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Comparison of the National Bureau of Standards and the Helsinki Temperature Scales and its Effect on the Heat Capacity of Liquid ^{3}He below 10 mK

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The Helsinki temperature scale, used earlier in measurements of the heat capacity of liquid ^{3}He (1–10 mK), is compared with the National Bureau of Standards (NBS) noise and nuclear-orientation temperature scale. The superfluid transition temperature (T_c) of ^{3}He at zero pressure and the superconductive transition temperatures of tungsten and beryllium were used as fixed points. T_c on the NBS scale was found to be 1.025 $\pm$ 0.02 mK, in close agreement with the Helsinki value 1.04 mK. The results support the Helsinki data on the heat capacity of ^{3}He.

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An internationally accepted temperature scale in the low-millikelvin region has recently become important in connection with experiments on normal and superfluid ^{3}He. The effective mass m^* of ^{3}He, inferred from the heat capacity data by Alvesalo *et al.*,[1] deviates about 30% from earlier results[2-4]; the major cause of the discrepancy could be due to different temperature scales. Because the important Fermi-liquid parameters are dependent on m^*, it is essential to know the correct specific heat.

The temperature scales used in the various heat capacity measurements cannot be compared directly. In the Helsinki experiment[1,5] the temperature scale is fixed to the phase separation line between the normal and superfluid phases of ^{3}He, but measurements of Refs. 2 and 3 did not reach this line. An attempt to resolve the discrepancy has been made by Roach, Meisel, and Eckstein,[6] who have measured the volume derivative of the heat capacity. Their conclusions are weak, however, because the experiment is also sensitive to the temperature scale used and it does not give the heat capacities themselves.

We report in this Letter measurements which check directly the Helsinki temperature scale employed in Ref. 1. The test was performed by comparing this scale with the National Bureau of Standards (NBS) cryogenic temperature scale,[7] believed to be accurate to $\pm$ 0.5% and thus one of the most reliable scales in the low-millikelvin region. The superconductive transitions of tungsten and beryllium and the superfluid transition of ^{3}He at zero pressure were used as fixed points in the experiment. The heat capacity data of Alvesalo *et al.*[1,5] are strongly supported by our results.

The Helsinki scale is based on the assumption that the nuclear spin susceptibility of platinum is inversely proportional to T. The Curie constant was found by measuring the spin-lattice relaxation time τ_1 and by employing the Korringa relation, $\tau_1 T = K = 29.9$ ms K. This value for the Korringa constant K was measured by Ahonen, Krusius, and Paalanen[8] using a nuclear-orientation thermometer. The same platinum powder was employed in Refs. 1 and 8, as well as in the measurements reported here. The Helsinki scale is given as a set of (P,T) coordinates along the phase separation curve between normal and superfluid ^{3}He.[1] The absolute accuracy of the scale, $\pm$ 5%, was estimated on the basis of knowledge on K and the precision of τ_1 measurements.

The NBS-CTS-1 scale[7] was established by directly intercomparing a Josephson junction noise thermometer and a nuclear-orientation thermometer between 10 and 50 mK and by employing noise thermometry from 50 to 500 mK. From the excellent agreement between the two thermometers the absolute accuracy of the NBS scale was estimated as $\pm$ 0.5% below 50 mK. The scale can be realized at other laboratories by means of calibrated superconductive fixed points.[9]

In our experiments we used the superfluid transition temperature T_c of ^{3}He at zero pressure (1.04 mK on the Helsinki scale) and the Curie susceptibility of platinum to produce the Helsinki scale. The superconductive transition temperatures of one pair of tungsten and beryllium samples (15.60 and 23.59 mK on the NBS scale, re-

spectively), immersed in ^{3}He liquid, as well as the transition temperatures of two other samples of the same metals (15.50 and 23.02 mK on the NBS scale), mounted on the outside of the cell, were measured on the Helsinki scale.

The experimental chamber, shown in Fig. 1, was thermally connected to the copper bundle of a nuclear refrigerator. The platinum NMR coil, located in a cylindrical appendage to the main chamber, was a compensated solenoid; the rf-field inhomogeneity at the platinum sample was less than 5%. The susceptibility of CLMN (cerium magnesium nitrate diluted to 3% molar solution by the corresponding lanthanum salt) was used as a secondary thermometer. The coil assemblies for the CLMN pill and the metal samples were identical; the secondary coils were connected in series and coupled to a SQUID. Two separate inductance bridges, with different operating frequencies, were employed for monitoring the susceptibilities of CLMN and the superconducting samples.

The tungsten and beryllium samples outside the cell (not shown in Fig. 1) were bound with varnish and cotton thread to a bundle of copper wires, welded to a cylindrical copper block. A coil form, with primary and secondary coils, was pushed around the samples and the spare copper wire then folded back over the coils. This unit was connected through a copper rod to the silver support of the ^{3}He cell. The superconductive transitions of the outside samples were observed with a simple mutual inductance bridge.[9]

Because the superconductive transition temperature is very sensitive to magnetic fields, Earth's field was compensated with a solenoid outside the helium Dewar. Furthermore, the tungsten and beryllium specimens were protected with Mumetal and superconducting niobium shields. This was accomplished by enclosing the samples inside the cell within three shields. The inner and outer ones were Mumetal and the middle one niobium. The samples outside the cell were shielded by a Mumetal can and a niobium cylinder.

The residual magnetic field at the superconducting samples inside the cell was determined by measuring the transition temperature as a function of external static field produced by the primary coil and by extrapolating linearly to zero field. The flux change caused by the Meissner effect was used as a measure of the magnetic field. The correction to be applied to the transition temperature turned out to be less than 1%. The residual field inside the shields of the outside samples was estimated to be small.

The calibration between the platinum and the

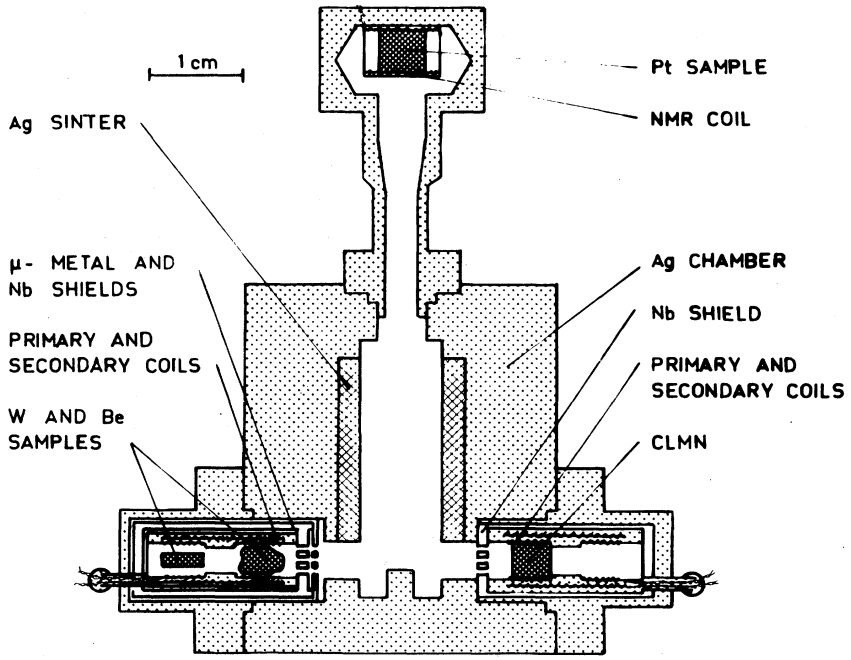

FIG. 1. Experimental cell.

TABLE I. Measured values of the superconductive transition temperatures on the NBS scale and on the Helsinki scale. The absolute accuracy of the NBS values is ± 0.1 mK and the precision of the data measured on the Helsinki scale is ± 1%.

	NBS scale (mK)	Helsinki scale (mK)					T_c of ^{3}He, NBS scale (mK)
		B = 28 mT	B = 28 mT	B = 0	B = 28 mT	B = 28 mT	
W inside	15.60	16.31	16.29	16.29	16.29	16.30	1.00
W outside	15.50	15.65	15.90	15.86	···	···	1.02
Be inside	23.59	23.73	23.66	23.54	23.68	23.60	1.04
Be outside	23.02	23.00	22.96	22.97	···	···	1.04

CLMN thermometers was made from 1 to 24 mK. The superfluid transition point of ^{3}He was found by means of the CLMN thermometer, with a precision of 0.1%, as a change in the slope of the temperature drift curve; this point was employed to fix the Curie constant of platinum. The tungsten and beryllium transition temperatures were recorded with both thermometers.

In Table I we show the measured superconductive transition temperatures from five different runs on the Helsinki scale. The external magnetic field (outside the shields) was either zero or 28 mT, the field employed for platinum NMR. The superfluid transition temperatures on the NBS scale were obtained by assuming that both scales are proportional to the absolute temperature and by multiplying the Helsinki T_c = 1.04 mK by the ratio of the NBS and averaged Helsinki transition temperatures for each superconductive sample.

In our measurements the tungsten transition is more precise because it is sharp and at a lower temperature. The scatter in the data of the sample outside the cell is possibly due to lack of thermal equilibrium between the sample and the thermometers. The beryllium transition occurred in a temperature interval of about 0.5 mK, but the width of the main part of the transition was less than 0.1 mK.

The values derived from the beryllium data agree with the Helsinki results T_c = 1.04 mK, whereas the data from tungsten inside and outside the cell differ from this result by 4.5% and 2%, respectively. Because the source of this discrepancy is not clear, we chose to take an average of the last column in Table I, giving equal weight to all of the samples. In this manner we find T_c = 1.025 ± 0.02 mK for the superfluid transition temperature of ^{3}He at zero pressure on the NBS scale. The difference from the Helsinki value is 1.4%, i.e., of the same order as the error limits of this experiment.

In summary we find that the Helsinki scale, with T_c = 1.04 mK, agrees well with the NBS scale. This implies that the Korringa constant for our platinum sample, K = 29.9 ms K, on which the Helsinki scale is based, is quite correct. The consistency of the two scales demonstrates that an accurate temperature scale in the millikelvin region can be established by using the nuclear Curie susceptibility of platinum, with the superfluid transition temperature of ^{3}He employed as a fixed point. Our results also clearly show that the heat capacity data of Alvesalo *et al.*[1] do not suffer from significant errors traceable to the Helsinki temperature scale.

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