

and Shawn-Yu Lin at the Watson Research Center embedded a hexagonal area of YBCO film in another YBCO film so that the six faces formed Josephson junctions.¹⁴ If only s-wave were present, the current would flow in the same direction across each face; with d-wave, however, the current would be positive across some faces, negative across others and zero across yet others. Chaudhari and Lin found that the total current across all faces was nonzero and that it decreased monotonically as the links across each face were successively removed, consistent with an s-wave picture. Some observers argue that spontaneous flux might be forming at the corners, confounding the experimental interpretation.¹⁵ Chaudhari and his colleagues have looked for trapped half-integer flux quanta and have found only flux of much lower magnitude, located all over and not just at the corners.

Tests for universality

The majority of the experiments probing the phase of the wavefunction have been done on YBCO. There's no reason why superconductivity has to arise in the same way in other types of copper-

oxide superconductors. So far, however, the experiments that have been repeated on other types support the hope for a universal mechanism governing superconductivity in all these materials. One exception could be neodymium cerium copper oxide, a high-temperature superconductor that is doped with electrons rather than holes; the experiments done to date, which do not include any phase-sensitive measurements, suggest an s-wave state.

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Experimenters Cool Helium below Single-Photon Recoil Limit in Three Dimensions

A group at the Ecole Normale Supérieure in Paris has placed a helium atom in a state that is going in six directions at once—a very confusing state for an atom. In such a superposition state, also called a dark state, the atom can't absorb light because the absorption amplitudes cancel out by destructive interference. The temperature corresponding to the velocity spread of each of the six wavepackets is a factor of 20 below the so-called recoil limit for laser-cooled atoms. The three-dimensional subrecoil experiment in helium was reported in the 4 December issue of *Physical Review Letters* by John Lawall (now at the National Institute of Standards and Technology in Gaithersburg, Maryland), Simone Kulin, Bruno Saubamea, Nick Bigelow, Michèle Leduc and Claude Cohen-Tannoudji.¹

Laser cooling uses momentum exchange between photons and atoms to reduce the velocity of atoms. Suggested independently twenty years ago by Theodor Hänsch and Arthur Schawlow for neutral atoms and by David Wineland and Hans Dehmelt for trapped ions, the manipulation of at-

A helium atom moving in six directions at once can be regarded as a six-legged Schrödinger cat.

oms by light has been an active field ever since. When an atom absorbs a photon from a laser beam with momentum $\hbar k$, where k is the wavenumber, it reemits the photon in a random direction. Repeating this process can bring the atoms almost to rest. However, it appeared to researchers in the first decade of laser cooling that the final momentum spread produced by laser cooling could not be less than $\hbar k$.

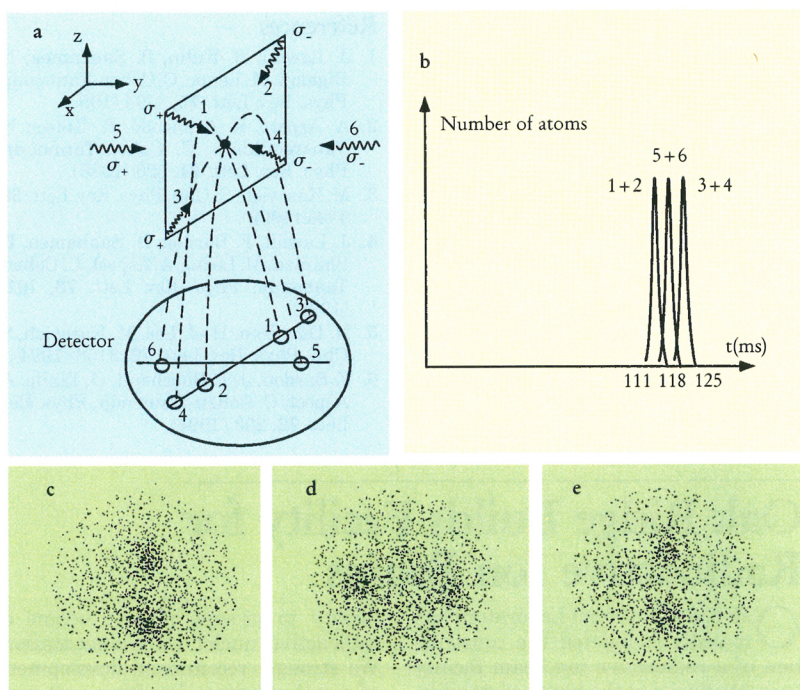
Below the limit in one dimension

In 1988 an Ecole Normale Supérieure group showed² that the single-photon recoil limit could be beaten (see Cohen-Tannoudji and William D. Phillips's article in *PHYSICS TODAY*, October 1990, page 33). As Cohen-Tannoudji recently told me in his lab at Ecole Normale, "You must prevent very cold atoms from absorbing light. Otherwise they recoil and are heated by the recoil. So we use a quantum interference effect that stops the absorption of light."

The experimenters employ a coherent dark state. It is a superposition state of the atom and two oppositely directed, circularly polarized laser beams. The amplitudes for excitation from the two beams interfere destructively and the system can't absorb radiation. For the same reason, however, the laser beams can't stimulate the transition of an atom into the dark state. Nevertheless, an excited atom can fall into the dark state by spontaneous emission, and once in the dark state, the atom simply stays there. This technique is known as velocity-selective coherent population trapping.

For an ensemble of atoms entering the dark state, says Cohen-Tannoudji, "You can predict that the lowest temperature you get varies inversely proportionally to the interaction time. There is no fundamental limit. You can go as low as you want, provided you have a long time."

In 1988 the Ecole Normale team prepared cooled helium atoms in a one-dimensional dark state.² The atoms actually were in a linear superposition of two wavepackets with a momentum spread that was a factor of



1.4 smaller than $\hbar k$. This is equivalent to delocalizing the atoms over a de Broglie wavelength, or more precisely, over a spatial coherence length that is $\hbar/\delta p$ larger than the light wavelength.

Four years later Mark Kasevich and Steven Chu at Stanford University used the somewhat related idea of Raman cooling to produce subrecoil temperatures in one dimension; they used sequences of stimulated Raman and optical pumping pulses with appropriate shapes and obtained in sodium atoms temperatures a factor of 20 below the recoil limit.³

Below the limit in 2D

In 1994 the Ecole Normale group extended its velocity-selective coherent population trapping to two dimensions.⁴ In this experiment, you start with a cloud of precooled helium atoms and apply the counterpropagating laser beams along the x axis and also along the y axis. When the beams are turned off, the atom is found in a linear superposition of four wavepackets moving apart, each with a momentum $\hbar k$. Each of these wavepackets has a momentum spread in the xy plane much smaller than $\hbar k$. The metastable atoms fall onto a microchannel plate detector. The detector shows four circular images, separated by a huge distance—over 1 centimeter. In this two-dimensional experiment, the helium atoms are cooled 16 times below the single-photon recoil temperature, to 250 nanokelvin.

Meanwhile, also in 1994, Chu and his Stanford collaborators (Nir David-

son, Heun-Jin Lee and Kasevich) reported producing two-dimensional Raman cooling of sodium atoms at roughly the recoil temperature.⁵

The new, three-dimensional experiment by the Ecole Normale group also uses velocity-selective coherent population trapping. The experimenters have cooled a cloud of helium atoms to 200 nanokelvin, 20 times below the single-photon recoil temperature. In this subrecoil regime, the coherence length of the atoms in the sample is about 5 microns, five times longer than the 1-micron wavelength of the laser used to do the cooling. Lawall says that in atom optics experiments done with thermal beams, the coherence length is 5 orders of magnitude smaller.

Below the limit in 3D

To achieve full three-dimensional subrecoil cooling, the Ecole Normale group used three pairs of laser beams. (See the figure above.) Two pairs of beams (1,2,3,4) are in the xz plane, at 45° to the horizontal, and the other pair of beams (5,6) are along the y axis.

The cooling occurs in six different reference frames, each moving along one of the laser beams and each moving with a speed due to the recoil from a single photon. A helium atom initially at rest that absorbed one photon would recoil with a velocity of 9 cm/s. The subrecoil cooling method prepares atoms in a linear superposition of six wavepackets, each packet recoiling with respect to the lab along one of the laser directions at 9 cm/s. Within these wavepackets, the dispersion of mo-

SUBRECOIL COOLING in three dimensions was produced by velocity-selective coherent population trapping. **a:** The six wavepackets follow ballistic trajectories to the detector. **b:** Beams 1 and 2 land first and are temporally distributed with their center at 111 milliseconds; beams 5 and 6 land next and are centered at 118 ms; beams 3 and 4 land last and are centered at 125 ms. **c, d and e:** Position distributions. In **c** are two spots, one above the other, corresponding to wavepackets 1 and 2; in **d** are two spots, side by side, corresponding to wavepackets 5 and 6; in **e** are two spots corresponding to wavepackets 3 and 4, aligned with 1 and 2. The data represent 150 successive releases of atoms following cooling. (Adapted from ref. 1.)

menta is very small, less than that of a single photon.

The experimenters use a sample of about ten thousand metastable helium atoms precooled to about 100 microkelvin in a magneto-optical trap. After the trap is shut off, the beams for the velocity-selective coherent population trapping are tuned to the appropriate transition ($2^3S_1-2^3P_1$) and are pulsed on.

When the laser is turned off, the six wavepackets follow ballistic trajectories (see part a of the figure). The first two, with an initial downward component (1, 2) land first on the detector (which records the temporal and spatial arrival coordinates of each detected atom). Next the horizontally launched packets land (5, 6), and finally the packets that were launched upward arrive (3, 4).

To resolve the six spots spatially, the experimenters use the correlations between the positions and arrival times of the wavepackets (see parts c, d and e of the figure above). The images were obtained using time windows of 6 milliseconds centered at 111, 118 and 125 ms. One can see two spots corresponding to wavepackets 1 and 2, then located at 90° are wavepackets 5 and 6, and finally wavepackets 3 and 4 are aligned with wavepackets 1 and 2. The separation between wavepackets 5 and 6 is proportional to $2\hbar k$ and to $\sqrt{2}\hbar k$ for pairs of spots 1 and 2 and 3 and 4. Says Lawall, "Just before the atom hits the detector, we can't know in which spot it will appear. Then there's the collapse of the wavefunction that gives us a single point in a single spot."

Adiabatic passage and beyond

Whimsically explaining the three-dimensional experiment, Cohen-Tannoudji said, "It's a six-legged Schrödinger's cat."

ger cat. I'm more interested to see how far can we go to get macroscopic linear superposition of states. It's clear that you can see it in the microscopic scale, but on the macroscopic scale it's not obvious at all. You must have some intermediate distance where the transition is between quantum physics and classical physics."

Very recently the group has used the so-called adiabatic passage technique to transform the six wavepackets into a single wavepacket. Says Cohen-Tannoudji, "Here we are already at the macroscopic scale since the wavepackets are separated by distances of the order of one centimeter, and we still have a linear superposition of states. The fact that we are able to recombine the six wavepackets into a single one is an *a posteriori* proof that the six wavepackets are coherent." The adiabatic passage experiment was reported at the Laser Physics Conference held in Moscow in August.

This kind of adiabatic recombination of coherent wavepackets (involving just two wavepackets) was first demonstrated by a group at the University of Munich—Tilman Esslinger, Matthias Weidemüller, Frank Sander, Andreas Hemmerich and Hansch, who used rubidium atoms. They reported their results at the Twelfth International Conference on Laser Spectroscopy held in Capri, Italy, in June.

Understanding the behavior of these subrecoil systems with very long interaction times requires the use of a new statistics, says Cohen-Tannoudji. The usual quantum optics methods become obsolete. He and his collaborators have analyzed subrecoil laser cooling in terms of Lévy flights,⁶ which are anomalous random walks dominated by rare events.

Helium is an excellent atom for subrecoil cooling because it has a small mass that gives high recoil velocity, a simple level structure with two $J=1$ states, and a metastable state. The metastable atom carries so much energy that when it hits the detector surface, it acts like a microscopic bomb. The atom can be detected with close to 100 percent efficiency, so the experimenters can find exactly where and when it landed.

Leduc says the Ecole Normale group is tempted to try producing Bose-Einstein condensation in helium now that this condensation has been achieved in rubidium by Eric Cornell, Carl Wieman, Michael Anderson and their collaborators. (See PHYSICS TODAY, August, page 17.) "Because helium has two isotopes," Leduc said, "we could compare the statistical properties of both boson and fermion gases." The group might be able to study the com-

petition between gas and superfluid behavior, she added, but that goal may be a distant one because it's not easy to start with a high density of metastable atoms.

The next experiment the Ecole Normale group plans is to have one helium wavepacket pass through a vibrating sheet of light. Thus a single de Broglie wavepacket will pass through a medium, introducing a modulated phase shift, the opposite to light passing through an electro-optic plate. The wavepackets would split into several components, giving rise to a splitting of the spot recorded by the detector.

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Oak Ridge Builds Facility for Radioactive Ion Beams

Oak Ridge National Laboratory has recently completed the construction of a radioactive ion beam facility to create nuclei at the limits of stability. The facility is now being commissioned. Created by reconfiguring two existing accelerators that have been used as a heavy-ion facility, the new Holifield Radioactive Ion Beam Facility is expected to be ready for experiments next summer. Because of the decreasing ratio of protons to neutrons for heavy stable nuclei, says Jerry Garrett, scientific director of the facility, the most efficient technique for producing proton-rich nuclei for nuclear structure studies involves heavy-ion induced fusion-evaporation reactions using proton-rich projectiles and targets with nearly equal masses. "This new facility should be well suited for such studies of proton-rich nuclei," Garrett says.

Over the last two decades, the ISOLDE facility at CERN has pioneered the use of radioactive ion beams, produced by bombarding a target with 600-MeV (later 1 GeV) protons and boiling off the radioactive ions. Those ions were then processed in the Isotope Separator On-Line facility. More recently the Cyclotron Research Center in Louvain-la-Neuve in Belgium has also operated an ISOL radioactive ion beam facility at energies below the Coulomb barrier appropriate for astrophysics measurements.

The new draft long-range plan of the Nuclear Science Advisory Committee says that the scientific opportunities provided "by world-class radioactive beams are extremely compelling and merit very high priority. The US is well-positioned for a leadership role in this important area. We strongly recommend the immediate upgrade of the MSU [Michigan State University]

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facility to provide intense beams of radioactive nuclei via fragmentation. We strongly recommend development of a cost-effective plan for a next generation ISOL-type facility and its construction when RHIC [the Relativistic Heavy Ion Collider at Brookhaven, scheduled for completion in 1999] construction is substantially complete." Construction of a major ISOL-type facility is estimated to cost a bit more than \$100 million.

Thus, the Holifield Radioactive Ion Beam Facility will also serve as a prototype for the ISOL facility. In the reconfiguration, a high-intensity proton beam from the Oak Ridge Isochronous Cyclotron strikes a target, producing radioactive particles, which are ionized. They are then mass analyzed and reaccelerated by the 25-MV tandem electrostatic accelerator. Finally, the accelerated radioactive beam strikes a target where the reaction to be studied occurs.

The new \$2.6-million facility is expected to be able to produce and study over a hundred new kinds of nuclei. It can produce beams above the Coulomb barrier (5 MeV per atomic mass unit for the heaviest species and 15 MeV/amu for the lightest species) for atomic mass less than 90.

The new facility will be used for studying the rapid proton capture process in nucleosynthesis and for studying nuclei far from stability, near the so-called proton drip line, where the nucleus becomes unbound and emits a proton.

In addition to Michigan State, other radioactive ion beam facilities that employ the projectile fragmentation technique are located at RIKEN in Japan, GANIL in France and GSI in Germany.

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