Dielectric Breakdown of Liquid Helium*

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The dielectric strength of liquid He^4 under its saturated vapor pressure has been determined from 1.2 to 4.2°K. With $\frac{3}{8}$-inch diameter spherical steel electrodes 0.15 mm apart the average breakdown field, $\bar{E}_b$, is approximately 1 Mv/cm, nearly independent of temperature. At spacings of 0.5 and 1 mm, $\bar{E}_b$ is lower, and appears to decrease with decreasing temperature below 2.5°K. The mechanism of breakdown is not clear, but field emission of electrons from the cathode is probably involved, because the average breakdown voltage $\bar{V}_b$, obtained with a point and plane electrode system when the point is negative, is about half that obtained when the point is positive, both above and below the λ-point. Pre-breakdown currents were never detected, and were probably less than 10^{-13} amp, implying an electrical resistivity for liquid helium of 10^{18} ohm-cm.

1. INTRODUCTION

Recent interest in the behavior of ions in liquid helium[1–4] prompted us to study liquid helium in high electric fields in order to examine pre-breakdown currents and dielectric breakdown[5] itself. The large effective mass of the ions implied[4] by these results was expected to reduce the chance of ionization of neutral helium molecules by collision of fast moving massive ion complexes immediately before breakdown. We have in fact never detected a pre-breakdown current, and believe that such currents are probably less than 10^{-13} amp. In the absence of detectable currents we have studied the process of dielectric breakdown of liquid He^4 under its saturated vapor pressure from 1.2 to 4.2°K. Most of these experiments were performed with $\frac{3}{8}$-inch diameter spherical steel electrodes spaced from 0.15 to 1 mm apart, using dc potentials up to 50 kv. The remainder of the experiments used either point and plane, or plane and plane electrodes.

2. EXPERIMENTS

The electrodes were located in a separate chamber immersed in liquid helium. The chamber[6] used was a Pyrex glass tube connected to a 2-inch o.d. copper tube by a copper-glass seal. This part of the chamber could be removed between runs to change electrodes, and resealed to the chamber top by the use of an indium *O*-ring. The electrode chamber was filled separately with liquid helium by condensation of helium gas purified by a liquid nitrogen cooled charcoal trap, in order to keep impurities out of the liquid helium. The temperature was adjusted by adjusting the bath temperature. The chamber pressure was measured by means of a Wallace and Tiernan precision dial manometer connected to the chamber. By keeping the chamber pressure at or very slightly above the saturated vapor pressure, boiling of liquid helium I was suppressed.

The movable upper electrode was attached to a $\frac{1}{8}$-inch diameter steel rod 48 inches long, extending up through the top of the cryostat. This rod was a press fit inside a $\frac{1}{8}$-inch diameter hole 45 inches long drilled down the center of a $\frac{3}{4}$-inch diameter Teflon rod.[7] The Teflon served as both vacuum and electrical insulation. The whole assembly was raised and lowered from the upper end using a sylphon bellows and three Starrett metric micrometer caliper heads, which also served to measure the electrode spacing.

A 0-50 kv Beta Electric Corporation variable high voltage dc power supply was connected to a bushing on the upper end of the $\frac{1}{8}$-inch rod. The lower electrode was fixed and the low voltage lead from it was connected through a Keithley Model 610 Electrometer to ground. This electrometer has 28 overlapping current ranges, starting at 10^{-13} amp full scale on its most sensitive range.

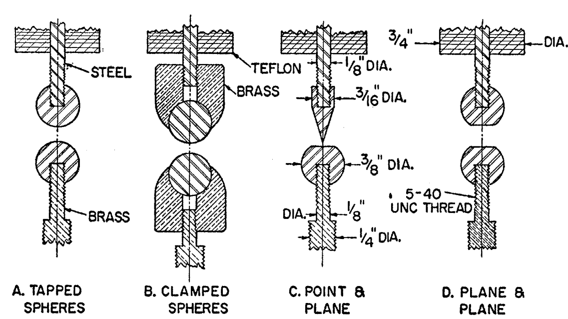

FIG. 1. Four configurations of steel electrodes used for dielectric breakdown measurements.

* Supported by the Office of Naval Research.

[1] R. L. Williams, Can. J. Phys. **35**, 134 (1957).
[2] L. Meyer and F. Reif, Phys. Rev. **110**, 279 (1958).
[3] G. Careri, F. Scaramuzzi, and J. O. Thomson, Nuovo cimento **13**, 186 (1959).
[4] K. R. Atkins, Phys. Rev. **116**, 1339 (1959).
[5] B. S. Blaisse, A. van den Boogart, and F. Erné, Bull. inst. intern. froid Annexe **1**, 333 (1958).
[6] H. Seki, Rev. Sci. Instr. **30**, 943 (1959).

[7] We are grateful to Mr. M. L. Hearn and Mr. T. Coyle for their skill in drilling this hole.

Four electrode configurations were used. They are shown to scale in Fig. 1. The spheres used were $\frac{3}{8}$-inch (9.52 mm) diameter spherical steel ball bearings. Some of these were specially drilled and tapped during manufacture before the hardening process. Other untapped spheres were mounted in brass holders (configuration *B* in Fig. 1). The "planes" were made by grinding flats 5.7 mm wide on some of the tapped ball bearings. The "points" were machined from steel to a fine point which was then smoothed by hand-filing under a microscope. All electrodes were polished with alumina before use. The electrode pitting that occurred after one breakdown was at least ten times as severe as the worst polished areas which remained before installation.

Breakdown Using Spherical Electrodes

The upper electrode was normally negative. For the spherical electrodes, (configurations *A* and *B* of Fig. 1), the voltage was raised slowly, and a current reading was taken roughly at 1 kv intervals. Breakdown either occurred as the potential was rising or after a fixed potential had been applied for some seconds. As soon as breakdown had occurred, the power supply was disconnected by a manually operated switch. The breakdown consisted of one or several bright white sparks between the electrodes, with an associated loud noise. About 10 such breakdowns were averaged to get $\bar{V}_b$ the mean breakdown voltage at any temperature and gap setting. Figure 2 shows the results for $\bar{V}_b$ for three gap settings at several temperatures. The standard deviation of the mean was usually around 2 kv, but the highest and lowest individual readings were often 50% higher and lower than the mean. Occasionally no breakdown would occur even with 50 kv applied at spacings of 0.5 and 1 mm.

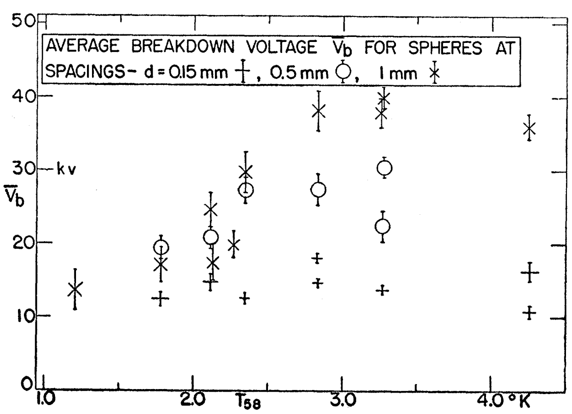

FIG. 2. Average breakdown voltage of liquid helium for steel spheres of diameter 9.52 mm as electrodes, at three gap lengths, as a function of temperature.

Figure 3 shows these results in terms of the electric field required for breakdown. The average breakdown field $\bar{E}_b$ shown is the calculated maximum field obtaining between the two spheres along their line of centers, and

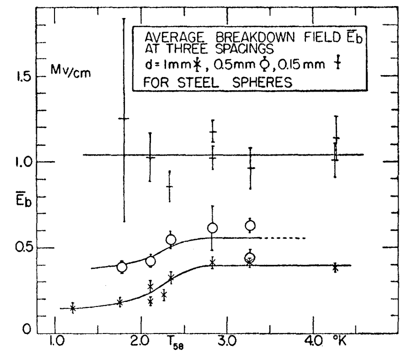

FIG. 3. Average dielectric strength of liquid helium using steel spheres of diameter 9.52 mm, for three gap lengths, as a function temperature.

is taken to be greater than $\bar{V}_b/d$ by 7.3% for $d=1$ mm., 3.6% for 0.5 mm., and 1.1% for 0.15 mm.[8] This calculation assumes there are no space charges present in the gap.

Apart from the displacement current which flowed when the voltage across the electrodes was changing (the electrodes behave as a capacitor in series with the input resistance of the electrometer), no pre-breakdown current was ever observed. Even when a radioactive source of 1 mC of Co^{60} as an aqueous solution of cobaltous chloride was attached to the outside dewar at the level of the gap, no current was detected, nor was the breakdown voltage altered. We believe we could have detected steady currents in excess of 10^{-13} amp. On one occasion breakdown occurred 10 seconds after such a current measurement had been concluded, and before the voltage had been changed. Assuming that the effective area of the electrodes is 0.1 cm.^{2}, then for the 0.15 mm gap just prior to breakdown, this implies an electrical resistivity for liquid helium of 10^{18} ohm-cm. This figure is considerably larger than the lower limit of 10^{15} ohm-cm. reported earlier by Wolfke and

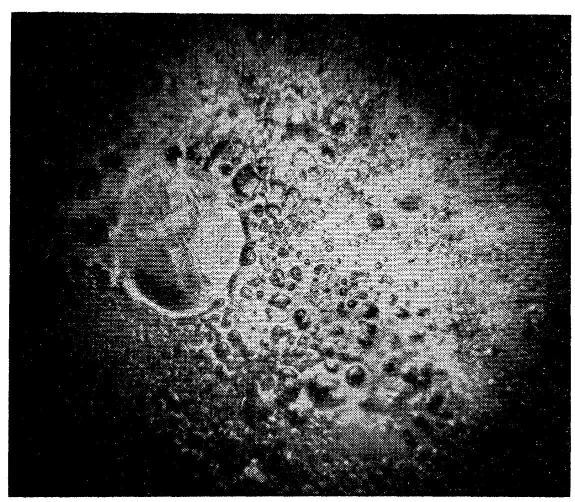

FIG. 4. Photomicrograph of a 0.1-mm diameter region of a cathode surface, showing detail near one large crater.

[8] F. W. Peek, Jr., *Dielectric Phenomena* (McGraw-Hill Book Company, Inc., New York, 1915), p. 27.

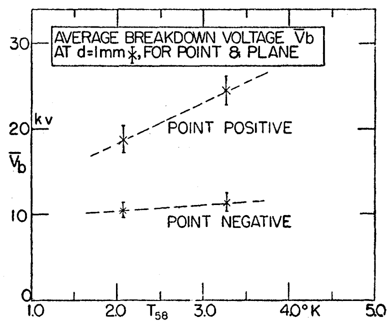

FIG. 5. Average breakdown voltage of liquid helium for steel point and plane electrodes, with two polarities, at two temperatures.

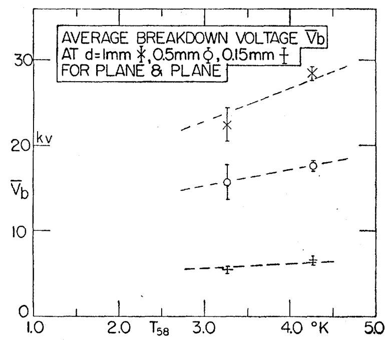

FIG. 6. Average breakdown voltage of liquid helium for steel plane and plane electrodes, for three gap lengths, at two temperatures.

Keesom.[9] In fact liquid helium has perhaps the highest resistivity of any liquid.

After several breakdowns, electrodes showed extensive pitting over about a 2-mm diameter region. Figure 4 is a photomicrograph of an 0.1-mm diameter region of one of the cathodes after about 65 breakdowns, showing one large crater and many small bumps and pits. The fact that we could detect no systematic reduction in the breakdown voltage later in a run, after such pitting became more severe, was puzzling, unless space charges were present in the gap.

Breakdown Using Point and Plane Electrodes

Figure 5 shows the effect of polarity on a point and plane electrode system (configuration C of Fig. 1). The radius of the tip of the point was approximately 0.075 mm. The average breakdown voltage $\bar{V}_b$, with the point negative is about half that obtained when the point is positive, both above and below the λ point. We take this as evidence that field emission of electrons from the cathode must occur for breakdown to take place. The inhomogeneous field in this case would make the buildup of space charges in the gap less likely than between spheres.

Breakdown Using Plane and Plane Electrodes

Figure 6 shows the average breakdown voltage, $\bar{V}_b$, obtained with a plane and plane system (configuration D of Fig. 1). In general the edges of such planes tend to make them behave as a pair of points in parallel with a pair of planes. In fact some of the characteristics of both Figs. 3 and 5 seem to be shown in Fig. 6.

3. DISCUSSION

Blaisse *et al.*[5] have studied dielectric breakdown of liquid helium in an ordinary dewar using a tungsten sphere and plane, with the plane as the cathode. They found that the *highest* values of breakdown voltage which they obtained implied a constant breakdown field of about 0.7 Mv/cm at 4.2 and 1.3°K independent of the gap d from 0.05 to 0.3 mm. Our results with spherical steel electrodes show in contrast a strong dependence of average breakdown field $\bar{E}_b$ on gap d. It is difficult to see how "too high" a value of dielectric strength can be obtained experimentally, however, and we did occasionally find that no breakdown would occur with 50 kv across the electrodes for our longer gaps. Our experiments with point and plane electrodes show that field emission of electrons from the cathode probably occurs at breakdown. A pitted electrode might then be expected to experience local field strengths near its surface, higher than the recorded fields.

As soon as electrons enter the liquid, they might tend to become "trapped" as part of a fairly massive entity by electrostriction as shown by Atkins.[4] These ion complexes, consisting of an electron and about 50 helium atoms then would drift across the gap. Atkins[10] has proposed that the mechanism of dielectric breakdown may involve the drift velocity of an ion exceeding the velocity of sound, and then leaving behind the density hump formerly associated with it, and proceeding on its way with greatly reduced effective mass and greatly increased velocity. Presumably multiplication of ions by collisions could then occur, leading to breakdown. The drift velocity $v_d = \mu E$ where μ is the ion mobility. Few measurements of ion mobility have been made at high fields. Extrapolation of Williams' measurements[1] at 1.4°K and 4.2°K from fields of 50 kv/cm and 130 kv/cm to 1 Mv/cm, assuming μ remains proportional to $E^{-\frac{1}{2}}$, yields mobilities of 0.02 and 0.08 cm^2/volt sec, respectively. At the breakdown field $\bar{E}_b = 1$ Mv/cm obtained with $d = 0.15$ mm, this implies that the drift velocity was indeed within a factor of two of the speed of sound at the time of breakdown. This apparent agreement can only be tested more carefully when mobility measurements at higher fields become available, and when the apparent dependence of the dielectric strength on the gap length is explained. As the variation with pressure of both sound velocity and liquid density are well known, a systematic investigation of ion mobilities and dielectric strength of liquid helium under higher pressures might well be informative.

4. ACKNOWLEDGMENTS

We are grateful to M. Caspari and K. R. Atkins for many discussions. One of us (M. H. E.) is particularly grateful to K. R. Atkins and his Low-Temperature group for their hospitality during his visit.

[9] M. Wolfke and W. H. Keesom, Physica 3, 823 (1936).

[10] K. R. Atkins, Office of Naval Research Tech. Rept. No. 3, under contract (Unpublished).

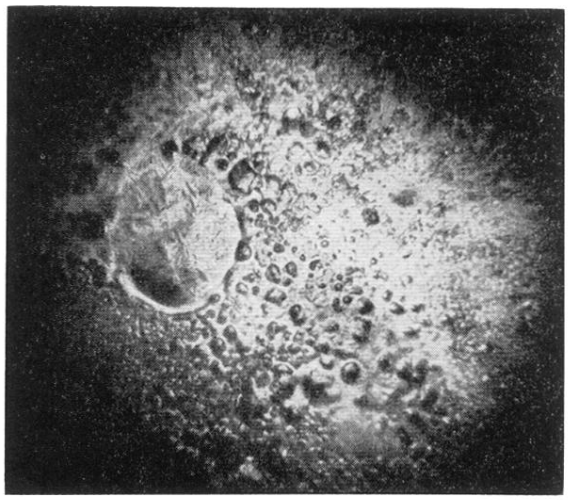

FIG. 4. Photomicrograph of a 0.1-mm diameter region of a cathode surface, showing detail near one large crater.