provided all the resistance values and other temperatures are known.[3] Consider the network of Fig. 1. By straightforward network analysis one obtains for v_0 and v_2:

$$v_0 = \frac{Z_0}{Z_T}\,[i_0(Z_1+Z_2)-i_1Z_1-i_2Z_2] \tag{2a}$$

$$v_2 = \frac{Z_2}{Z_T}\,[i_0Z_0+i_1Z_1-i_2(Z_1+Z_0)] \tag{2b}$$

where

$$Z_T = Z_0+Z_1+Z_2, \quad Z_0 = R_0/(1+j\omega C_0R_0), \text{ etc.}$$

and v_0, i_0, etc. are complex vectors. If one multiplies v_0 and v_2 and takes the time average over the product, then one forms:

$$\operatorname{Re}(\overline{v_0v_2^*}) = \operatorname{Re}\left\{\frac{Z_0Z_2^*}{|Z_T|^2}\,[\overline{|i_0|}^2 Z_0^*(Z_1+Z_2)+\overline{|i_2|}^2 Z_2(Z_0^*+Z_1^*)-\overline{|i_1|}^2|Z_1|^2]\right\}, \tag{3}$$

where

$$\overline{|i_0|}^2 = 4kT_0\,df/R_0$$

(the Planck factor is assumed to be unity), similarly $\overline{|i_1|}^2$ and $\overline{|i_2|}^2$. The time average of the products $\operatorname{Re}(\overline{i_0i_1^*})$, etc. are zero because the resistors are independent noise sources. The product $\operatorname{Re}(\overline{v_0v_2^*})$ appearing in equation (3) corresponds to the direct multiplication of the physical voltages v_0 and v_2. From equation (3) one sees that if either $R_0C_0 = R_1C_1 = R_2C_2$ or $(\omega R_nC_n)^2 \ll 1$ the product $\operatorname{Re}(\overline{v_0v_2^*})$ can have a positive or a negative sign provided $T_1 > (T_0+T_2)$. For either of the above conditions the value of R_1 required to make $\operatorname{Re}(\overline{v_0v_2^*}) = 0$ can be calculated from equation (3):

$$R_1 = \frac{T_0R_2+T_2R_0}{T_1-T_0-T_2}. \tag{4}$$

In this experiment R_0 and R_2 were both kept in the helium bath so that $T_0 = T_2$. R_2 and R_0 were matched to better than 1/2%, and T_1 was in an isothermal bath at room temperature. If T_1 and the resistances are measured, T_0 can be calculated from

$$T_0 = T_1\frac{R_1}{R_0+2R_1+R_2}. \tag{5}$$

II. THE THERMOMETER AND EXPERIMENTAL PROCEDURES

The first requirement for an absolute noise thermometer of the kind described above is to find some resistors which are stable at liquid helium temperatures, whose values are preferably reproducible for several experiments, which produce no noise in addition to thermal noise, and whose resistive component

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[3] This idea was proposed by Dr. J. B. Garrison to Prof. A. W. Lawson of Chicago University (verbal communication by Prof. R. E. Burgess).

is the same as the d-c. resistance (within a specified accuracy) over the frequency interval in which the measurements are performed. Many resistors have been tried at helium temperatures. The ones found most suitable are those manufactured by the Daven Co., series 850. They are hermetically sealed precision metal film type resistors composed of an alloy of pure, noble metals. They are stable over a period of at least 7 hours to better than 1 part in 10^4 and they are reproducible to that accuracy for several experiments. A 20-kΩ resistor has a resistive component of 20kΩ±1% at 3 Mc/sec. The resistance values used in equation (5) should be those appropriate to the frequency range in which the noise measurements are performed. Because no sufficiently accurate audio-frequency bridge was available the metal film deposit resistors were measured at d-c. and at 3 Mc/sec. Since the 3-Mc/sec values differed from the d-c. values by less than 1%, it seems reasonable to conclude that the deviation of the resistance in the audio-frequency range from the d-c. value was less than 0.1% for the above resistors. A 20-kΩ Davohm resistor has a resistance of approximately 17.9 kΩ at liquid helium temperatures (1.3° K to 4.3° K) and the resistance value over this range varies less than 0.05%.

R_1 was a precision wire wound resistance box and C_1 a variable condenser, both kept at room temperature. C_0 and C_2 were the parasitic capacitance between the wires and the shielding, and the input to the amplifiers (including effects due to Miller capacitances), and they were equal within 3%. Unfortunately the parasitic capacity to ground was very large ($\sim$220 $\mu\mu$f), and about three-fifths of this was due to the shielding of C_1 and R_1 which was reflected into the input of each amplifier.

Figure 2 shows the block diagram of the thermometer. The shielding requirements of the input circuit and the preamplifiers were very stringent and great care was required to avoid ground loops and to eliminate magnetic pickup in the π network which in effect acts like a loop. The first tube of the preamplifier was a 6922 (American equivalent to the Philips E88CC) double triode connected as a grounded-cathode-grounded-grid amplifier (cascode) followed by two RC coupled stages (7025 double triode). The cascode and the first RC coupled stage were constructed of wire wound resistors, and their filament currents were supplied by batteries. The lower and upper half power points of the amplifiers were approximately 3 and 7 kc/sec respectively. Both input voltages to the multiplier were constantly monitored by two oscilloscopes and two r.m.s. voltmeters to check the randomness of the noise spectrum and

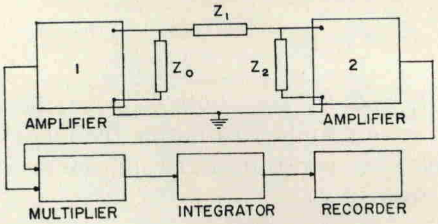

FIG. 2. The block diagram of the noise thermometer.