is now called Bose–Einstein condensation.

In late 1930's, it was discovered that liquid ^{4}He becomes a **superfluid** when cooled below about 2.2 K. Superfluidity is a quantum-mechanical state of matter with very unusual properties, such as the ability to flow through very small capillaries with no measurable viscosity. Speculation arose as to whether this state of matter was connected with Bose–Einstein condensation.

Example 30.9

Estimate the Bose–Einstein condensation temperature for liquid ^{4}He, given that $m_{\mathrm{He}} \approx 4m_{\mathrm{p}}$ and that the density $\rho \approx 145\,\mathrm{kg\,m^{-3}}$.

Solution:

Using $n = \rho/m$, eqn 30.53 yields $T_{\mathrm{c}} \approx 3.1\,\mathrm{K}$ which is remarkably close to the experimental value of the superfluid transition temperature.

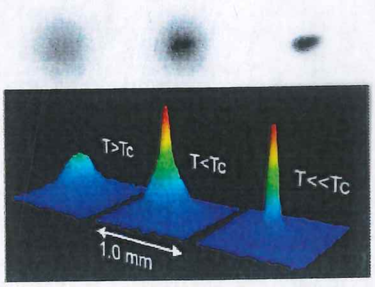

Fig. 30.6 Observation of Bose–Einstein condensation by absorption imaging. The data are shown as shadow pictures (upper panel) and as a three-dimensional plot (lower panel); the blackness of the shadow in the upper panel is here represented by height in the lower panel. These pictures measure the slow expansion of the trapped atoms observed after a 0.006 s time of flight, and thus measure the momentum distribution inside the cloud. The left-hand picture shows an expanding cloud cooled to just above the transition point. In the right-hand picture we see the velocity distribution well below T_{C} where almost all the atoms are condensed into the zero-velocity peak. (Image courtesy W. Ketterle.)

Despite the agreement between this estimate and the experimental value, things are a bit more complicated. The particle density of ^{4}He is very high and interactions between helium atoms cannot be ignored; ^{4}He is a strongly interacting Bose gas, and therefore the predictions of the theory outlined in this chapter have to be modified.

A more suitable example of Bose–Einstein condensation is provided by the very dilute gases of alkali metal atoms[9] that can be prepared inside magnetic ion traps. The atoms, usually about 10^4–10^6 of them, can be trapped and cooled using the newly developed techniques of laser cooling. These alkali atoms have a single electronic spin due to their one valence electron and this can couple with the non-zero nuclear spin. Each atom therefore has a magnetic moment and thus can be trapped inside local minima of magnetic field. The density of these **ultracold atomic gases** inside the traps are very low, more than seven orders of magnitude lower than that in ^{4}He, though their masses are higher. The Bose–Einstein condensation temperature is therefore also very low, typically 10^{-8}–10^{-6} K, but these temperatures can be reached using laser cooling. The low density precludes significant three-body collisions (in which two atoms bind with the third taking away the excess kinetic energy, thus causing clustering), but two-body collisions do occur which allow the cloud of atoms to thermalize. Example data are shown in Fig. 30.6 from one such experiment which clearly show that below a critical temperature Bose–Einstein condensation is taking place.[10]

Superfluidity is also found in these ultracold atomic gases; it turns out that the very weak interactions that exist between the alkali atoms are important for this to occur (a non-interacting Bose gas does not show superfluidity). Other experiments have explored the intriguing consequences of **macroscopic quantum coherence**, the property that in the condensed state all the atoms exist in a coherent quantum superposition.

[9] Alkali atoms are in Group I of the periodic table and include Li, Na, K, Rb and Cs.

[10] The 2001 Nobel Prize was awarded to Eric Cornell and Carl Wieman (who did the experiment with rubidium atoms) and to Wolfgang Ketterle (who did it with sodium atoms).