PHYSICAL REVIEW
LETTERS

VOLUME 7 SEPTEMBER 15, 1961 NUMBER 6

DENSITY OF LIQUID HELIUM-3 BETWEEN 0.045 AND 1.3°K*

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(Received August 7, 1961)

We have measured the density of liquid helium-3 at various pressures up to 28.0 atm in the temperature range between 0.045 and 1.3°K. At pressures above about 15 atm, an unexpected minimum in density was found to occur, the temperature of this minimum increasing to 0.09°K when the pressure is increased to 28 atmospheres. For a pressure of 0.18 atm and below 0.08°K the coefficient of expansion was found to be proportional to *T*, as predicted by Brueckner.[1]

The method used for these measurements was the same as that used by Lee, Fairbank, and Walker,[2] who determined the density of liquid helium-3 down to about 0.15°K. It consisted in measuring the dielectric constant of the liquid from the resonant frequency of an *LC* circuit, in which the capacity was a coaxial cylindrical capacitor containing the liquid. The density of the liquid was then obtained using the Clausius-Mosotti relation. The assumption was, as in earlier work,[2] that the polarizability stayed constant with temperature and pressure.

The cylindrical capacitor was made of parts machined from electrolytic copper, the gap being 4×10^{-2} mm between the concentric cylinders. These were held together at their upper extremity by an araldite seal capable of withstanding pressures at least up to 29 atmospheres. Helium-3 could be introduced into the gap through a 2×10^{-1}-mm i.d. capillary. The inductance of the tank circuit consisted of a coil of copper wire soldered directly on top of the capacitor and shielded from external pickup by a thin copper cylinder connected to the ground side of the capacitor. The tank circuit was thermally connected via 500 No. 34 copper wires to the paramagnetic salt pill made up of about 30 g of freshly grown chromium methylammonium sulphate mixed with Apiezon oil J. The salt was adiabatically demagnetized from a field of about 12 kilogauss at about 0.45°K, and the lowest temperatures reached were about 0.035°K. The temperature was measured by two 470-ohm Speer carbon resistors, the first soldered to the tank circuit, the other embedded in the salt pill. These resistors were calibrated in each series of experiments against the susceptibility of the chrome alum, which in turn had been directly measured against that of cerium magnesium nitrate down to 0.06°K in a different apparatus. The temperatures below 0.06°K were determined by extrapolation of the calibration curve of the carbon resistors. While the temperature should be known to within 6% down to 0.07°K, the systematic error may increase to about 15% at the lowest temperatures.

The tank circuit was part of a Franklin oscillator[3] and the frequency was measured by a Hewlett Packard 524 B Electronic Counter. The resonance frequency of the tank circuit was about 31 Mc/sec and was stable within 5 cycles over periods of an hour. The power input into the tank circuit was so small that it did not affect the warming up of the sample even at the lowest temperatures. The change in frequency between 0.045°K and 1.2°K due to the change in density of liquid helium-3 at constant pressure was only of the order of 4 kc/sec, and hence during the experiments, the pressure had to be held very constant, as a change in pressure of 0.1% produced a frequency shift in the tank circuit of the order of 30 cps. During

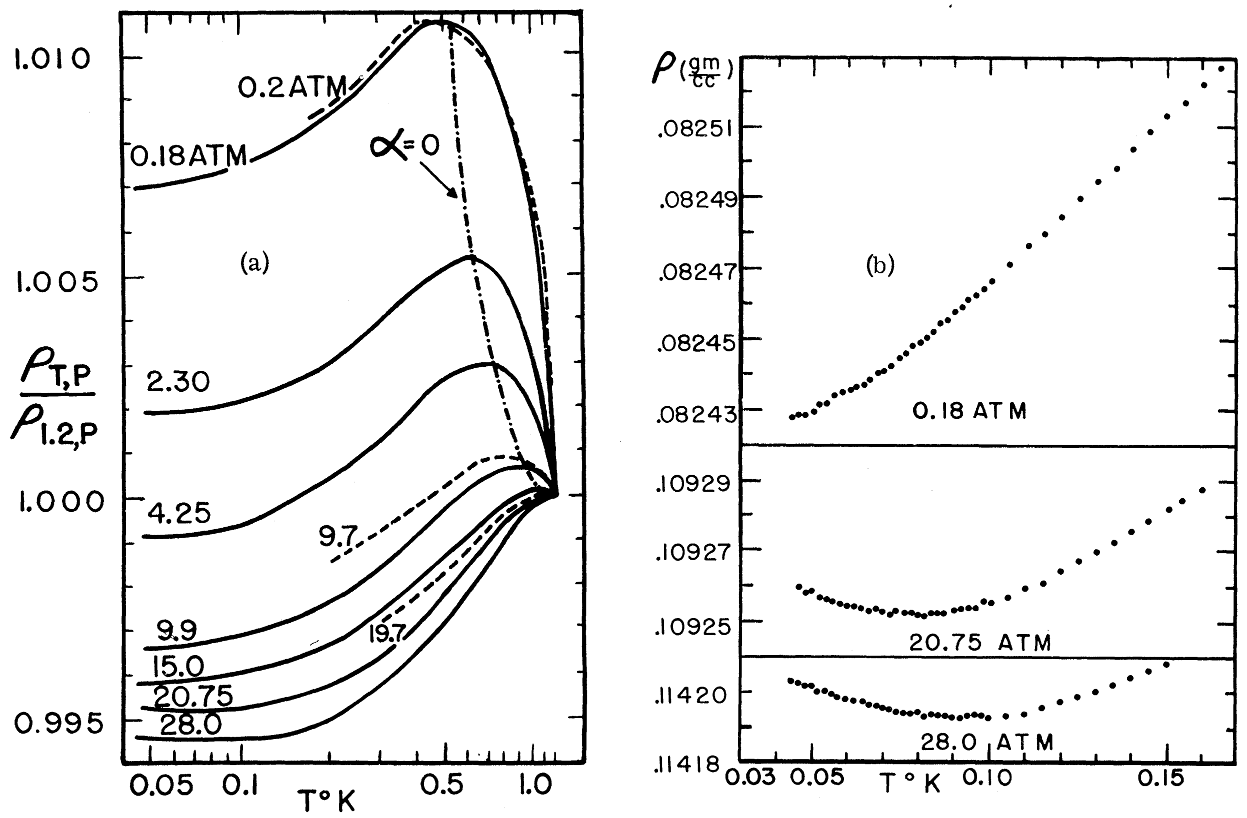

FIG. 1. (a) Density of helium-3 normalized to its value at 1.2°K for several pressures. --- Data of Lee, Fairbank, and Walker. (b) Some density curves of liquid helium-3 below 0.15°K.

each series of experiments, the frequency of the empty tank circuit was first measured over the whole temperature range. At several temperatures above 1°K the density of liquid helium-3, obtained in arbitrary units, was normalized to the accurate density values obtained by Sherman and Edeskuty[4] and the results were found to be very consistent.

Our results are shown in Fig. 1(a), where for convenience we have plotted the ratio $\rho(T,P)/\rho(1.2,P)$, where $\rho(1.2,P)$ is the density at 1.200°K and at the pressure P as found by Sherman and Edeskuty.[4] Our density results, extrapolated to zero pressure, agree satisfactorily with those of Kerr and Taylor[5] and are somewhat different from those of Lee, Fairbank, and Walker.[2] As can be seen from Fig. 1(a) and especially Fig. 1(b), the density at pressures above about 15 atm and at temperatures below 0.1°K passes through a minimum, the temperature of this minimum increasing with pressure. Several experiments were carried out to check this effect and gave reproducible results. The coefficient of expansion $\alpha_p = (1/V)(\partial V/\partial T)_p$ as derived from the ρ values is plotted in Fig. 2 for a few pressures. In the region below 0.08°K, we found $\alpha_{0.18\,\mathrm{atm}} = -(0.12 \pm 0.02)T$ in qualitative agreement with Brueckner's theory[1] which predicts $\alpha_p = -0.076T$. The figure also suggests that the density minimum

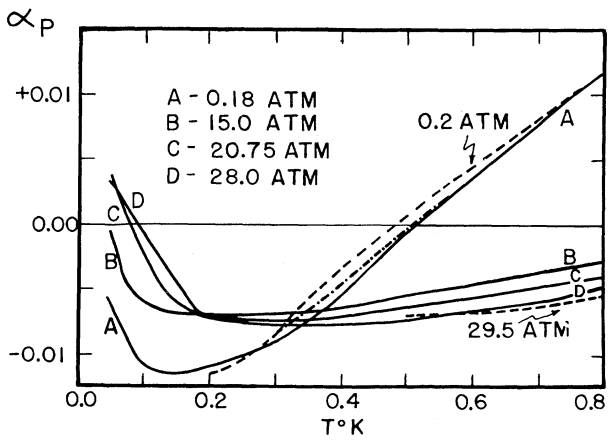

FIG. 2. The expansion coefficient of liquid helium-3 for some pressures. --- Data of Lee, Fairbank, and Walker; -·-·- data of Kerr and Taylor.

may be found for pressures below 15 atm at temperatures below 0.045°K. As a consequence, below 0.09°K, the entropy of isothermal compression ΔS, where

$$\Delta S = S_P - S_{\mathrm{svp}} = -\int_{\mathrm{svp}}^{P} V\alpha_p dp,$$

will pass through a maximum. Here S_{svp} is the entropy at saturated vapor pressure and V is the molar volume.

The quantitative value of ΔS as obtained from our density measurements can be checked by specific heat measurements at various pressures. At temperatures above 0.3°K, the agreement with ΔS as calculated by Brewer and Daunt[6] is very satisfactory. On the other hand, there are some systematic differences between our curves and those calculated from the earlier density measurements of Lee, Fairbank, and Walker.[2] It may be mentioned that no discontinuity of α_p, characteristic of a second order transition to another phase, such as predicted by Emery and Sessler[7] and by Brueckner et al.[8] for liquid helium-3, was found in these experiments over the whole temperature and pressure range. Previous specific heat measurements[9] on liquid helium-3 under a pressure of 0.18 atm down to 0.008°K had already failed to show this transition.

The temperature at which the maximum of density occurred for a given pressure agreed very well with the results of Brewer and Daunt[6] up to about 15 atmospheres and at higher pressures agreed better with those of Sherman and Edeskuty.[4]

A new and improved apparatus is being constructed in order to extend our measurements down to 0.01°K and obtain more accurate values for α_p below 0.07°K.

The initial stages of this experiment were supervised by Dr. W. M. Fairbank, whom we wish to thank for his valuable advice. We also acknowledge the help of Mr. C. Boghosian in some experiments. We also thank Dr. N. Kurti, Dr. H. London, and Dr. D. M. Lee for helpful discussions.

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*This work has been supported by the National Science Foundation, the Alfred P. Sloan Foundation and the Office of Ordnance Research.

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