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Introduction

The importance of temperature is very often not fully recognized, the reason probably being that our life is restricted to an extremely narrow range of temperatures. This can be realized if we look at the temperatures existing in nature or accessible in laboratories (Fig. 1.1). These temperatures range from about 10^9 K, the temperature at the center of the hottest stars and necessary to form or destroy atomic nuclei, to 2×10^{-6} K, the lowest temperatures

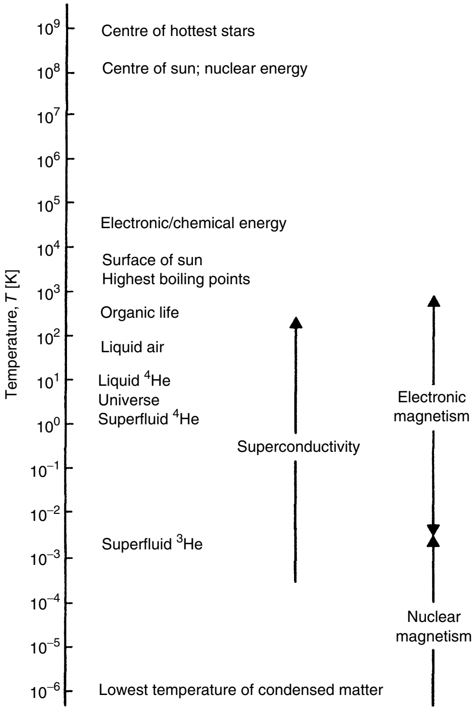

Fig. 1.1. Logarithmic temperature scale with some characteristic phenomena

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accessible today in the laboratory in condensed matter physics experiments. This lower limit means that we have been able to refrigerate condensed matter to within two microkelvin of absolute zero (0 K = −273.15°C). Indeed, nuclei have been investigated at nuclear-spin temperatures which are another four orders of magnitude lower, to below the nanokelvin temperature range. The nanokelvin temperature range has also been reached for magneto-optically trapped and laser as well as evaporatively cooled highly dilute gases. With these achievements, low-temperature physics has surpassed nature by several orders of magnitude, because the lowest temperature in nature and in the universe is 2.73 K. This background temperature exists everywhere in the universe because of the photon energy which is still being radiated from the "big bang". If we compare low-temperature physics to other branches of physics, we realize that it is actually one of the very few branches of science where mankind has surpassed nature, an achievement which has not yet proved possible, for example, in high-pressure physics, high-energy physics or vacuum physics. The very wide range of temperatures accessible to experiments has made temperature probably the most important among the parameters which we can vary in the laboratory in order to change the properties of matter, to obtain a better understanding of its behavior and to make practical use of it.

The historical development of refrigeration to lower and lower temperatures is illustrated in Fig. 1.2. Air, N_2 and O_2 were liquefied and eventually

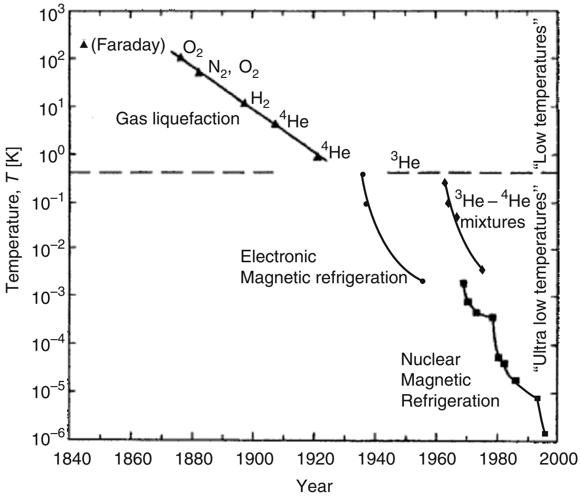

Fig. 1.2. Historical development of refrigeration temperatures of condensed matter, starting about 160 years ago with Faraday's gas liquefaction. The low temperature range was made accessible by liquid air, liquid H_2 and liquid ^{4}He (▲). Ultralow temperatures were attained by magnetic refrigeration with electronic magnetic moments (●) and later with nuclear magnetic moments (■). Refrigeration with liquid ^{3}He and liquid ^{3}He–^{4} He mixtures (◆) developed as the rare helium isotope became available in sufficient quantities

solidified 1883 in Cracow by Z. Wroblewski and K. Olszewski. This was the first time that mankind reached temperatures below 100 K. The scientists and engineers involved in this venture had two aims. A very practical one was to devise a means of refrigerating meat for its journey from other continents to Europe. The scientific aim was to discover whether permanent gases exist, in other words, are there any substances which do not exist in the liquid and/or solid state? This latter aim led to the liquefaction and solidification of hydrogen by James Dewar in 1898; he reached temperatures of 20 K and later 13 K. At about that time the last gaseous element to be discovered, helium, was detected first in spectroscopic investigations of solar protuberances and then as a gas escaping from various minerals on earth. The Dutch scientist Heike Kamerlingh Onnes won the race to liquefy this last element; he liquefied helium-4 at 4.2 K in 1908. Kamerlingh Onnes' work opened up the Kelvin temperature range to science, and scientists at his low-temperature laboratory at the University of Leiden dominated low-temperature physics for at least 20 years, making many fundamental investigations in helium physics, in the physics of metals and in the physics of magnetism, for example. In particular, he discovered superconductivity of metals by refrigerating Hg to 4.2 K in 1911, and in the early 1920s he found some unexpected behavior in the properties of liquid ^{4}He, which later turned out to result from its superfluid transition at 2.2 K. Today Kamerlingh Onnes is considered "the father of low-temperature physics". The gradual introduction of low-temperature physics to hundreds of research laboratories was eventually made possible by the development of commercial ^{4}He liquifiers with counter-flow heat exchangers and Joule-Thompson expansion or/and expansion engines by S.C. Collins after World War II. In the last decade, the style of low-temperature experimentation has again seen a quite substantial change from building most of the equipment at home toward purchasing most of the equipment, like cryostats, closed-cycle refrigerators, ^{3}He-^{4}He dilution refrigerators, magnetometers, SQUID amplifiers, resistance and capacitance bridges, etc. Hence, I have added a list of suppliers of cryogenic equipment.

In 1922, H. Kamerlingh Onnes reached 0.83 K by pumping on the vapour above a bath of boiling ^{4}He; this temperature record was lowered to 0.71 K in 1932 by his successor W.H. Keesom. Because at these temperatures the vapour pressure of ^{4}He becomes extremely small, the development of a fundamentally different technology, magnetic refrigeration, was necessary to attain temperatures appreciably below 1 K. By adiabatic demagnetization of paramagnetic salts, a method proposed in the late 1920s, we can approach absolute zero to within a few millikelvin (Fig. 1.2). An advanced version of this magnetic refrigeration method, adiabatic demagnetization of *nuclear* magnetic moments, is the only method known today by which we can reach temperatures far into the microkelvin temperature range. While these "one-shot" magnetic cooling methods were being perfected, another refrigeration technique, again based on the properties of liquid helium, the dilution of the rare isotope ^{3}He by the common isotope ^{4}He, enabled the development of a continuous refrigeration method to reach the low millikelvin temperature range. This method was proposed in the 1960s and put into practice in the early 1970s. Today it is very well developed and has probably approached its limits; it has largely replaced adiabatic demagnetization of paramagnetic salts. Therefore, I shall discuss dilution refrigeration at length and devote only a short chapter to electronic paramagnetic refrigeration. Nuclear magnetic refrigeration – the refrigeration method for the microkelvin temperature range – will, of course, be discussed in detail. I shall also briefly describe two additional refrigeration methods based on the properties of ^{3}He even though they are of minor importance today: refrigeration by evaporation of liquid ^{3}He and refrigeration by solidification of liquid ^{3}He (Pomeranchuk cooling).

As a result of these developments, three refrigeration methods dominate low-temperature physics today (Table 1.1). Temperatures in the Kelvin range down to about 1 K are obtained by evaporation of liquid ^{4}He, the evaporation of pure ^{3}He for cooling is now only of minor importance. The millikelvin temperature range is completely dominated by the ^{3}He–^{4}He dilution refrigeration method, which in a simple apparatus can reach minimum temperatures of about 20 mK and in a more complicated apparatus 5 mK; the present record is about 2 mK. The other two millikelvin refrigeration methods, Pomeranchuk cooling and adiabatic demagnetization of electronic magnetic moments, are of minor importance today. Finally, in the microkelvin temperature range, we have only one method, nuclear adiabatic demagnetization. This method has opened up the microkelvin temperature range (with a present minimum of 1.5 μK) to condensed-matter physics, and the nanokelvin temperature range to nuclear-spin physics. At these extremely low temperatures it makes sense, as we will see, to distinguish between a temperature of the nuclear magnetic spin system and a temperature of the electrons and of lattice vibrations. When

Table 1.1. Refrigeration techniques. The methods which dominate in the three temperature ranges are in italics

Temperature range		Refrigeration technique	Available since	Typical T_{min}	Record T_{min}
I	Kelvin	Universe			2.73 K
		Helium-4 evaporation	1908	1.3 K	0.7 K
		Helium-3 evaporation	1950	0.3 K	0.23 K
II	Millikelvin	**^{3}He–^{4}He dilution**	1965	10 mK	2 mK
		Pomeranchuk cooling	1965	3 mK	2 mK
		Electronic magnetic refrigeration	1934	3 mK	1 mK
III	Microkelvin	**Nuclear magnetic refrigeration**	1956	100 μK	1.5 μK[a]

[a] The given minimum temperature for the microkelvin temperature range is the *lattice* (*electronic*) *equilibrium* temperature. *Nuclear spin* temperatures as low as 0.3 nK have been reached (Table 10.2)

I speak about “temperature” in this textbook, I always mean the latter, unless I explicitly state otherwise.

Low-temperature physics and technology are not possible without knowledge of the relevant properties of liquid and solid matter at low temperatures. And many fundamental properties of matter were only found and/or understood after matter had been cooled to the Kelvin range or to even lower temperatures. Among these properties are the quantization of lattice vibrations (phonons), the electronic excitations leading to the linear temperature dependence of the specific heat of conduction electrons, superconductivity, superfluidity and many aspects of magnetism. Hence, this textbook begins with chapters on the properties of liquid and solid matter at low temperatures relevant for the performance and design of low-temperature experiments. But even though a major part of the book will deal with solid-state physics, it is not intended to replace more general textbooks on this subject. Indeed, readers are assumed to have a basic knowledge of condensed-matter physics as found in [1.1–1.6], for example. I have included extensive information on materials properties at low temperatures and how to measure them.

Experiments at low temperatures make no sense without thermometry. In fact, the measurement of a low or very low temperature and its relation to the thermodynamic temperature scale are as important as the attainment of that temperature itself, and very often just as difficult. This has become increasingly apparent in the last decades as lower and lower temperatures have been reached. Hence, after discussion of the various refrigeration techniques, I shall discuss temperature scales and the various thermometric methods at low temperatures. The book closes with a chapter on various “cryogenic devices and design aids”, a discussion of various tools and tricks helpful for low-temperature investigations, as well as some comments on low-temperature electronics.

There are several excellent books on the properties of matter at low temperatures [1.5, 1.6] and on the technology of cryogenics above about 1 K [1.7, 1.8] and below 1 K [1.9–1.12]. The reader should consult them for subjects not included or not discussed in detail in this book; for example, the SQUID and its various applications in low-temperature experiments, for which the relevant literature can be found in Chap. 14. The two most comprehensive monographs [1.9, 1.10] on the subject of this book were published in 1974 and 1976, respectively, but the field of experimental physics at milli- and microkelvin temperatures has been rapidly expanding since then, and therefore a new monograph devoted to this field seemed to be very appropriate. The first two editions of this textbook were written in the years 1991 and 1995, respectively. Its new edition reflects the state of the art of experimental low-temperature physics at the current time, i.e., in 2006. Endeavours in low-temperature physics and technology have been rewarded by a great number of fundamental discoveries that are important for our understanding of matter, in particular of its quantum behavior, and for practical applications. These achievements were only possible by overcoming substantial experimental difficulties, in particular when the range below 1 K was entered, and the (slightly modified) statement from the first page of Lounasmaa's book [1.9] provides a good summary of the essentials:

> An experimentalist wishing to pursue research at low temperatures faces four technical difficulties: how to reach the low temperature, how to measure it, how to reduce the external heat leak so that the low temperature can be maintained for a sufficiently long time, and how to transfer cold from one place to another. Many experimental methods have been developed to provide a satisfactory solution to these problems.

The progress in these areas will be discussed in the present book. I shall restrict the discussion of the properties of matter and experimental techniques mostly to temperatures below about 10 K. Higher temperatures will only be considered if we need them in order to understand what is going on at temperatures of interest in this book. Therefore, some properties of materials are given for temperatures up to 300 K.

References are made preferentially to books or to review articles. Original publications are cited when I consider them necessary for obtaining more details than can be given in a monograph. In many instances I cite not according to priority but to pertinence for the purpose of this book. Since more than a decade has passed since I had worked on the preceding edition of this book, I had to add about 250 new references. I will use cgs and/or SI units, whatever seems appropriate and as is typical for practical work in today's low-temperature laboratories. Equations – as for specific heat or susceptibility – are given for one mole.