butions from higher levels, are very important in the explanation of the population of laser states. These results also strongly suggest that a two-step process can occur in a cw laser system.

[1]W. R. Bennett, Jr., *et al.*, Appl. Phys. Lett. 4, 180 (1964).

[2]W. R. Bennett, Jr., *et al.*, Phys. Rev. Lett. 17, 987 (1966).

[3]P. N. Clout and D. W. O. Heddle, in *Sixth International Conference on the Physics of Electronic and Atomic Collisions. Abstracts of Papers, Boston, 1969* (Massachusetts Institute of Technology Press, Cambridge, Mass., 1969), p. 290.

[4]I. D. Latimer and R. M. St. John, in *Sixth International Conference on the Physics of Electronic and Atomic Collisions. Abstracts of Papers, Boston, 1969* (Massachusetts Institute of Technology Press, Cambridge, Mass., 1969), p. 287.

[5]W. B. Bridges and A. N. Chester, Appl. Opt. 4, 573 (1965).

[6]S. H. Koozekanani, IEEE J. Quant. Electron. 2, 770 (1966).

[7]R. I. Rudko and C. L. Tang, J. Appl. Phys. 38, 4731 (1967).

[8]H. S. Brandi, Ph. D. thesis, Massachusetts Institute of Technology, 1971 (to be published).

[9]F. Herman and S. Skillman, *Atomic Structure Calculations* (Prentice-Hall, Englewood Cliffs, N. J., 1963).

[10]H. Statz *et al.*, J. Appl. Phys. 36, 2278 (1965).

[11]V. F. Kitaeva, Yu. I. Osipov, and N. N. Sobolev, Zh. Eksp. Teor. Phys., Pis'ma Red. 4, 213 (1966) [JETP Lett. 4, 146 (1966)], and IEEE J. Quant. Electron. 2, 635 (1966).

Search for the ac Josephson Effect in Liquid Helium

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In the presence of an ac sound field, we have found stable states of zero flow between two baths of liquid helium connected by a small orifice which we believe are the same as those which had been previously identified as the ac Josephson effect. We show that these states are not Josephson states.

We report an attempt to observe the ac Josephson effect in liquid helium. Previous investigators[1-5] have reported positive observation of the effect by monitoring the level difference between two baths separated by a small orifice. Our experiment was designed so that a temperature difference and the frequency of the sound field could be controlled as independent parameters.

For two superfluid helium baths that are weakly coupled by a small orifice, the chemical potential difference, as shown by the fountain-effect experiment, is given by the expression

$$\Delta\mu = mg\,\Delta Z - S\,\Delta T, \qquad (1)$$

where ΔZ is the level difference, ΔT is the temperature difference, and the other terms have their usual meaning. In the theory of the ac Josephson effect,[6] the phase slippage produced by the chemical potential difference is synchronized to an impressed ac chemical potential of frequency ν, and anomalies in the flow through the orifice should occur whenever

$$l\,\Delta\mu = nh\nu, \qquad (2)$$

where l and n are integers.

The experimental apparatus, Fig. 1, is constructed to allow for the independent variation of several of the parameters that apply to the Josephson effect. A coaxial capacitor is used to monitor the bath level confined within its annular region and a plunger is situated in the outside bath to change the liquid level by a known amount. Two resistance thermometers, $R_{\rm in}$ and $R_{\rm out}$, allow both the temperature T and temperature difference ΔT of the two baths to be measured; a heater inside the capacitor is used to supply a dc temperature bias to the inside bath. By convention, ΔZ is defined to be positive when the inside bath is higher than the outside and ΔT is defined to be positive when the inside bath is hotter than the outside. A nonresonant piezoelectric transducer of PZT was used in some of these experiments, so that the frequency of the ac sound field could be varied as an independent parameter.

Experimentally, ΔZ is the parameter that is generally monitored in time[1-5] and according to Eqs. (1) and (2) anomalies should occur when

$$\Delta Z = nh\nu/mg + S\,\Delta T/mg, \qquad (3)$$

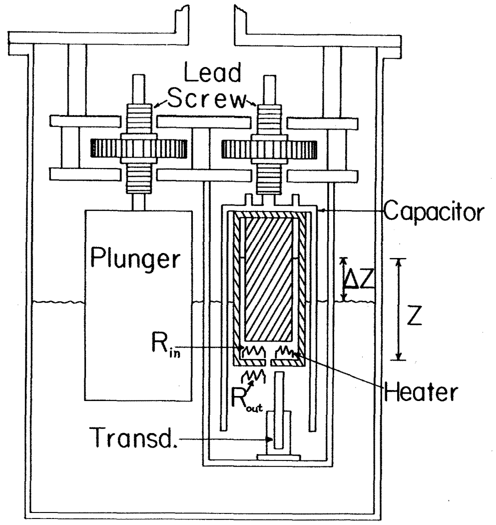

FIG. 1. Experimental apparatus. The level of the helium within the capacitor is indicated by Z and is measured from the bottom of the capacitor. The level difference ΔZ is positive if the inner level is higher than the outer level. The transducer is either a quartz crystal or a PZT ceramic transducer.

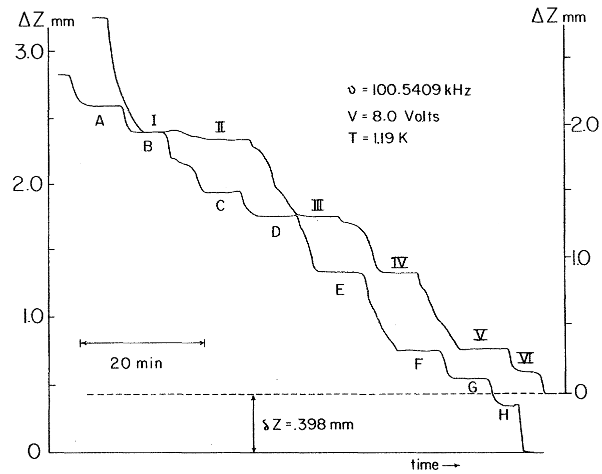

FIG. 2. Two emptying curves taken under the same experimental conditions except that the $\Delta Z = 0$ point has been adjusted slightly to a higher value of Z by means of the plunger for the second curve. Several stable "steps" are seen and labeled for each curve. Notice that when the variation δZ in Z is taken into account, there appears to be a correspondence between "steps" I and B, III and D, IV and E, V and F, and VI and G.

where n is an integer or ratio of small integers. This expression gives three separate criteria that any anomaly must satisfy in order to be considered a Josephson state of the system. (A) Any anomaly occurring when $\Delta Z = nh\nu/mg$ should respond with the linearity of the fountain effect, $S\,\Delta T/mg$, when a dc temperature bias ΔT is applied to the system. (B) The anomaly must depend on ΔZ, the level difference, independent of Z, the liquid level within the capacitor. (C) The anomaly must respond to the frequency of the ac sound field according to $d(\Delta Z)/d\nu = nh/mg$.

By monitoring ΔZ versus time we have observed many instances of "stable steps," values of ΔZ which are stable in time and experimentally indistinguishable from the steps reported by previous authors.[1-5] Of those steps seen, only a few could be interpreted as Josephson "steps" based on the values of ΔZ at which they occur. However, by simultaneously monitoring the ΔZ-ΔT plane, criterion (A) may be applied to those "steps" seen.[7] Once a "step" has occurred and stabilized, a dc temperature bias may be applied to the inner bath, and the resultant response of the system monitored. Experimentally, it is observed that ΔZ changes very little with ΔT for small values of ΔT.[8] This agrees with previous observations.[7,9] However, to satisfy criterion (A) the path in the ΔZ-ΔT plane should be a straight line parallel to the fountain-effect curve, which is observed and measured when the transducer is off. Thus, the "steps" fail criterion (A).

Next, consider Fig. 2 which shows two emptying curves containing many "steps" that are taken under the same experimental conditions except that the initial $\Delta Z = 0$ level has been shifted by 0.398 mm by the plunger for the second curve. Considered separately as ΔZ-versus-time plots they appear quite dissimilar and no correspondence between "steps" (labeled $A, B, \ldots$ in the left-hand plot and I, II, ... in the right-hand plot) can be made. However, considered as Z-versus-time curves there is a strong correspondence between stable steps. This correspondence is made unambiguous when the concurrent ΔZ-versus-ΔT plots measured simultaneously are considered.[10] Figure 3 shows the ΔZ-versus-ΔT curves corresponding to the ΔZ-versus-time curves of Fig. 2 and the points corresponding to the "steps" are indicated by $A, B, \ldots$, and I, II, ... Individual "steps" occur at particular points on the Z-ΔT structure[7] and this establishes the value of Z at which the "steps" occur. A comparison of the two ΔZ-ΔT planes with the individual "steps" superimposed on the Z-ΔT structure shows that the "steps" match on the Z-ΔT plane but not on the ΔZ-ΔT plane. Thus, these "steps" occur when the liquid level is at a particular value of Z with-

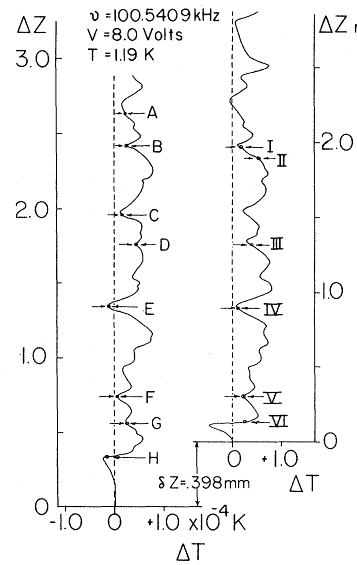

FIG. 3 ΔZ versus ΔT for the two emptying curves of FIG. 4. This curve illustrates the fact that the structure in the ΔZ-versus-ΔT curve produced by the transducer is a Z-ΔT structure rather than a ΔZ-ΔT structure. A particular variation in ΔT occurs when the liquid level is at a particular value of Z, independent of from where ΔZ is measured. The stable "steps" seen in Fig. 4 are superimposed on the Z-ΔT structure of this figure and labeled accordingly. The correspondence of "steps" I and B, III and D, IV and E, V and F, and VI and G shows that these stable "steps" occur at particular values of Z regardless of where ΔZ is measured from. Thus these "steps" are Z rather than ΔZ dependent.

in the capacitor, independent of the point from which ΔZ is measured.[11] Thus, these steps fail criterion (B).

The Z or ΔZ dependence of the stable "steps" can be studied as a function of frequency by taking successive flow curves over the same region of the capacitor where the frequency of the ac sound field is the only parameter allowed to vary. The results of such a study are shown in Fig. 4. The points represent stable "steps" and the bars represent points where the flow velocity dropped significantly (approaching zero) but did not stabilize at a zero flow rate. The frequency dependence of these "steps" and "near steps" is opposite that given by Eq. (3). Thus, these "steps" fail criterion (C).[12]

In conclusion we have found stable "steps" of zero flow through an orifice in the presence of an ac sound field which we believe to be the states identified previously[1-5] as the ac Josephson states. These states depend on the total height of the fluid in the inner bath and not on the level difference. They are insensitive to a temperature difference for small differences and they exhibit a frequency dependence opposite to that expected for the Josephson effect. These states are clearly not connected with the Josephson effect.

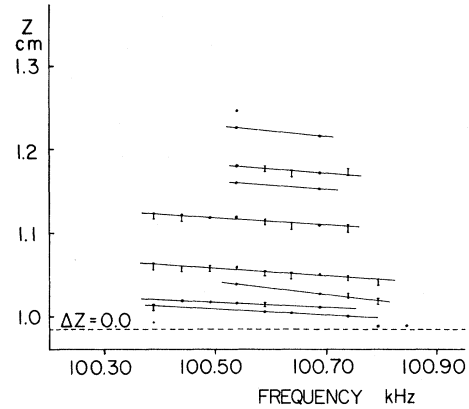

FIG. 4. Position of stable steps versus frequency. The stable steps are plotted as the points while the "near steps" are the bars, whose extent is determined by the points of inflection on the emptying curves.

Finally, we also report that careful examination of all our curves (several hundred runs) at those values of the parameters satisfying Eq. (3) shows no anomalies in the flow rate and hence no evidence for the ac Josephson effect.

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[1]P. L. Richards and P. W. Anderson, Phys. Rev. Lett. 14, 540 (1965).
[2]B. M. Khorana and B. S. Chandrasekhar, Phys. Rev. Lett. 18, 230 (1967).
[3]B. M. Khorana, Phys. Rev. 185, 229 (1969).
[4]P. L. Richards, Phys. Rev. A 2, 1534 (1970).
[5]J. P. Hulin, C. Laroche, A. Libchaber, and B. Perrin, Phys. Rev. A 5, 1830 (1972).
[6]P. W. Anderson, Rev. Mod. Phys. 38, 298 (1966).
[7]D. L. Musinski and D. H. Douglass, in Proceedings of the Thirteenth International Conference on Low Temperature Physics, Boulder, Colorado, August, 1972 (to be published).

[8]As ΔT is increased, a point is finally reached where ΔZ begins to respond to the applied ΔT and eventually establishes a new state of the system. The amount of ΔT bias needed to cause ΔZ to respond varies, but it has been recorded as high as 0.5 mK.

[9]B. M. Khorana and D. H. Douglass, in *Proceedings of the Eleventh International Conference on Low Temperature Physics, St. Andrews, Scotland, 1968,* edited by J. F. Allen, D. M. Finlayson, and D. M. McCall (St. Andrews University, St. Andrews, Scotland, 1969), Sect. A 3.2.

[10]We found that it is important to measure ΔT at all

times because the transducer, in addition to producing a level difference, also produces a temperature difference between the two baths, ΔT, which is uniquely dependent on Z, the amount of fluid within the capacitor. We have shown that this reproducible variation of ΔT, or "structure," depends on Z rather than ΔZ (see Ref. 7). In addition, all of the various "peaks," local positive maxima of ΔT, have been studied as a function of frequency. The positions Z of these individual peaks all display an inverse relationship with the frequency of the ac sound field. The slopes observed, $-dZ/d\nu$, fall within the range (3 to 10) $\times 10^{-4}$ mm/Hz. Thus, the Z-ΔT "structure" produced by the transducer is not related to Josephson states.

[11]One could mistake some of these "steps" as the Josephson effect if the helium level were placed at the "right" value. For example, state E in Fig. 2 would appear to be the $n=1$ Josephson step if the initial $\Delta Z=0$ level were raised by 0.38 mm.

[12]This dependence of the "steps" and ΔT "peaks" on frequency suggests that they may be explainable in terms of sound resonances within the annular region of the capacitor. This suggestion is further strengthened by the work of P. Leiderer [Diplomarbeit, Technischen Hochschule München, 1968 (unpublished)] and P. Leiderer and F. Pobell (private correspondence) who observed stable "steps" in the level difference for the geometry where the capacitor was replaced with a closed capillary. In that work the distance between successive "steps" was the wavelength of first sound rather than the expected Josephson relation. By comparison, the coaxial capacitor must be considered as a three-dimensional resonator, so that the spectrum for sound resonances is expected to be more complicated than for the capillary geometry. In particular, not only is there the possibility of standing waves in the dimension Z, but there is the added degree of freedom in the angular variable θ, i.e., standing waves about the annulus. The dimensions of the capacitor are such that one can fit up to thirteen wavelengths of first sound around the circumference of the annulus. In light of the added degrees of freedom for this three-dimensional resonator, the large number of ΔT "peaks" observed along with their range of values for $dZ/d\nu$ as well as the stable "steps" may be explainable in terms of sound resonances.

Effect of Magnetic Field on Electron Density Growth during Laser-Induced Gas Breakdown*

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The avalanche growth rate of CO_2-laser–induced gas breakdown in a magnetic field has been studied by measuring the time elapsed between the initiation of the laser pulse and the onset of observable breakdown effects such as a sharp decrease of laser transmission through the gas. The main features of the observed magnetic field dependence of this time difference can be explained in terms of the inhibition of electron diffusion from the laser focal region.

Considerable effort has been devoted to the study of the threshold pressure for laser-induced gas breakdown,[1] including recent investigations of the dependence of the threshold pressure upon magnetic field.[2] Very little attention, however, has been given to the study of the time evolution of the breakdown process.[3] In this paper we describe the first investigation of the influence of a magnetic field upon the time elapsed between the initiation of a laser pulse and the onset of observable breakdown effects such as the sharp decrease in laser transmission through the gas. The experimentally observed magnetic field dependence of this time of transmission decrease is compared with that predicted by a simple model of avalanche breakdown controlled by both free and ambipolar diffusion.

The experimental measurements were made by subjecting argon gas to focused 10.6-μm radiation from a 10-J CO_2 laser.[4] The laser was run without nitrogen in order to eliminate the long tail at the end of the pulse. The absence of the long tail made it possible to obtain more reproducible values of the transmission decrease time. With no nitrogen in the laser cavity, the laser pulses were reproducible to within 5–10%. The laser beam was directed through an NaCl beam splitter where about 15% of the radiation was directed to a reference germanium photon drag detector. The remainder of the beam passed through a CaF_2 attenuator and then through a lens of 10-cm focal length. The lens formed one end