1. **Our student Clara asked, “How are temperatures close to absolute zero achieved and measured?”**
2. **“And how can liquid helium be made?”**

2. First the explanation to how liquid helium can be made----similar to the method to liquefying air:

To liquefy air, the most used industrial process are the Hampson-Linde cycle or the Siemens cycle. The first is efficient at low T only, while the second at higher T too. The Hampson-Linde cycle is based on the Joule-Thompson effect that is the ability of nearly all gases to cool down if expanded in a hollow chamber.

The gas starts from an initial temperature T_o and it is compressed in A. This causes an increase of its T, at first; hence, this gas is send in heat exchanger B where it’s cooled at the same high P and then into an expansion chamber E where it suddenly cools down at $T_1 < T_o$, after a drastic reduction of its P.

The cooled gas is made pass into a heat exchanger H where it cools down the gas flow directed from B to the expansion chamber E (so, absorbing a limited amount of heat from this flow) and it comes back in A where it’s compressed again, in B where its cooled and in E to be expanded a second time, reaching a $T_2 < T_1$.

The cycle is repeated several times with a progressive cooling of the air until, at Teb < T2, air begins to liquefy and it can be collected on the bottom of E.

The Siemens process is very similar, except for the presence of an expansion-machine in E where heat is extracted from the gas while this does an expansion work.

then

1)Wolfgang Ketterle of the Massachusetts Institute of Technology, who won the Nobel Prize in Physics for his work with ultracold atoms, explains.

First, let me introduce the scientific meaning of temperature: it is a measure of the energy content of matter. When air is hot, the molecules move fast and they have high kinetic energy. The colder the molecules are, the smaller their velocities are and, subsequently, their energy. Temperature is simply a way to characterize the energy of a system.

Temperature can be measured in different units. In everyday life the Celsius and Fahrenheit scales are common, but they both lack the natural property that the zero of the temperature scale should correspond to zero velocity of the gas particles (that is, zero energy). Thus the natural temperature scale is the absolute temperature measured in Kelvin. Zero kelvin is the lowest possible temperature. At absolute zero, all motion comes to a standstill. It is obvious that a lower temperature is not feasible because there is no velocity smaller than zero and no energy content less than nothing. (As a side remark, energy in this instance means only the energy that can be taken away from the particles and does not include the rest mass or quantum mechanical zero-point energies for confined particles.) Absolute zero corresponds to –273 degrees Celsius and –460 degrees Fahrenheit.

Cooling an object requires extracting energy from it and depositing it somewhere else. In household refrigerators, for example, the heat exchanger at the back gets warm because the energy extracted from the objects inside is deposited there. (In addition, there is some heat created just from running the refrigerator.)

In the 1980s and 1990s new methods for cooling atomic gases were developed: laser cooling and evaporative cooling. By combining these methods, temperatures below one nanokelvin (one billionth of a degree Kelvin) have been achieved. The lowest temperature recorded so far, described in a publication from our group in the September 12, 2003 issue of *Science,* is 450 picokelvins, which beat the previous record holder by a factor of six. Two recent Nobel prizes (in 1997 and 2001) were awarded for these developments.

In laser cooling, atoms scatter laser light. An incoming laser photon is absorbed and then reemitted in a different direction. On average, the color of the scattered photon is slightly shifted to the blue relative to the laser light. That is, a scattered photon has a slightly higher energy than an absorbed photon did. Because total energy is conserved, the difference in photon energy is extracted from the atomic motion--the atoms slow down. Shifts in wavelength can occur because of the Doppler effect (which is a shift proportional to the atomic velocity) or because of Stark shifts (due to the electric field of the laser beams) and offers one explanation of how the atoms lose energy.

A second description emphasizes how momentum is transferred to the atoms. If atoms are exposed to several laser beams with carefully chosen polarization and frequency values, then they preferentially absorb photons from the forward hemisphere, where the photon angular momentum and the atomic velocity are at an angle larger than 90 degrees. The photon momentum has a component that is opposite to the atomic motion and, as a result, the momentum kick of the absorbed photon slows the atom down. The subsequent emission of a photon occurs at random angles and as a result, averaged over several absorption-emission cycles, there is no momentum transferred due to the photon emission. The crucial step is making the atoms absorb photons preferentially from the forward direction and is achieved by utilizing the Doppler shift. When the photon momentum and the atomic velocity are at an angle larger than 90 degrees, the atom and the light are counterpropagating and the Doppler shift is an upward shift in frequency. When the laser light is detuned to the red of the atomic resonance, the Doppler shift brings the light closer into resonance and enhances the light absorption. For light coming from the backward direction, for which the angle between the photon momentum and the atomic velocity is smaller than 90 degrees, the Doppler shift is opposite and shifts the light even further away from the atomic resonance, decreasing its absorption.

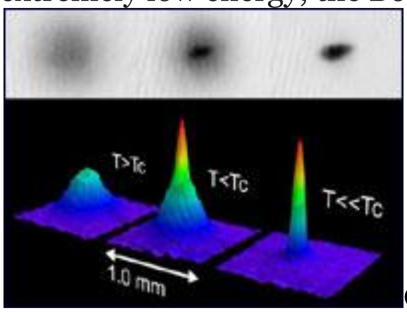
When an atomic cloud becomes denser and colder, the cooling effect described above becomes dominated by other processes, which cause heating. This includes energy release in collisions between atoms, and the random recoil kicks in light scattering, which average to zero, but still result in some trembling motion of the atoms and therefore limit the lowest achievable temperature. At this point, however, the atoms are cold enough that they can be confined by magnetic fields. We choose atomic species that have an unpaired electron and therefore a magnetic moment. As a result, these atoms behave like little bar magnets. External magnetic fields exert forces on them, levitate them against gravity and keep them together; the atoms are trapped in a magnetic cage with invisible walls formed by magnetic fields.

Further cooling is done by evaporative cooling, by selective removal of the most energetic atoms from the system. The same process cools a cup of coffee when the most energetic molecules escape as steam, thus lowering the average energy and therefore the temperature of the remaining molecules. In a magnetic trap, the most energetic atoms can move farther against the pull of the magnetic forces, and can therefore reach regions with higher magnetic fields than the colder atoms can. At those high magnetic fields, they get into resonance with radio waves or microwaves, which changes the magnetic moment in such a way that the atoms fly away and escape from the trap. Nice animations of the cooling procedure can be found at
http://www.colorado.edu/physics/2000/bec/temperature.html

How do we measure very low temperatures of atoms? One way is to simply look at the extension of the cloud. The larger the cloud is, the more energetic the atoms must be, because they can move farther against the magnetic forces. This is similar to the atmosphere on Earth, which is about 10 kilometers thick. That is, 10 kilometers is how far atoms at room temperature can move against the gravitational force of our planet. If the temperature of the air were 10 times smaller (which is about 30 K or –240 degrees C), the atmosphere would be only one kilometer thick. At 30 microkelvins, the atmosphere would shrink to a mere millimeter, and at 30 nanokelvins, the height of the atmosphere would be one micron, or a hundred times less than the thickness of the human hair. (Of course, air is not an ideal gas and would have liquified by then.) In our experiments, the atoms are exposed to both magnetic and gravitational forces. In the center of the cloud, the gravitational force is exactly compensated by the magnetic force.

The size of the atomic cloud is determined by illuminating the cloud with laser light, which is strongly absorbed by the atoms, and they cast a shadow. With the help of several lenses, the shadow is imaged onto an electronic sensor similar to those in digital cameras. Because the magnetic fields are precisely known, the size of the cloud is an absolute measure of the atoms' energy and temperature. (More scientifically, the density distribution of the atoms reflects the distribution of potential energy.)

Another method to determine temperature is to measure the kinetic energy of the atoms. For that, the magnetic trap is suddenly switched off by switching off the current running through the magnet coils. In the absence of magnetic forces, the atoms simply fly away, and the cloud expands ballistically. The cloud size increases with time, and this increase is a direct observation of the velocity of the atoms and therefore their temperature. (More technically, an absorption image of an expanding cloud shows the distribution of the kinetic energy in the cloud.) For a fixed time of ballistic expansion, the size of the shadow is a measure of the temperature (temperature is proportional to the square of the size). The achievement of lower and lower temperature is monitored by a shrinking shadow. When Bose-Einstein condensation was discovered in 1995, its hallmark was that the shrinking shadow suddenly showed a dense core of atoms at extremely low energy, the Bose-Einstein condensate (*see image below*).



OBSERVATION OF BOSE-EINSTEIN condensation by absorption imaging. Shown is absorption vs. two spatial dimensions. The top row shows shadow pictures, which, in the lower row, are rendered in a three-dimensional plot where the blackness of the shadow is represented by height. The "sharp peak" is the Bose-Einstein condensate, characterized by its slow expansion observed after 6 msec time of flight. The left picture shows an expanding cloud cooled to just above the transition point; middle: just after the condensate appeared; right: after further evaporative cooling has left an almost pure condensate. The width of the images is 1.0 mm. The total number of atoms at the phase transition is about 700,000 and the temperature at the transition point is 2 microkelvin. *Image: WOLFGANG KETTERLE*