Low-Temperature Thermometry

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Abstract

There are so many different temperature-measuring devices available to present-day thermometry that their very enumeration is difficult. Here review is given on some of the methods of measuring low temperature in Condensed Matter Physics. In order to provide a coherent discussion of many of these types of thermometers within a limited space, we categorize these thermometers according to the physical principles upon which their operation relies. Although we mention many different types of thermometers, our discussion will be more thorough, the more precise the thermometer.

Low-temperature thermometry is the measurement of temperature below 0°C (32°F). A variety of techniques and designs are used in instruments known as thermometers. Some of these depend on the expansion of a liquid or metal for the indicating means. Others employ the change in pressure of a gas to detect the temperature. Still others use the change in electrical resistance which occurs with temperature changes. Examples of these practical thermometers used at low-temperature include wide varieties of resistance thermometers (employing pure metals like platinum and rhodium-iron, or semiconductors, the latter including carbon thermometers, germanium thermometers, and thermistors), themoelectric thermometers (thermocouples), liquid-in-glass thermometers, vapor-pressure thermometers, and magnetic thermometers. But very few thermometers are truly wide-range, and hence most of the conventional methods of thermometry tend to fail the further the temperature drops below room temperature.

1 Resistance thermometers

In this type of thermometers the change in resistance of conductors or semiconductors with temperature change is used to measure temperature. Usually, the temperature-sensitive resistance element is incorporated in a bridge network which has a reasonably constant power supply. Although a deflection circuit is occasionally used, almost all instruments of this class use a null-balance system, in which the resistance change is balanced and measured by adjusting al least one other resistance in the bridge. All of the resistors in the bridge, except the measuring resistance, have low temperature coefficients, and the entire bridge circuit is designed to be insensitive to ambient temperature effects.

Metals commonly used as the sensitive element in resistance thermometers are platinum, nickel, and copper. These are the most satisfactory metals, since they are stable, have a reasonable temperature coefficient of resistance, and can be drawn into fine homogeneous wires with a high resistance per unit length. With calibrated industrial-grade resistance thermometers the uncertainty in temperature values may be about ±0.5°F (±0.3°C), while with a good, well-calibrated, and well-maintained laboratory instrument the uncertainty may be in the range of ±0.02°F (±0.01°C).

The defining instrument for the lower regions, the platinum resistance thermometer, rapidly loses sensitivity below 30 K, and its official limit is set at 13.81 K, the triple point of equilibrium hydrogen. Nickel and copper wire elements can be used satisfactory down to −150°C and −200°C, respectively. The Fig. 1 shows how the resistance varies with temperature for platinum.

As at room temperature and above, resistance thermometers tend to be accorded highest favor as far as practicality is conserved, but very few types having adequate sensitivity exist. Doped germanium semiconductors and carbon resistors are much in use down to temperatures as low as a few milikelvins, the germanium being somewhat more reproducible, if much more costly. A normally resistive rhodium-iron alloy (0.5% Fe) is also useful for the region above 0.1 K (and up to 300°C).

2 Thermistors

The device is made of a solid semiconductor with a high temperature coefficient of resistance. The thermistor has a high resistance, in comparison with metallic resistors, and is

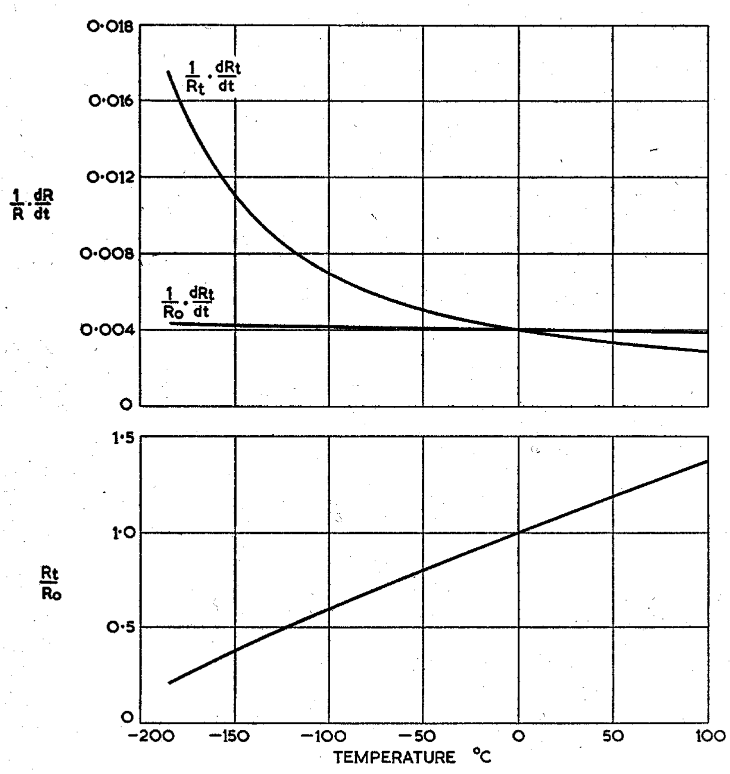

Figure 1: *Resistance temperature curves for platinum*

used as one element in a resistance bridge. Since thermistors are more sensitive to temperature changes than metallic resistors, accurate readings of a small changes are possible. Thermistors are not as stable as metallic resistances, but certain compositions with good protection and care may change less than 1% per year.

3 Liquid-in-glass thermometers

This thermometer consists of a liquid-filled glass bulb and a connecting partially filled capillary tube. When the temperature of the thermometer increases, the differential expansion between the glass and the liquid causes the liquid to rise in the capillary. A variety of liquids, such as mercury, alcohol, toluene, and pentane, and a number of different glasses are used in thermometer construction, so that various designs cover diverse ranges. Liquid-in-glass thermometers may be used down to about $-439°$C or $-38°$F (mercury), about $-100°$C or $-148°$F (ethyl alcohol), and almost down to 70 K with various organic fluids. A liquid becomes sluggish at the lower end of its range, and also, with the exception of mercury, it presents problems of wetting the capillary wall and draining.

4 Thermocouples

A device in which the temperature difference between the ends of a pair of dissimilar metals wires is deduced from a measurement of the difference in the thermoelectric potentials developed along the wires. The presence of a temperature gradient in a metal or alloy

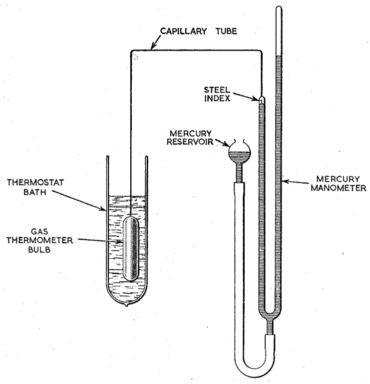

Figure 2: *Essentials of a gas thermometer*

leads to an electric potential gradient being set up along the temperature gradient. This thermoelectric potential gradient is proportional to the temperature gradient and varies from metal to metal. It is the fact that the thermoelectric emf is different in different metals and alloys for the same temperature gradient that allows the effect to be used for the measurement of temperature. For very low temperatures, below −420°F (−250°C or 20 K), thermocouples made from copper-nickel and gold-iron alloys have been developed. These make use of the Kondo effect and give useful thermoelectric emfs down to 1 K (−48°F or −272°C).

5 Gas thermometers

This devices use gas as the thermometric fluid. It is most accurate means available for determining thermodynamic temperature down to 2 K, but it is an exacting and time-consuming technique, and is usually reserved for those programs in which thermometry is the subject of the research. The values of temperature are derived from the pressure-volume-temperature relationship of a gas expressed by its equation of state,

$$pV = n[RT + Bp + O(p^2)] \tag{1}$$

where p is the pressure, V the volume, n the number of moles of gas, R the molar gas constant, T the temperature, and B the second virial coefficient; $O(p^2)$ represents terms of second and higher order in p. In the idealized constant-volume thermometer a fixed mass of perfect gas is confined in a bulb of invariant volume. It is connected by a tube of negligible volume to a manometer of negligible volume to allow the pressures p and p_0 to be measured when the bulb is thermostated at corresponding temperatures of T and T_0. The equation for an idealized constant-volume gas thermometer is obtained by equating numbers of moles n: $p/p0 = T/T_0$. Hydrogen and helium are the gases commonly used, the former covering the temperature range from ambient or higher down to about 20 K, the latter down to 4 K, if the pressure in the thermometer, at 0°C, p_0, is 1000 mm of mercury. The essential components of a constant-volume thermometer are shown in Fig. 2.

6 Vapor-pressure thermal systems

This filled-system thermometer utilizes the vapor pressure of certain stable liquids to measure temperature. A nonlinear relationship exists between the temperature and the vapor pressure, so the motion of the bourdon tube is greater at the upper end of the vapor-pressure curve. The greatest advantage of the filled-system thermometer is its ability to provide a good, low-cost, temperature indication or record at a convenient point reasonable remote (up to 200 ft or 60 m) from the temperature being measured.

In the liquid cryogen region, the saturation vapor pressure is used as a convenient and sensitive indicator of temperature. The usable range from 10 Pa pressure, for example, up to the critical point for the "permanently" liquid helium corresponds to a temperature range from 0.45 to 3.32 K (at 1.15 atm or 116.5 kPa) for ^{3}He and 0.95 to 5.20 K (at 2.26 atm or 229.0 kPa) for ^{4}He. The method is also quite commonly used for equilibrium hydrogen between the triple point and the normal boiling point or above, but not much in modern times for liquid nitrogen (triple point of 63.15 K, normal boiling point of 77.35 K).

7 Magnetic thermometers

The region below 1 K is special, not only because quantum phenomena are present on a macroscopic scale, but also because of the intrusion of a thermodynamic uncertainty principle: the small heat capacities of many systems studied preclude measurement techniques which gratuitously introduce energy and modify the state of the subject. In addition, relaxation times are long, and a system, once perturbed, may take much time to return to a state of equilibrium. Thus it is difficult to find an accurate, reproducible, and "well-behaved" thermometer that is very sensitive, small, and of low heat capacity.

Below 1 K (-458°F), the traditional method for measuring temperature has been that of magnetic thermometry, wherein the susceptibility C of paramagnetic salts which closely obey the Curie law, $C \propto T$, is utilized. By measuring the magnetization M in a constant polarizing field H, the absolute temperature T can be determined if the thermometer constant C is known from a calibration with some other thermometer. The magnetic moments in the thermometric material may be of either electronic or nuclear origin. A sample is calibrated at a known temperature in the 1–4 K region, and then, for lower temperature, a "magnetic temperature" $T^\star$ is extracted from inversion of Curie's law. The relation between magnetic temperatures and the absolute temperature is shown by the curves in Fig. 3. In the temperature region 1 mK to 1 K, the material is preferably an electronic paramagnet, typically a non-conducting rare-earth salt such as cerium magnesium nitrate. Enhanced detection sensitivity is available through superconducting quantum interference device (SQUID) technology, so that very much smaller sensors can be employed, always an important advantage for low-temperature research.

The much weaker nuclear paramagnets are used for thermometry only in the ultra low temperature regions. The nuclear thermometer loses adequate sensitivity for calibration purposes above 50–100 mK unless it is operated in a high polarizing field (H greater than 0.1 Tesla). Nuclear paramagnetism is most convenient monitored with nuclear magnetic resonance techniques.

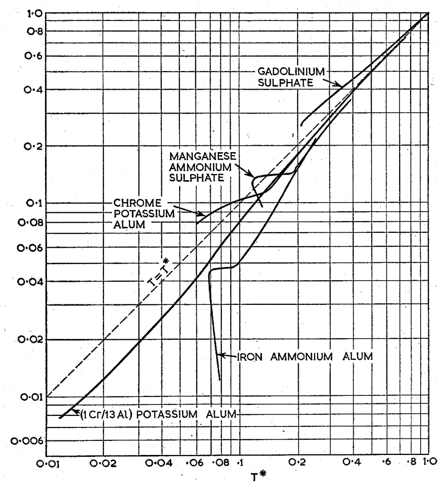

Figure 3: *The relation between magnetic temperatures and the absolute temperature*

8 Other thermometers

Although primary in principle, the ^{3}He melting-curve thermometer seems to deliver the highest accuracy as a secondary instrument, making use of a pressure-temperature relation obtained by temperature calibration. It is used over the range 1 mK to 1 K and offers very high precision (better than 1 mK at the low-temperature end).

The electronic thermometer based upon the thermal expansion of a quartz frequency-controlling element may be used down to −40°C (−40°F).

The least practical thermometer, perhaps, is the acoustic thermometer, which uses the property that, extrapolated to zero pressure, the speed of sound in a gas is proportional to $T^{\frac{1}{2}}$. This has been used in the range 2–20 K as an alternative to, and check upon, the gas thermometer. The Johnson noise in a resistor can be used with particular advantage at low temperature when allied with SQUID detector technology. This yields a value of temperature through a restricted form of the Nyquist relation $P(t) = 4kTR\omega_f$, where $P(t)$ is the mean noise power (averaged over infinite time, to be rigorous), R the resistance, k the Boltzmann constant, and ω_f the frequency bandwidth.

In suitable system it is possible to spatially orient atomic nuclei at very low temperatures, and if these nuclei are emitters of gamma rays, the emission pattern is anisotropic to a degree which is a measure of the thermodynamic temperature.

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