



FIG. 1. Schematic diagram of the density cell and He<sup>4</sup> pot for the temperature range between 4.2 and 1.25°K. The vacuum jacket is surrounded by liquid He<sup>4</sup> at 4.2°K.

## II. APPARATUS AND EXPERIMENTAL PROCEDURE

We have determined the molar volume of liquid He<sup>4</sup> by measuring the dielectric constant of a small sample of the liquid. This sample was contained in a capacitor which was part of an LC tank circuit, the resonance of which determined the frequency of a tunnel-diode oscillator. This circuit has been discussed previously,<sup>9</sup> where it was shown that

$$\epsilon = \left\{ (\nu_0/\nu)^2 + K[(\nu_0/\nu)^2 - 1] \right\} [1 + B(P)]^{-1}, \quad (1)$$

where  $\epsilon$  is the dielectric constant of the sample,  $\nu$  and  $\nu_0$  are the frequencies of the circuit with and without sample, respectively, and  $K$  and  $B(P)$  are terms which correct for, respectively, part of the capacitive space being unavailable to the sample and pressure distortion of the capacitor. The molar volume  $V$  was then determined from the dielectric constant by using the Clausius-Mosotti relation

$$\frac{(\epsilon - 1)}{(\epsilon + 2)} = \frac{4\pi}{3} \left( \frac{A}{V} \right). \quad (2)$$

A fundamental assumption that has been made in this work is that the molar polarizability  $A$  is a constant which we have taken to have the value<sup>3</sup> 0.1230. The justification for this assumption lies in the excellent

<sup>9</sup> C. Boghosian, H. Meyer, and J. E. Rives, *Phys. Rev.* **146**, 110 (1966).

agreement of the density data with the pycnometric data of Edeskuty and Sherman,<sup>10</sup> as will be described later.

The apparatus is very similar to those that have been described in detail elsewhere,<sup>9</sup> and is only discussed briefly here.<sup>11</sup> The heart of the cryostat is shown schematically in Fig. 1. It is an improvement over an original version in that the oscillator elements were close together (electrically as well as mechanically) and rigidly mounted with respect to each other so that the frequency was very stable. The operating frequency was about 14 MHz and did not change by more than  $\pm 0.2$  Hz over periods of about 1 h, as long as temperature and pressure were held constant. This made it possible to detect volume changes as small as 1 part in  $10^6$ . This in turn made it meaningful to approach the  $\lambda$  line to a resolution of about  $10 \mu^\circ\text{K}$ , since the molar volume changes by about 1 part in  $10^6$  in an interval of this size near the transition. The thermometers were  $\frac{1}{10}$ -W Allen Bradley carbon resistors, attached as shown in Fig. 1. A 110- $\Omega$  resistor attached to the capacitor was the main thermometer, while a 64- $\Omega$  resistor attached to the capacitor was used for work below 1.6°K, and a 64- $\Omega$  resistor attached to the pot was used to detect the presence of thermal gradients introduced by the sample in the superfluid phase. Resistances were measured on an ac Wheatstone bridge at a power level of about  $10^{-3}$  W dissipated in the resistor; at 2.2°K this gave a resolution of about  $5 \mu^\circ\text{K}$  on the main thermometer. The signal from the bridge was amplified and fed into a phase-sensitive detector, and this detector in turn fed a dc signal to a chart recorder to give a continuous display of the temperature change.

The sample pressure was held constant to  $\pm 0.1$  mm of Hg throughout a pressure run. The absolute accuracy to which the pressure was known varied with the measuring device. It was  $\pm 0.2$  mm Hg for pressures up to 1 atm, where a mercury manometer was used. In runs I and II a bourdon gauge was used with a pressure resolution of  $\pm 0.05$  atm. In run III, a Heise bourdon gauge with a resolution of about  $\pm 0.01$  atm was used. Both Bourdon gauges were calibrated against a dead weight tester and were accurate to the resolution to which they could be read. Hysteresis of the gauges was found to be negligible. The external pressure control system was connected to the sample capacitor by a 0.010-in. i.d. stainless-steel capillary that had an 0.008-in. wire in it between a thermal anchor at 4.2°K and the He<sup>4</sup> pot. This reduced the heat influx along the pressure line considerably but, for pressures below 1 atm lead to a small lag (2 or 3 sec) between pressure adjustment and frequency equilibrium. Thus there was

<sup>10</sup> F. J. Edeskuty and R. H. Sherman, in *Proceedings of the Fifth International Conference on Low Temperature Physics, Madison, Wisconsin, 1957*, edited by J. R. Dillinger (University of Wisconsin Press, Madison, 1958), p. 102.

<sup>11</sup> A detailed description of the apparatus and tabulation of all the results can be found in the Ph.D. thesis by D. L. Elwell, Duke University, 1967 (unpublished).