optics & photonics focus

The Coolest Thermometer

Temperature measurements are key in science and technology. Close to absolute zero, however, they are extremely difficult. A new method now allows the measuring of some of the coolest temperatures ever produced.

Physicians measuring their patient's fever, cooks checking if the roast is ready, and drivers worried about icy roads — all of them, and many more, depend on reliable thermometers. Measuring ambient temperatures with limited accuracy is a rather trivial task. Close to absolute zero, however, accurate temperature measurements are still a major challenge. Researchers of the Ketterle-Pritchard group at the Massachusetts Institute of Technology (MIT) in Cambridge MA, USA, have now presented a technique to measure ultra-cold temperatures, which are needed for many quantum physics experiments. The new tool is capable of measuring temperatures in the order of a billionth of a kelvin above absolute zero, holding the promise of taking us a step further in the control of quantum gases.

Intuitively speaking, temperature is a measure of how much the particles constituting an object are moving. For example, in a *classical gas* like air at room temperature particles behave like tiny billiard balls bouncing through space at rather high speeds. The temperature of the gas is proportional to the mean kinetic energy of the particles and a powerful parameter in thermodynamics.

For an ideal classical gas, temperature increase means that the particles are bouncing around more. Consequently, the gas will either expand its volume or its pressure. Interestingly, the same intuitive argument holds for most solids and fluids. For example, steel expands with temperature, which is important to consider for the construction of railway lines. For some materials, expansion with temperature is so uniform over large temperature scales that they are used for building good thermometers. A typical mercury thermometer, for example, simply links the expanding liquid mercury to a temperature scale, allowing one to easily deduce the temperature. Other approaches, such as bimetal thermometers, also rely on the expansion of matter

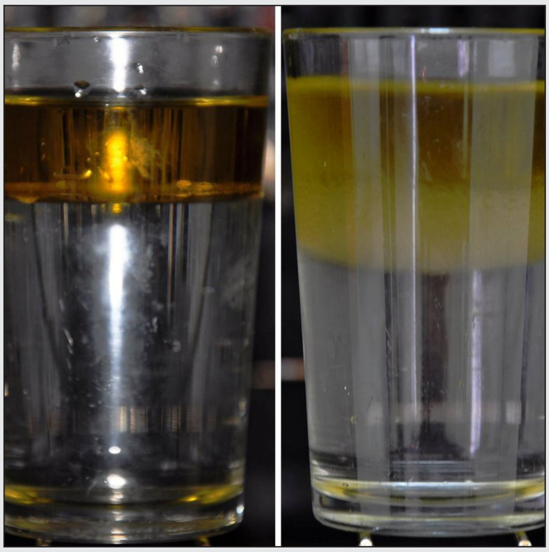

Figure 1: Oil-water Illustration of spin gradient thermometry. At low temperatures, oil and water do not mix and form clearly separated phases with a tiny interface (left). At higher temperatures, the interface region is considerably larger, allowing one to deduce the temperature of the fluids (right).

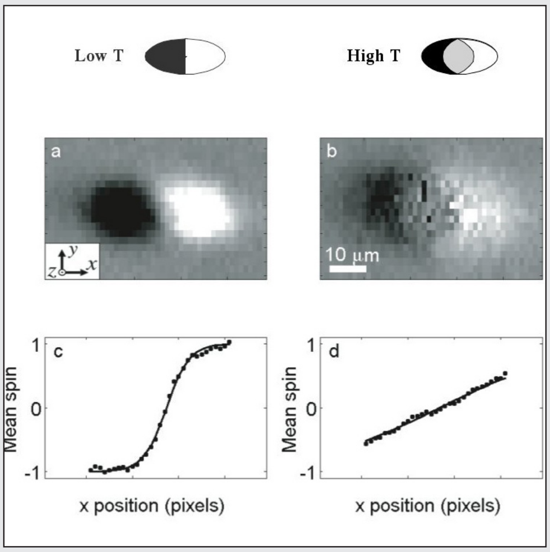

Figure 2: Spin gradient thermometry experiment with Mott insulators. At low temperatures, the two components of the quantum gas — spin up and spin down — are clearly separated (a), whereas they overlap considerably at higher temperatures (b). Image analysis (c,d) allows one to deduce the temperature by comparison to the known, theoretical temperature dependency of the two phases and their interface region.

to indicate the temperature. Such direct ways of measuring temperature have been very successful for many centuries and work with great accuracy in a temperature range from -200°C up to several hundred degrees Celsius.

By their nature, low temperatures are characterized by very small amounts of kinetic energy of the constituting particles. In a classical picture of the world, the absolute zero is, by definition, the temperature at which all particles are at zero motion: -273.15°C, defined as 0K. As it turns out, however, the concepts of classical physics are of little use at such temperatures and matter exhibits an increasing number of unique quantum physical phenomena. Experiments at temperatures of less than a millionth of a degree above absolute zero have to be shielded considerably against heating from the surrounding laboratory in which the experiments are done. Furthermore, measurement accuracy in these regions needs to be far better than the usual 0.1°C or 1°C of an everyday fever thermometer. New technological approaches are therefore needed at such low temperatures.

Current ultra-low temperature measurements typically analyze the expansion of a free atomic cloud, a *quatum gas*. The atomic distribution is compared to the model description of the cloud and thus indicates the experimental temperature. This method works well in a broad range of experimental setups — but as soon as the experiment is performed in an optical lattice, this approach is severely limited. Examples that cause these limitations include the removal of the optical lattice in order to study the free expansion of the cloud, or the difficulty to estimate the many parameters needed for the calculation of the free expansion.

The MIT group has now introduced a new way of measuring ultra-low temperatures of quantum gases that are held in an optical lattice, called *spin-gradient thermometry*. “Our method,” David Weld, member of the MIT group, explains, “can be compared to a receptacle containing two fluids of different density, one on top of the other. The two components we use are almost exactly on the border between miscible and immiscible, which is what allows the applied gradient to control the energy of the domain wall.” In this picture, the gravitational force (gradient) is responsible for the separation of the two fluid phases and the interface between the two fluids depends on the temperatures. One fluid may be thought of as *spin up*, the other as *spin down*. The more the particles of the fluids move, the more they mix. Therefore higher temperatures lead to a larger interface between the two fluids and thus to a different *spin gradient*. Now, one can predict the expected overlap of two components of a quantum gas — ultra-cold rubidium atoms in a Mott Insulating phase in the MIT experiment — and compare it to the observed overlap. A fitting between calculation and observation then indicates the temperature of the quantum gases.

“Ubiquitous phase transitions such as the melting of ice illustrate the fundamental significance of temperature for the macroscopic properties of matter,” Dominik Schneble from Stony Brook University, NY, USA explains. As another example, he points out that ferromagnetism requires temperatures below the so-called Curie temperature. “Magnetic behavior, for sufficiently low temperatures,” he continues, “is also predicted to exist in bulk systems of ultra-cold atoms in optical lattices, which may thus be used to simulate and study fundamental magnetic phenomena in solid-state physics, with ultimate experimental control. However, the observation of magnetism in these systems will require extremely low temperatures in the sub-nanokelvin range, which have not yet been achieved. In the ongoing quest to reach the necessary temperatures experimentally, it is important to have a suitable diagnostic tool for temperature. The thermometer developed by Weld and coworkers provides exactly that.”

In these first experiments, the error bars on the measurements are still rather large: 15-20%. “Even so,” Weld points out, “the thermometer already works in situations where no other thermometer does and can measure extremely low temperatures.” Both Weld and Schneble are therefore intrigued by the potential of this new approach. “Spin-gradient thermometry,” Schneble concludes, “is a powerful, simple and unique diagnostic tool to determine ultralow temperatures in strongly correlated atomic systems, and I think that it will play an important role in the future.”

Armand Niederberger

David M. Weld, Patrick Medley, Hirokazu Miyake, David Hucul, David E. Pritchard, and Wolfgang Ketterle, **Spin Gradient Thermometry for Ultracold Atoms in Optical Lattices**, Physical Review Letters (2009) **103**, 245301.