Chapter 1
Introduction

Abstract Quantum fluids have emerged from scientific efforts to cool matter to colder and colder temperatures, representing staging posts towards absolute zero (Figure 1.1). They have contributed to our understanding of the quantum world, and still captivate and intrigue scientists with their bizarre properties. Here we summarize the background of the two main quantum fluids to date, superfluid helium and atomic Bose-Einstein condensates.

1.1 Towards absolute zero

The nature of cold has intrigued humankind. Its explanation as a primordial substance, *primum frigidum*, prevailed from the ancient Greeks until Robert Boyle pioneered the scientific study of the cold in the mid 1600s. Decrying the "almost totally neglect" of the nature of cold, he set about hundreds of

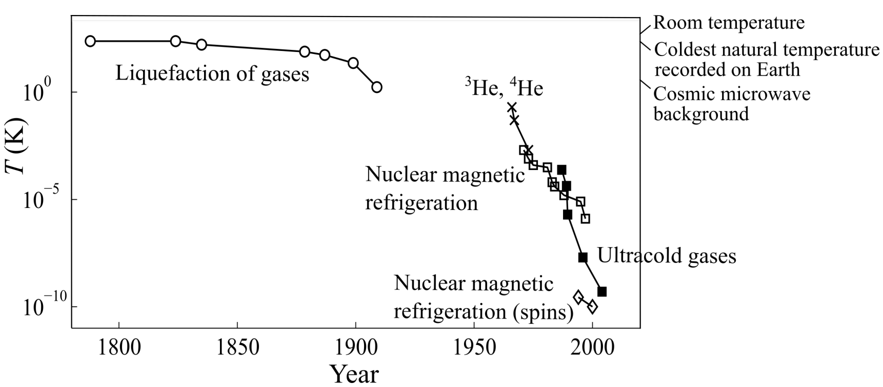

Fig. 1.1 Timeline of the coldest engineered temperatures, along with some reference temperatures.

experiments which systematically disproved the ancient myths and seeded our modern understanding. While working on an air-based thermometer in 1703, French physicist Guillaume Amontons observed that air pressure was proportional to temperature; extrapolating towards zero pressure led him to predict an "absolute zero" of approximately -240 °C in today's units, not far from the modern value of -273.15 °C (or 0 K). The implication was profound: the realm of the cold was much vaster than anyone had dared believe. An entertaining account of low temperature exploration is given by Ref. [1].

The liquefaction of the natural gases became the staging posts as low temperature physicists, with increasingly complex apparatuses, raced to explore the undiscovered territories of the "map of frigor". Chlorine was liquefied at 239 K in 1823, and oxygen and nitrogen at $T = 90$ K and 77 K, respectively, in 1877. In 1898 the English physicist James Dewar liquefied what was believed to be the only remaining elementary gas, hydrogen, at 23 K, helped by his invention of the vacuum flask. Concurrently, however, chemists discovered helium on Earth. Although helium is the second most common element in the Universe and known to exist in the Sun, its presence on Earth is tiny. With helium's even lower boiling point, a new race was on. A dramatic series of lab explosions and a lack of helium supplies meant that Dewar's main competitor, Heike Kamerlingh Onnes, pipped him to the post, liquifying helium at 4 K in 1908. This momentous achievement led to Onnes being awarded the 1913 Nobel Prize in Physics.

1.1.1 Discovery of superconductivity and superfluidity

These advances enabled scientists to probe the fundamental behaviour of materials at the depths of cold. Electricity was widely expected to grind to a halt in this limit. Using liquid helium to cool mercury, Onnes instead observed its resistance to simply vanish below 4 K. *Superconductivity*, the flow of electrical current without resistance, has since been observed in many materials, at up to 130 K, and has found applications in medical MRI scanners, particle accelerators and levitating "maglev" trains.

Onnes and his co-workers also observed unusual behaviour in liquid helium itself. At around 2.2K its heat capacity undergoes a discontinuous change, termed the "lambda" transition due to the shape of the curve. Since such behaviour is characteristic of a phase change, the idea developed that liquid helium existed in two phases: helium I for $T > T_\lambda$ and helium II for $T < T_\lambda$, where T_λ is the critical temperature. Later experiments revealed helium II to have unusual properties, such as it remaining a liquid even as absolute zero is approached, the ability to move through extremely tiny pores and the reluctance to boil. These two liquid phases, and the fact that helium remains liquid down to $T \to 0$ (at atmospheric pressure), mean that the phase diagram of helium (Figure 1.2) is very different to a conventional liquid (inset).