causing a change in the balance point of the bridge proportional to $\epsilon_\perp - \epsilon_\parallel$.

The capacitors, each ~150 pF, are stacks of brass plates with 130-μm gaps and will be discussed in more detail later. The balance element of the bridge is an eight-decade ratio transformer.[9] The bridge is driven at frequencies of the order of 600 Hz and amplitudes of the order of 20 V (rms), dissipating typically 10^{-9} W in the experimental cell. Both a numerical estimate and the evidence presented in the next paragraph indicate that this heat does not significantly orient $\hat{l}$. The bridge output is detected by a low-noise preamplifier[10] ($v_n \simeq 10^{-9}$ V/Hz$^{1/2}$, $i_n \simeq 2\times10^{-15}$ A/Hz$^{1/2}$) and a commercial phase-sensitive detector. A microcomputer monitors the phase-sensitive detector and the ^{3}He temperature (measured by ^{195}Pt pulsed NMR), and controls the texture-orienting magnetic field and the field on the copper nuclear demagnetization refrigerator.

We have taken data with two different sets of capacitors. In our first measurements, each capacitor consisted of a stack of 31 plates, each 130 μm thick and 1 cm square, with each plate supported at four points near its four corners. A typical temperature sweep warming across T_{AB} is shown in Fig. 2(a). Each point is obtained by fixing the texture-control field, averaging the bridge balance point for 60 sec, rotating the field 90°, averaging for another 60 sec, and subtracting the two averages. Since this difference, which we shall call the anisotropy signal X, seems to depend not only on the temperature of the ^{3}He but also on the current in the refrigeration magnet, and is not exactly reproducible from day to day, we use only the abrupt step in X ob-

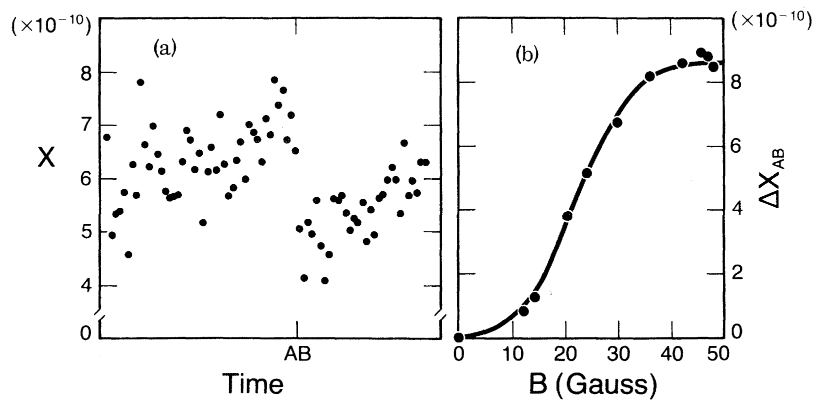

FIG. 2. (a) The anisotropy signal X, which is the change in bridge balance $2\Delta(C_1 - C_2)/(C_1 + C_2)$ when the texture-control field is rotated 90°, vs time in a typical warmup across T_{AB}. (b) Observed dependence of the step ΔX_{AB} in (a) on the magnitude of the texture-control field. The solid curve is intended as a guide to the eye.

served at T_{AB}, ΔX_{AB}, as indicative of an anisotropic property of the ^{3}He-A. The dependence of the size of ΔX_{AB} on the magnitude of the texture-control field is shown in Fig. 2(b), at 29 bars and with a bridge excitation of 1126 Hz and 41 V. The saturation observed at $B \simeq 30$ G is in agreement with Fetter's prediction of the magnetic field required to orient $\hat{l}$ in this geometry. As will be discussed below, at such a high bridge drive voltage ΔX_{AB} is not due to dielectric-constant anisotropy; nevertheless the measurement shown in Fig. 2(b) is evidence for textural control in the 130-μm experimental geometry.

Before presenting more results we must discuss an effect which complicates the experiment. The bridge drive voltage $V_d \sin(\omega t)$ produces an electrostatic force between adjacent capacitor plates proportional to $V_d^2 \sin^2(\omega t)$. If the plates are flexible, they can vibrate in the superfluid in response to this force. Analysis of the capacitance-bridge equations shows that such motion produces a signal at ω and also at 3ω, both proportional to V_d^2. Anisotropic flow properties of the A phase[11] may couple to the moving capacitor plates and manifest themselves as spurious signals at ω and 3ω, proportional to V_d^2. In contrast, the dielectric constant anisotropy should not depend on V_d and should generate no signal at 3ω.

In Fig. 3(a) we display the size of steps in the anisotropy signal at T_{AB} vs V_d^2 for three different bridge drive frequencies. Each point in Fig. 3 is derived from a sweep across T_{AB} as was shown in Fig. 2(a). The straight lines are least-squares fits to the data. The linear dependence on V_d^2 is evident, as is the nonzero intercept in the limit $V_d \to 0$. Although the slope is strongly frequency dependent, the intercept is not. We interpret this intercept as being the dielectric-constant anisotropy. Data taken with the phase-sensitive detector tuned to 3ω show the same linear dependence on V_d^2 but with zero intercept, as expected from the plate vibration model. A room-temperature test with a single plate identical to those comprising the capacitors showed an extremely complicated mechanical resonance spectrum, with the resonant frequencies depending very strongly on how tightly the plate was held at its four support points.

In order to confirm the interpretation of the voltage-dependent part of the anisotropic signal as being due to capacitor-plate motion, a second pair of capacitors, much more rigid than the first pair, was constructed. The plates in the new

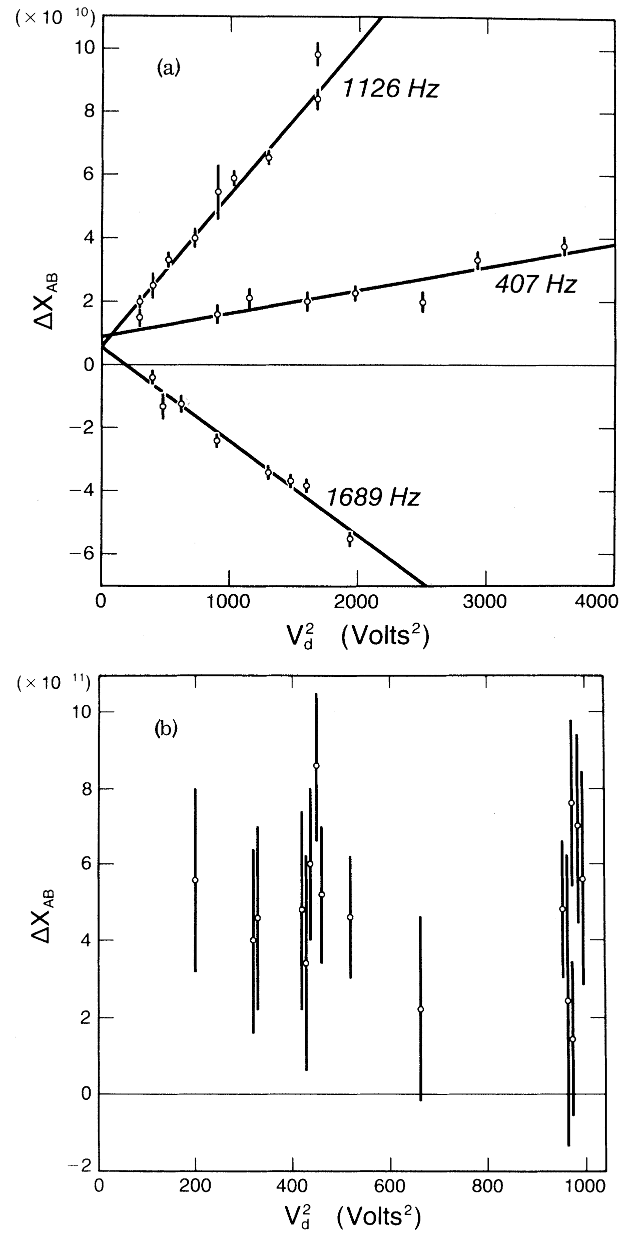

FIG. 3. The anisotropy step at T_{AB} vs bridge drive voltage squared at 29 bars for $B \simeq 40$ G for (a) the more flexible capacitors and (b) the more rigid capacitors.

capacitors are 3 times thicker than in the earlier version, and are more rigidly supported along their edges. Each capacitor was tested at 77°K in vacuum by monitoring its capacitance while simultaneously applying a large static potential; the results showed that the new capacitors are at least 25 times more rigid than the earlier ones. Data taken in the superfluid with these new capacitors, some of which are displayed in Fig. 3(b),

TABLE I. Estimates of $\epsilon_{\hat{l}\perp\vec{E}} - \epsilon_{\hat{l}\parallel\vec{E}}$ and $\langle R^2\rangle$. The stated uncertainties in our results are standard deviations derived from the scatter in the measurements of ΔX_{AB}, and hence represent 67% confidence intervals.

	$(\epsilon_{\hat{l}\perp\vec{E}} - \epsilon_{\hat{l}\parallel\vec{E}})/(1-T/T_c)$	$\langle R^2\rangle$
Theory:		
Delrieu (Ref. 2)	$\sim 1\times 10^{-6}$	1
Maki (Ref. 3)	$\sim 3\times 10^{-7}$	0.3
Fomin *et al.* (Ref. 4)	$\sim 1\times 10^{-10}$	$\sim 10^{-4}$ (30 bars)
Experiment:		
Paulson and Wheatley (Ref. 6)	$< 1\times 10^{-9}$	$< 10^{-3}$ (30 bars)
Paalanen *et al.* (Ref. 7)		$< 4\times 10^{-4}$ (32 bars)
This work	$(3.6\pm 0.8)\times 10^{-10}$	$(2.9\pm 0.7)\times 10^{-4}$ (29 bars)
	$(3.0\pm 1.1)\times 10^{-10}$	$(2.1\pm 0.8)\times 10^{-4}$ (32 bars)

show an anisotropy step at T_{AB} consistent with the $V_d \to 0$ limit of the original data, and without observable drive voltage dependence.

The results of this experiment and of previous work are summarized in Table I. Our 32-bar value $\langle R^2\rangle = (2.1\pm 0.8)\times 10^{-4}$ was obtained with the flexible capacitors; the 29-bar value $\langle R^2\rangle = (2.9\pm 0.7)\times 10^{-4}$ is a weighted average of values obtained with the flexible capacitors $[\langle R^2\rangle = (2.7\pm 1.1)\times 10^{-4}]$ and the more rigid capacitors $[\langle R^2\rangle = (3.0\pm 0.7)\times 10^{-4}]$. The observed effect is of the same sign as predicted by theory, and its magnitude is consistent with the estimates of Fomin, Pethick, and Serene, whose theory is admittedly uncertain to at least a factor of 3.

In conclusion, we have for the first time demonstrated the existence of a coupling between the ^{3}He-A $\hat{l}$ field and an applied electric field. The magnitude of the observed effect is consistent with existing theory, but the resolution of the present measurement calls for improved theoretical estimates.

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[1]For a review of superfluid ^{3}He see, for example, D. M. Lee and R. C. Richardson, in *The Physics of Liquid and Solid Helium, Part II,* edited by K. H. Bennemann and J. B. Ketterson (Wiley, New York, 1978).

[2]J. M. Delrieu, J. Phys. (Paris), Lett. 35, L-189 (1974), and 36, L-22(E) (1975).

[3]K. Maki, Phys. Lett. 56A, 101 (1976).

[4]I. A. Fomin, C. J. Pethick, and J. W. Serene, Phys. Rev. Lett. 40, 1144 (1978).

[5]W. J. Gully, C. M. Gould, R. C. Richardson, and D. M. Lee, Phys. Lett. 55A, 27 (1975).

[6]D. N. Paulson and J. C. Wheatley, J. Low Temp. Phys. 33, 277 (1978).

[7]M. A. Paalanen, M. C. Cross, W. O. Sprenger, W. van Roosbroeck, and D. D. Osheroff, J. Low Temp. Phys. 34, 607 (1979).

[8]A. L. Fetter, Phys. Rev. B 14, 2801 (1976).

[9]Made from parts of two seven-decade transformers, DT72A, Electro Scientific Industries Inc., Portland, Ore.

[10]A cascade circuit with two 2N5434 field-effect transistors, Siliconix, Inc., Santa Clara, Cal.

[11]For example, see J. E. Berthold, R. W. Gianetta, E. N. Smith, and J. D. Reppy, Phys. Rev. Lett. 37, 1138 (1976); C. J. Pethick and H. Smith, Physica (Utrecht) 90B, 107 (1977).