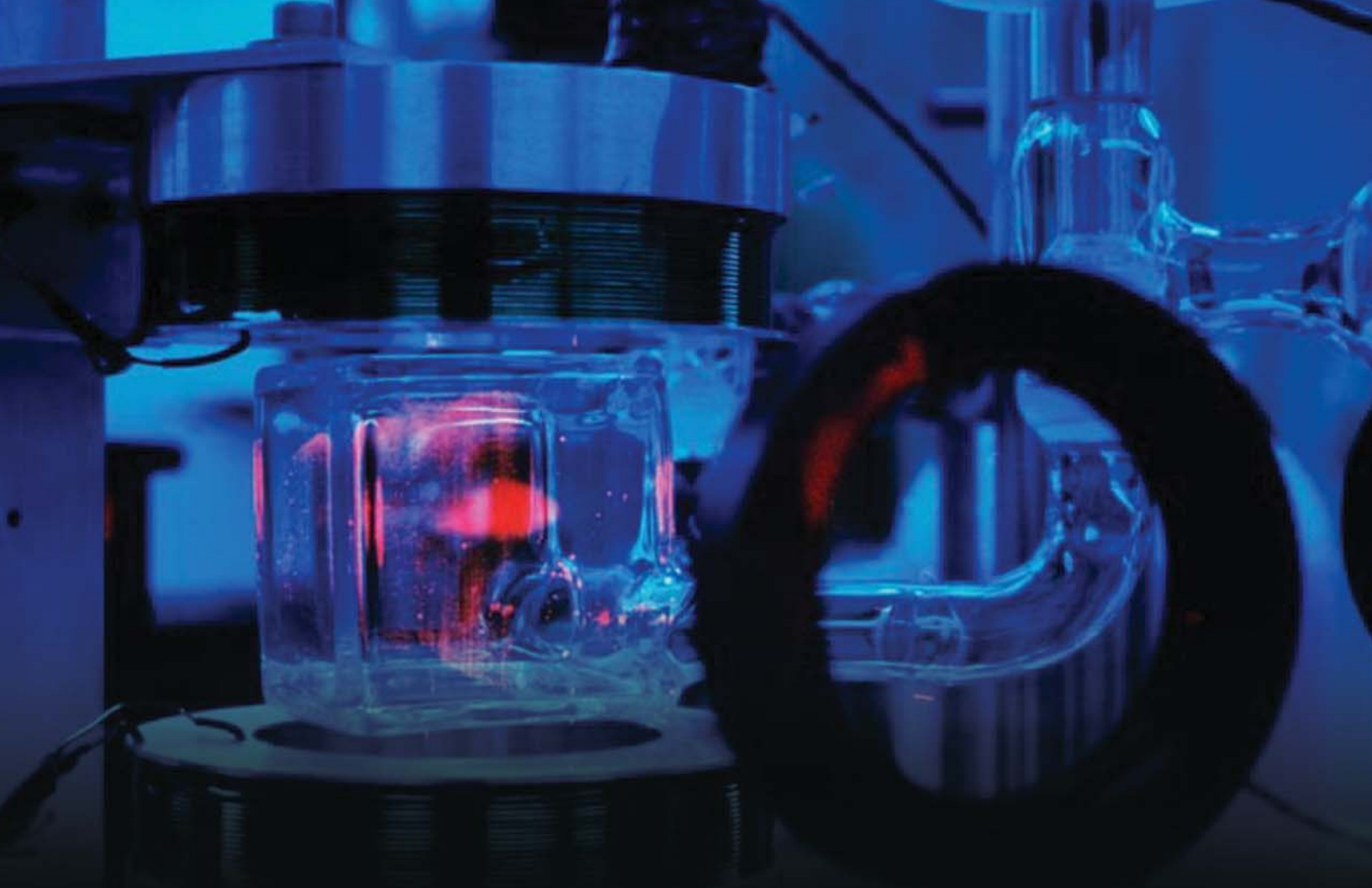




Experiments on Cold Trapped Atoms

David J. Vieira and Xinxin Zhao

Those of us who have fun trying to take a picture of a fast moving object usually end up with a blurry, imprecise image. Something similar happens when we try to make precision measurements on moving atoms—the movement results in a broadening of intrinsic atomic line widths, and we end up with an imprecise understanding of the subtle atomic processes that produce those lines. Likewise,

detailed studies of the interactions between atoms are hindered by motion because energetic collisions between atoms tend to complicate the system's dynamics and/or mask quantum effects. In general, if we are interested in making precision measurements on the individual or collective properties of free atoms, we have to slow the atoms down.

Kinetic theory tells us that the velocity of an atom in a gas is pro-

portional to the square root of the temperature and inversely proportional to the atom's mass. The atoms and small molecules in the air that we breathe, for example, move about at astonishingly high velocities at room temperature—about 4000 kilometers per hour. Because the velocity varies only as the square root of the temperature, one must make a gas very cold in order to substantially slow the atoms. At one degree above

absolute zero (1 kelvin), atoms still cruise at a few hundred kilometers per hour. Only when temperatures of a few millionths of a kelvin (a few microkelvins) are reached do free atoms move slowly enough that we can make high-precision spectroscopic measurements.

Several methods have been developed that use laser light to cool gases to the microkelvin temperature range. The cold atoms can then be contained within different kinds of atom traps, where they can be studied very accurately or cooled to even lower temperatures. The traps also allow us to concentrate a large number of atoms into a small volume. As the number density increases, the individual atoms begin to “feel” one another, and we can begin to study the transition from individual to collective behavior. With certain “bosonic” atomic species, cooling and trapping techniques enable us to create one of the most fascinating—and fragile—states of matter in the universe, the Bose-Einstein condensate (BEC). See the box “The Bose-Einstein Condensate” on the next page and the article “Atom-Trap BECs” on page 136.

The atom-trapping team at Los Alamos National Laboratory has adapted cooling and trapping techniques to radioactive atoms for both fundamental and applied research. We are in the process of

making sensitive measurements of parity violation in nuclear beta-decay as a means to test the Standard Model of electroweak interactions. We are also trying to cool a dilute gas of fermions to a degenerate quantum state (degenerate Fermi matter), where the density is comparable to that found in a BEC. Aside from displaying interesting quantum mechanical properties, ultracold fermions could undergo a phase transition to a superfluid state, and our apparatus should give us unprecedented control in forming and studying this system. Finally, we are using atom-trapping technology to trap and measure isotopic ratios of selected nuclear species at ultrasensitive levels for nonproliferation treaty verification and environmental studies.

Cooling and Trapping Techniques

Laser cooling of neutral atoms was proposed in 1975 by Theodore Hänsch and Arthur Schawlow, both then at Stanford University. The basic idea was to use the momentum transfer between a photon and an atom to slow the atom down.

When an atom absorbs a photon, its momentum is reduced by an amount $p = h\nu/c$ where h is Planck’s constant, ν is the frequency of the light, and c is the

speed of light. When the atom emits a photon, it gains momentum of the same magnitude (a so-called momentum kick). If, as in laser light, all the absorbed photons come from the same direction, then after many photon scattering events (rapid absorption and emission events), the net change in momentum will be unequal, since the fluorescent photons are emitted in all directions and the sum of the momentum kicks averages to zero. The result is a net loss of momentum.¹

To get laser cooling to work, we use the Doppler effect to ensure that only those atoms moving into the laser beam will absorb photons. The Doppler effect relates the intrinsic frequency of a source to the frequency “sensed” by an observer moving relative to the source. The pitch of a siren, for example, sounds higher when we move quickly toward it (or it moves quickly toward us) and lower when we move rapidly away. Similarly, an atom “sees” the frequency of a photon increase when the atom moves toward the photon. Thus, if we tune a laser to have a

¹ The change in momentum due to light scattering means that the atom feels a pressure, which can be quite large (up to 10,000 times larger than the force of gravity). Radiation pressure provides a very effective means of moving atoms around.

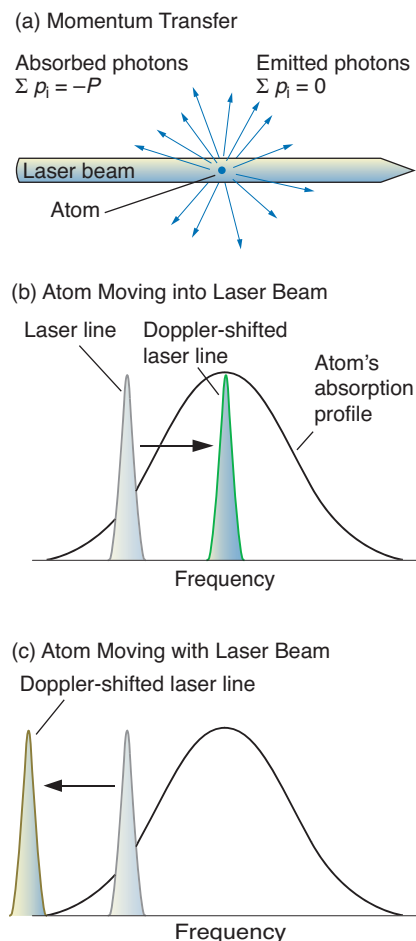


Figure 1. Laser Cooling

(a) An atom illuminated by laser light will absorb and reemit (scatter) many photons. (b) If the laser frequency is tuned below the atomic resonance line (red detuned), then an atom moving against the laser beam “sees” a laser frequency that is Doppler-shifted closer to the absorption maximum. It absorbs the low-energy laser photons. The atom then emits a higher-energy photon at the resonance frequency of its transition line. The atom loses energy with each absorption/emission event and begins to cool. (c) An atom moving in the same direction as the laser beam “sees” the detuned laser frequency Doppler-shifted still farther away from its absorption maximum. The atom absorbs few photons and is not cooled.

The Bose-Einstein Condensate

Elementary particles—and collections of particles such as nuclei and atoms—are either fermions (and have half integer spin) or bosons (and have integer spin). In the mid-1920s Albert Einstein, building on the work of Satyendra Nath Bose, predicted that, at exceptionally low energies, an ensemble of massive bosons should undergo a transition into a state that is described by a single, coherent wave function. This coherent state—now called the Bose-Einstein condensate (BEC)—would be as different from ordinary matter as laser light is from sunlight.

Physicists believed that a dilute gas of bosons could form a BEC, but the conditions needed to produce one are extreme. In order to become coherent, or establish a common phase relationship amongst themselves, the atomic wave functions must overlap significantly with one another. The spatial extent of the atomic wave function is given by its de Broglie wavelength λ , and it can be shown that the BEC will form if the atom density, expressed as the number of atoms in a λ -sided cube, exceeds 2.6. Both the de Broglie wavelength and the density of a gas depend on temperature, and one can calculate how cold it must be to achieve the critical density in a cold boson gas. The answer is, on the order of a few hundred billionths of a kelvin.

Certainly, one problem in creating a BEC was to find a gaseous system that would not coalesce into a solid as the temperature plunged toward absolute zero. The solution was to use certain alkali atoms (atoms from group I of the Periodic Table). When spin-polarized, these atoms have a weak repulsive force between them that would ensure that the system remained a gas. A BEC of rubidium-87 atoms was finally created and observed in 1995 by Carl Weiman’s and Eric Cornell’s group at the University of Colorado / JILA (Joint Institute for Laboratory Astrophysics). Four months later, Wolfgang Ketterle’s group from the Massachusetts Institute of Technology created a BEC from sodium-23 atoms. Since that time, a BEC has been observed in several other bosonic alkali species, such as hydrogen-1 and lithium-7. All the efforts involved cooling the atoms (except hydrogen atoms) to less than a millikelvin in what is called a magneto-optical trap (MOT), reducing the temperature by another order of magnitude by laser cooling, and then transferring the atoms to a magnetic trap. There, the atoms are cooled by a technique known as evaporative cooling to less than 200 nanokelvins to create a BEC.

slightly lower frequency than the resonance frequency of an atom’s

absorption line (detuning), only atoms that happen to be moving against the beam see the frequency of the photon Doppler-shift into resonance (see Figure 1). These atoms lose momentum and are slowed down (cooled). Atoms moving in the same direction as the detuned laser beam are Doppler-

shifted farther away from resonance. They do not readily absorb photons and are consequently unaffected.

To cool the atoms in three dimensions requires six intersecting laser beams—one pointing in each of the six directions $\pm x$, $\pm y$, and $\pm z$. Then any atom that emerges from the intersection region will be moving against a properly tuned laser beam and will be cooled.

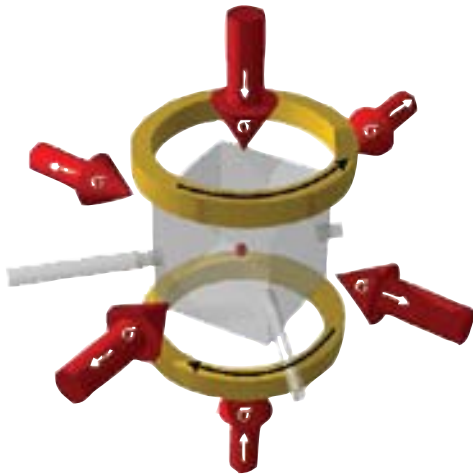
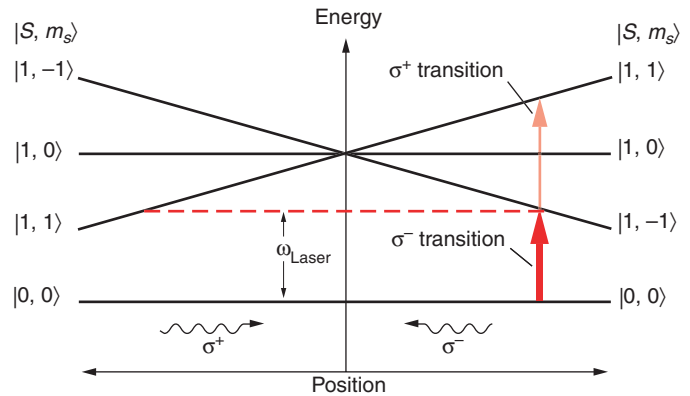


Figure 2. The Magneto-optical Trap (MOT)

(a) The MOT consists of six circularly polarized laser beams that intersect at the zero point of a magnetic field (produced by the set of anti-Helmholtz magnetic coils). The tube projecting from the left is used to bring atoms into the evacuated glass cell located between the coils. (b) This schematic energy diagram indicates why trapping occurs.

The σ^- polarized light induces a transition from the ground state $|S, m_s\rangle = |0, 0\rangle$ to the $|1, -1\rangle$ excited state, whereas the σ^+ polarized light will induce a transition from $|0, 0\rangle$ to $|1, +1\rangle$. The atom's magnetic substates are Zeeman-split by the magnetic



field. As the atom drifts away from the center of the MOT, say, to the right of the diagram, an atomic transition to the $m_s = -1$ substate shifts onto resonance with the σ^- polarized laser and starts to preferentially absorb these photons over the σ^+ polarized laser coming from the opposite direction. The resulting laser-induced pressure “pushes” the atom back toward the center. The result is the same if the atom moves out in any direction from the center of the trap.

[Part (b) of the figure was adapted from *Phys. Rev. Lett.* 59 (1987), p. 2631, with permission from the authors.]

The force experienced by an atom during laser cooling is velocity dependent; that is, its magnitude depends on the atom's velocity as it moves toward the laser beam. (The three-dimensional laser cooling is often called an optical molasses because velocity-dependent forces are viscous forces and the atom behaves as if it were entrained in a viscous liquid. The term optical molasses was coined by Steven Chu of Stanford University.) Velocity dependence means that the cooling rate decreases as the atom slows down. When the velocity gained by the atom as it emits a photon (the atom recoil) equals the loss of velocity due to the scattering process, the cooling ceases altogether. The minimum velocity of the atom at the “recoil limit” translates into a mini-

um temperature.² For sodium atoms, the recoil limit is 2.4 microkelvins and for somewhat heavier cesium atoms it is about 0.2 microkelvin.

The Magneto-optical Trap (MOT). Although optical molasses cools atoms down to very low temperatures, the atoms can diffuse out of the laser region through random Brownian motion. The MOT was invented to prevent this loss and to confine the atoms. The idea behind the MOT is to combine the optical molasses with an external magnetic field and thereby create a spatially dependent force that acts only on atoms that wander from the trap's center. The MOT was fully developed in David Pritchard's laboratory at MIT in 1987. Because of its relative ease of construction and great utility, it is perhaps the most commonly used atom trap.

For this trap, three pairs of counterpropagating, circularly polarized

laser beams (σ^+ and σ^- polarizations) establish an optical molasses within a vacuum chamber, as seen in Figure 2. Outside the molasses region are two magnetic coils. The current in each coil runs in opposite directions (anti-Helmholtz configuration) and creates a “quadrupole” magnetic field, which has zero field value at the center between the two coils. The field gradient increases linearly as one moves out from the center in any direction.

The trap works because an atom's magnetic substates (m -states) have different energies in a magnetic field (the Zeeman effect), and due to the field gradient, the m -state energy increases (or decreases) as the atom moves out from the center of the MOT. With reference to Figure 2(b), an atom in the trap will be illuminated with both σ^+ and σ^- circularly polarized laser light. Suppose the atom moves away from the center of the trap, say, in the $(+z)$ -direction, so that it moves into the σ^- laser beam, but

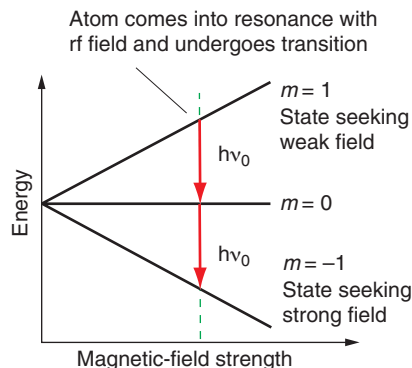
² There are also subrecoil laser-cooling mechanisms that can cool atoms below the recoil limit.

in the same direction as the σ^+ laser beam. Both lasers are tuned slightly below the $|S=0\rangle \rightarrow |S=1\rangle$ resonance frequency. At some distance from the MOT center, the drifting atom will come into resonance with the incoming σ^- radiation (but not with the σ^+ light). Similar to the way in which it absorbs light in an optical molasses, the atom will begin to absorb more of the σ^- light and will feel a pressure that pushes it back toward the center of the MOT. Likewise, an atom moving in the $(-z)$ -direction (or $\pm x, \pm y$ directions) will preferentially absorb photons from the inward-directed laser beam and will be pushed back toward the trap's center. Because the magnetic field is symmetric, the atom becomes trapped in three dimensions.

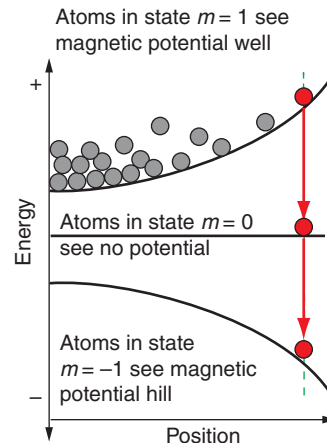
Magnetic Traps, Evaporative Cooling, and the Time-Orbiting Potential (TOP). While the MOT requires lasers to trap the atoms, magnetic fields alone can create a trapping potential. A pure magnetic trap makes use of the fact that atoms will experience a magnetic dipole force in a magnetic field gradient $\mathbf{F} = -\boldsymbol{\mu} \cdot \nabla \mathbf{B}$, where $\boldsymbol{\mu}$ is the atom's magnetic moment and $\nabla \mathbf{B}$ is the magnetic field gradient. If the atom is polarized into the $|m=1\rangle$ substate, the force will be toward lower magnetic-field values. The atom is diamagnetic and can be trapped by a simple magnetic quadrupole field, which has a zero magnetic-field value at the center.

Magnetic traps are easy to construct, but they have fairly weak trapping potentials (about 1000 times weaker than found in a MOT). They can only trap atoms that are already very cold, with thermal energies equivalent to 1 millikelvin or less. Once inside a magnetic trap, the atoms can be cooled to the limits of laser cooling. To reach the temperatures needed to create a BEC, however, we need another cooling technique, namely, evaporative cooling.

(a) Zeeman-Split Magnetic Sublevels



(b) Principles Underlying Evaporative Cooling

**Figure 3. Evaporative Cooling**

(a) The figure shows the magnetic sublevels of an atom as a function of magnetic-field strength. An atom in the state $|m=1\rangle$ is diamagnetic because it has lower energy in weaker magnetic fields. (Therefore the atom is attracted to regions of weaker field.) Conversely, atoms in the state $|m=-1\rangle$ are paramagnetic (that is, attracted to regions of higher magnetic fields). If the atom is illuminated by an rf radiation of frequency ν_0 , then at some magnetic-field value, the atom can come into resonance with the radiation and undergo a transition from $|m=1\rangle$ to $|m=0\rangle$, and then from $|m=0\rangle$ to $|m=-1\rangle$. The diamagnetic atom converts into a paramagnetic one. (b) The evaporative cooling technique removes the most energetic atoms from a magnetic trap. Atoms in the trap are polarized in the $|m=1\rangle$ (diamagnetic) state and are trapped by the quadrupole magnetic field. The most energetic atoms make the greatest excursions from the trap center and move into regions of higher magnetic field. These atoms come into resonance with an rf field and are converted to paramagnetic atoms, which are ejected from the trap. (They move to high-field regions outside the trapping volume.) After reequilibration through atomic collisions, the remaining atoms reach a lower temperature.

Temperature is a measure of the average kinetic energy of a system, and in a gas, the energy is distributed amongst the atoms according to a Maxwell-Boltzmann distribution. This means that some atoms always have greater than the average energy. We can efficiently cool a gas by removing the highest-energy atoms. After the remaining gas re-equilibrates, it will have a lower average energy. The common name for this process is evaporation. A liquid that is evaporating (say a steaming cup of coffee) cools down because the most energetic atoms leave (and form the rising steam).

To further cool the already cold

atoms, we actively eject the most energetic particles. We stated that the magnetic trap holds onto diamagnetic atoms. But atoms polarized in the $|m=-1\rangle$ substate are paramagnetic and will be attracted to the higher magnetic fields outside the trapping region. A radio-frequency (rf) field can be used to induce transitions between magnetic substates and convert an atom that is diamagnetic to one that is paramagnetic, at which point it is ejected from the trap. The frequency of the rf field is chosen such that only atoms with enough energy to move to the edge of the magnetic potential well come into resonance with the rf field (see Figure 3).

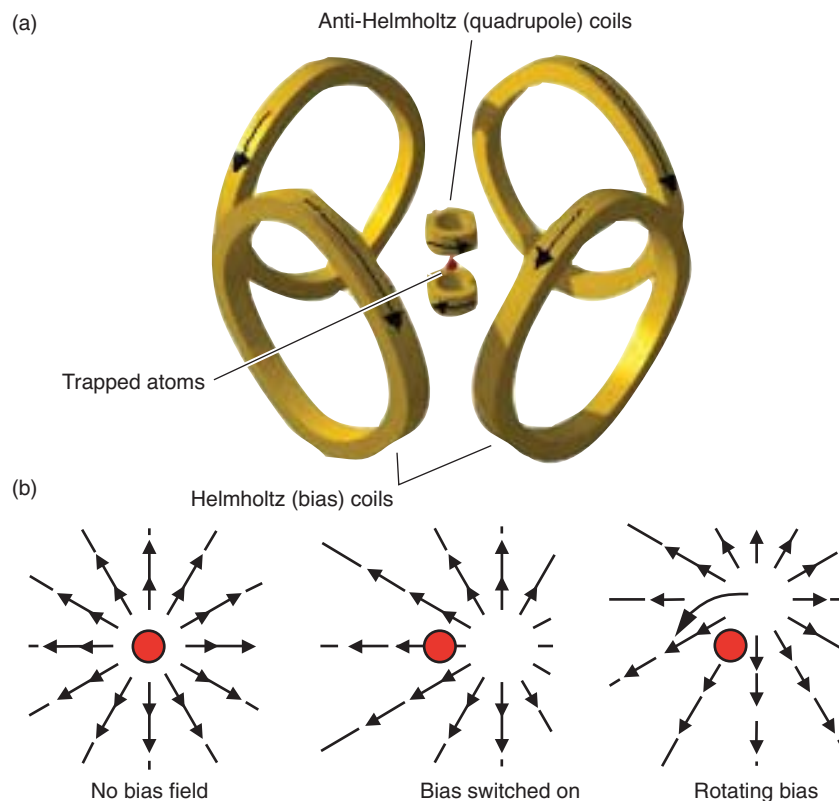


Figure 4. The Time-Orbiting-Potential (TOP) Trap

(a) The TOP trap is a magnetic trap that combines two magnetic fields: a quadrupole field (produced by the central, anti-Helmholtz coils) and a bias field (produced by the outer Helmholtz coils). (b) With the addition of the bias field, the potential minimum of the magnetic trap shifts off-axis. By adjusting the current in the Helmholtz coils, we make the bias field rotate around the trap axis and produce a time-averaged total field with a positive field strength at the center of the trap. As long as the bias field rotates fast enough, the atoms will remain polarized and stay trapped.

After ejecting the most energetic atoms from the trap, the rf frequency is readjusted so that once again the most energetic atoms of the now colder gas are ejected. In this way, it is possible to successively skim off the hottest atoms and thereby evaporatively cool the atoms.

One problem with this cooling scheme is that the quadrupole field has zero field strength at the center of the trap. Consequently, the magnetic substates are not Zeeman-split at the center of the trap, so polarized atoms can undergo spontaneous spin-flip transitions to the $|m = 0\rangle$ or $|m = -1\rangle$ substates in this region. The loss rate by this mechanism increases as the atoms become colder, making it difficult to achieve the critical BEC conditions of high atom density and low temperature.

The TOP trap, developed by Eric Cornell and collaborators, eliminates this problem by adding an off-axis bias field to the static quadrupole

field. As seen in Figure 4, the minimum of the total magnetic field becomes shifted away from the trap center. By rotating the bias field, the time-averaged total field still retains its basic quadrupole configuration, but now it has positive field strength at the center, so the atoms remain polarized. The bias field must rotate faster than the atoms can respond,³ but this objective is easily achieved. The TOP trap allows the density of atoms in the trap to increase sufficiently as the atoms are evaporatively cooled to reach the conditions for a BEC.

Atom Trapping at Los Alamos

³ The atoms oscillate within the harmonic potential well of the TOP trap. If the atoms are to experience the time-averaged magnetic field, the bias field must rotate faster than the atoms' period of oscillation.

Having cold, almost frozen, atoms at our disposal allows us to perform high-precision experiments to test quantum theories of ultracold ensembles of atoms and the nature of fundamental forces. Our system at Los Alamos, illustrated in Figure 5, combines several of the techniques and traps discussed above. A high-efficiency MOT that is coupled to an off-line mass separator is used for trapping radioactive atoms. Once the atoms are trapped, they can be counted with high sensitivity (via fluorescence detection) or transferred to another trap, where various experiments can be performed. At present, we are pursuing a number of research initiatives.

Parity Violation in Nuclear Beta-Decay. Spatial reflection symmetry, otherwise known as parity conservation, maintains that the fundamental processes of nature should be the same under a spatial inversion of all

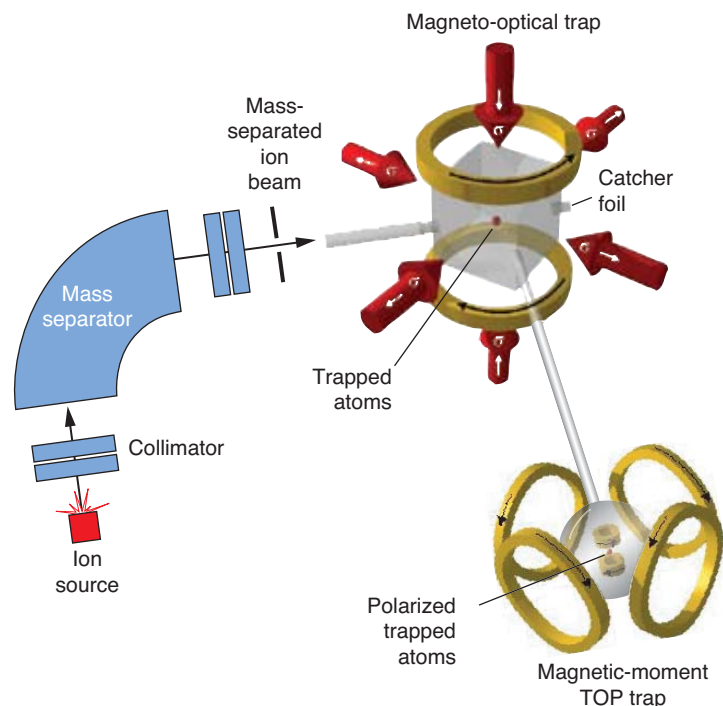


Figure 5. Los Alamos Setup to Trap Radioactive Atoms

Cooling atoms to ultralow temperatures must be done in stages, with several traps and laser configurations. In the setup at Los Alamos, energetic, radioactive atoms from an ion source are implanted into a thin metal foil that sits within an evacuated glass cell, around which are the MOT field coils. Heating the foil releases the atoms into the cell where they are trapped in the MOT and cooled to about 100 μ K. The MOT is turned off, and a laser pushes the atomic cloud into the evacuated chamber of a second MOT, where the atoms are recaptured. The magnetic field of this second MOT is turned off and an optical molasses is established by detuning the frequency of the laser further to the red (that is, to lower frequency). Within a few milliseconds, the atoms have cooled to approximately 20 μ K, and then they are optically pumped into a diamagnetic substate with a polarized laser beam. The optical pumping beam is then turned off, and the magnetic field is quickly ramped up in a TOP configuration. We plan to use evaporative cooling to bring the atoms to a final temperature of a few hundred nanokelvins.

vector parameters. Parity conservation was verified in electromagnetic and strong interactions, but as a startled physics community discovered in the 1950s, not in the weak interaction. Despite the astounding progress that has been made in understanding fundamental forces over the past fifty years, the origin of parity violation in the weak interaction remains a mystery of modern science. We hope to make a very precise measurement of the degree of parity violation in rubidium-82 as a means to test current theories.

One way the weak interaction man-

ifests itself is through a type of nuclear beta-decay, whereby a proton in a parent nucleus decays to a neutron, a positron (also known as a beta particle) and an electron neutrino. A daughter nucleus with a different atomic number is created in the process. For example, in rubidium-82 decay,



For the initial and final states of interest, this decay involves pure Gamov-Teller transitions that proceed solely

through the axial-vector (parity-violating) component of the weak interaction and is predicted by the Standard Model to be maximally parity violating. If the rubidium-82 nucleus is polarized by a magnetic field, then parity violation would manifest itself as an asymmetry in the angular distribution of the emitted positrons relative to the nuclear spin direction. For the primary beta-decay branch (in which the rubidium-82 nucleus decays to the 0^+ ground state of krypton-82), the positron is emitted in the direction of the nuclear spin. (In a secondary, less probable decay branch, the positron comes out in a direction opposite to that of the nuclear spin.)

We have recently demonstrated the trapping of polarized, radioactive rubidium-82 atoms. A radiochemically separated sample of strontium-82 ($t_{1/2} = 25$ days) is loaded into the ion source of a mass separator. The strontium-82 decays by electron capture to rubidium-82 ($t_{1/2} = 76$ seconds). The rubidium-82 atoms are thermally ionized, electrostatically extracted, mass separated, and implanted into a zirconium catcher foil located inside a glass cell that sits at the center of a high-efficiency MOT. Heating the foil releases the atoms as a dilute vapor into the glass cell where they are trapped and cooled.

The atoms are rapidly transferred to a second chamber by resonant laser light “pushing” on them. In the second chamber, the atoms are retrapped in a second MOT, further cooled, optically pumped into a specific magnetic substate, and loaded into a TOP magnetic trap. Being in a stretched state, the nuclear spin is aligned with the overall spin of the atom. Consequently, the nuclei are polarized and aligned with the local field. In the center of the TOP, the strongest field is in the direction of the bias field, so the direction of the nuclear spin rotates with the bias field.

By keeping track of the varying

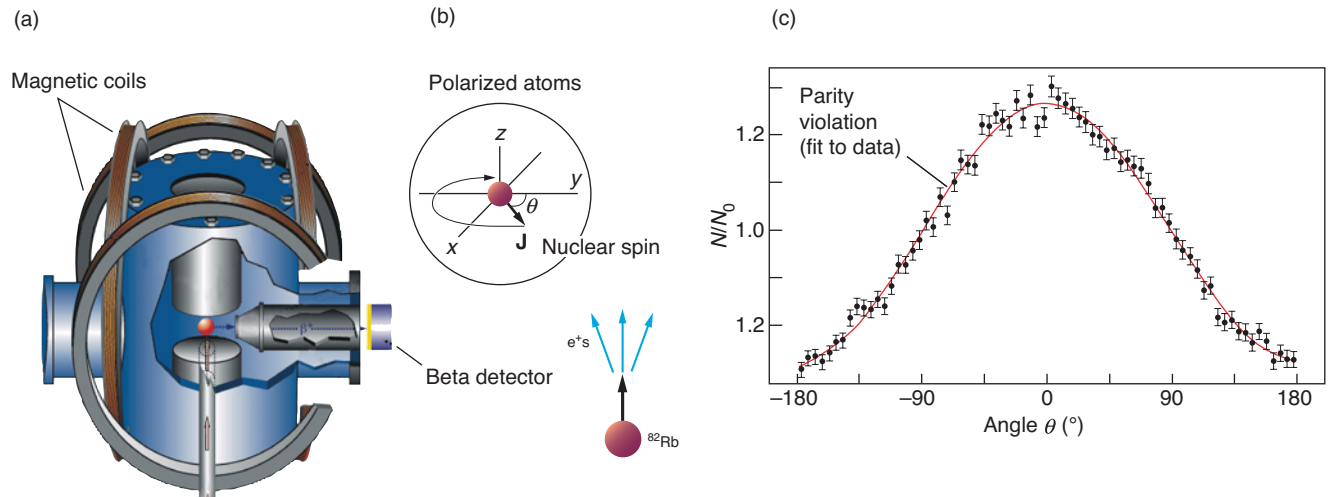


Figure 6. Measurement of Parity Violation

(a) The figure shows the TOP trap of our experimental system. The nuclei of the trapped rubidium-82 atoms are spin polarized and always point in the direction of the TOP's rotating bias field. By monitoring the currents that produce the bias field at any given time, we can reconstruct the magnetic-field orientation; hence, we know the nuclear spin direction. A plastic scintillator is used to detect the emitted positrons. When a positron is detected, we reconstruct the nuclear-spin direction and can

determine the angle θ between it and the positron emission direction. (b) Because parity is not conserved in the weak interaction, the spin-polarized rubidium-82 nuclei will decay by preferentially emitting positrons in the direction of the nuclear spin. (c) This plot of rubidium-82 beta-decay data, accumulated over a period of 6 hours for positrons with energies above 800 keV, shows the parity violating the angular distribution of the positrons. The red line is a cosine fit to the distribution.

currents in the bias coils of the TOP trap, we can reconstruct the direction of the bias field, hence the spin alignment, as a function of time. We can then correlate each beta event with the orientation of the nuclear spin, and record the angle between the beta and the nuclear-spin direction. In Figure 6, we show our initial proof-of-principle results, which indicate that parity is, as expected, violated in the beta decay of polarized rubidium-82 atoms. This is the first time that the entire angle-dependent parity-violating amplitude has been measured.

We are in the process of making a 1 percent measurement of this correlation in order to place stringent limits on the maximal parity-violating nature of the weak interaction. We hope to extend that measurement to 0.1 percent and to search for new physics beyond the Standard Model.⁴

⁴ This work is done in collaboration with scientists from the Chemistry and Physics Divisions at Los Alamos. See Crane et al. 2001.

Ultracold Atoms / Quantum Degenerate Matter. The ability to trap and cool different isotopes enables us to explore mixed fermionic and bosonic systems. In particular, we are working to produce a BEC of bosonic rubidium-87 and overlap it with a magnetically trapped cloud of radioactive, fermionic rubidium-84. In doing so, we hope to sympathetically cool, via atomic collisions, the rubidium-84 atoms down to the Fermi degenerate regime (approximately 10 to 100 nanokelvins). We want to study the fermion-fermion and fermion-boson collision dynamics at temperatures approaching absolute zero.

Recent calculations show that rubidium-84 is a good fermionic candidate for sympathetic cooling because it has a large and positive scattering length with rubidium-87. Calculations also indicate, however, that, in the presence of a relatively low magnetic field ($B \sim 100$ gauss), a Feshbach resonance should be present in rubidium-84. This resonance allows two colliding atoms to form a temporary molecule before separating, and

by adjusting the magnetic-field value, we can fine-tune the energy at which the resonance occurs. In doing so, we can control the collision cross section and effectively “tune” the temperature at which a phase transition to a superfluid state will occur.

The radioactive rubidium-84 atoms ($t_{1/2} = 33$ days) for our experiments are produced by proton spallation reactions on a molybdenum target at the Los Alamos Neutron Scattering Center. The rubidium is chemically extracted from the molybdenum and loaded into the ion source of a mass separator. The rubidium-84 is implanted and captured in the MOT in a similar procedure to that described in the previous section.

As an initial step toward achieving our goal, we have demonstrated the trapping of rubidium-84. Figure 7(a) shows the time-dependent trapping signal from roughly one million trapped rubidium-84 atoms. At high atom densities, the losses from the trap are dominated by laser-light-assisted collisions between trapped atoms.

By overlapping a cloud of 3×10^5

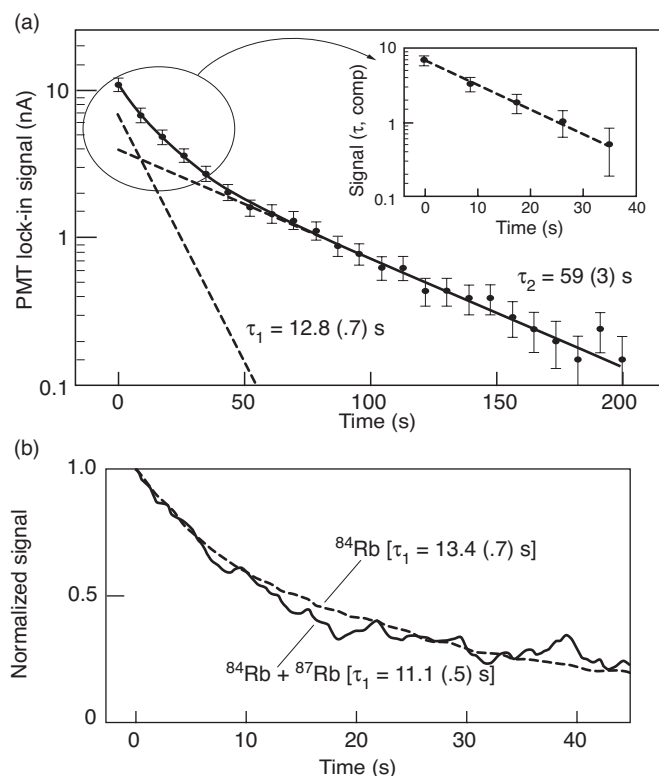


Figure 7. Lifetimes in a MOT: Rubidium-84 with and without an Overlapping Cloud of Rubidium-87

How long will a MOT confine half a million rubidium-84 atoms? The data indicates that the answer depends on the atomic density. (a) At high densities (short times), light-assisted collisions between trapped atoms dominate. These give rise to the short-lived component ($\tau_1 = 12.8$ s) of the overall trap lifetime. (The inset shows a fit to the short-lived component.) As the number of trapped atoms decreases and the density goes down, light-assisted losses become negligible and only collisional losses between the cold atoms and the hot background gas remain. The collisional losses correspond to the long-lived component, with a lifetime of about 59 seconds. (b) Introducing rubidium-87 atoms into the trap could lead to collisions between the rubidium isotopes and an enhanced loss rate. This figure shows the normalized lifetime in the trap of rubidium-84 atoms with and without an overlapping cloud of rubidium-87 atoms (solid line and dashed line, respectively). The additional loss rate is sufficiently small that it does not present a problem for the sympathetic cooling experiment discussed in the text.

cold atoms of rubidium-84 with a large cloud of 7×10^7 atoms of stable rubidium-87, we have also been able to set a limit on the inelastic-collision loss rate of the atoms from the trap, which could affect the rubidium-84 trapping lifetime—see Figure 7(b). Fortunately, this loss rate was found to be sufficiently small and did not present a problem for the sympathetic cooling experiment. We are currently optimizing the evaporative-cooling

process to achieve quantum degeneracy for the bosonic rubidium-87 and to study its cooling of rubidium-84 (Crane et al. 2000).

Ultrasensitive Detection. As a result of fallout from atmospheric nuclear tests, the two radioactive isotopes cesium-135 ($t_{1/2} = 2.3 \times 10^6$ years) and cesium-137 ($t_{1/2} = 30$ years) are ubiquitous in the environment, at a relative abundance of roughly 1 part per billion with respect to stable cesium-

133. (The fission product isotopes are man-made, that is, anthropogenic.) Cesium adsorbs strongly and rapidly to soil particles, and because the heavier isotope cesium-137 is relatively easy to detect through gamma-ray spectrometry, it has served as a chronometer and tracer in a diverse array of scientific endeavors, including studies of soil erosion and lake sedimentation.

The long radioactive lifetime of cesium-135, however, severely limits its detection by gamma-ray spectrometry. This is unfortunate, since a measurement of the cesium-137/cesium-135 isotope ratio would lead to a relatively unambiguous determination of a sample's age. Furthermore, that particular ratio is of interest for nonproliferation and treaty verification because the cesium-137/cesium-135 content of nuclear-fuel effluent can provide valuable information about nuclear-reactor operations.

Detecting both isotopes, especially from random environmental samples, requires that we have a highly sensitive, highly selective technique. Several advanced technologies, including resonant ionization mass spectrometry (RIMS), have been successfully applied to the problem, with the RIMS method achieving a detection limit of about 1×10^8 atoms, an estimated isotopic selectivity of about 10^{10} , and an overall efficiency (from source size to detectable sample size) of 2×10^{-6} .

We recognized that, when coupled to a mass separator, a MOT could do even better. Because the trapping potential of a MOT derives from a multiphoton, near-resonant absorption process, it is very species selective (atomic, isotopic, and isomeric) with respect to what it traps. The mass separator also has high isotopic selectivity, so a mass separator/MOT system affords a huge suppression of signals from unwanted species. A MOT “detector” should also have high sen-

sitivity. Each trapped atom can scatter (rapidly absorb and emit) about 10^7 photons per second, so even small numbers of atoms can be detected.

We are the first group to have succeeded in trapping and detecting cesium-135 and cesium-137 in a MOT. A sample containing both isotopes was placed in the source of a mass separator, and each isotope was sequentially measured with a MOT. Trapped-atom numbers in the case of either isotope ranged from 10^4 to 10^7 , as determined from the MOT fluorescence signal. Over this trapped-atom range, the MOT fluorescence signal was found to increase linearly with the number of atoms implanted into the foil with no sign of an isotopic dependence to within 4 percent.

Direct measurement of the cesium fluorescence signals should yield the cesium-137/cesium-135 ratio. In principle, our mass separator/MOT technique can make that determination to within 10 percent of uncertainty. Currently, the system has a detection limit of about 10^6 atoms, an isotopic selectivity of greater than 10^{12} , and an overall efficiency of 0.5 percent. As such, our work represents a significant advance in efficiency and isotopic selectivity among other methods applied to the detection of cesium radioisotopes (Di Rosa et al. 2002.). More important, our results demonstrate the advantages of applying atom-trapping techniques to the general problem of ultrasensitive detection.

Conclusions

Over the last decade, advances in the laser cooling and trapping of atoms have revolutionized the prospects of fundamental research and applied quantum-based projects. In atomic physics, scientists have gained unprecedented control over quantum ensembles, as witnessed by the cre-

ation and wide study of BECs today. But the new trapping and cooling techniques should not be viewed as simply a workhorse for quantum optics and atomic physics. Their use has spread to nuclear physics (as in our rubidium-82 experiment), biophysics, condensed-matter physics, quantum information, and environmental science (as demonstrated by our cesium experiments). The results of this "cross-fertilization" have in turn enriched the field of atomic physics. We believe the atom-trapping revolution is just beginning and that in the years to come there will be many new exciting interdisciplinary opportunities. ■

Further Reading

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David J. Vieira is the nuclear chemistry team leader in the Isotope and Nuclear Chemistry Group at Los Alamos. He obtained his Ph.D. in nuclear chemistry from the University of California, Berkeley, in 1978, after which he came to Los Alamos. He has been an Adjunct Professor of Physics at the Utah State University since 1984 and was an Alexander von Humboldt Fellow (1990–91). David received a Los Alamos Distinguished Team Performance Award in 1993 for the development of a He-jet system at the Los Alamos Neutron Science Center (LANSCE) and the Fellows Prize (1998) for the development of the time-of-flight isochronous (TOFI) recoil spectrometer, the study of exotic nuclei using TOFI, and the trapping of radioactive atoms. David's current interests include fundamental atomic and nuclear physics experiments involving trapped radioactive atoms, ultrasensitive detection, quantum information and control using trapped atoms, as well as fundamental symmetries, radioactive beams, and neutron-induced cross section measurements.



Xinxin Zhao received his Ph. D. from Rice University in 1993. After three years of post-doctoral research on single-ion high-precision spectroscopy at the University of Washington, he came to Los Alamos National Laboratory to work on laser cooling and trapping of radioactive atoms. In 1999, he became a technical staff member at the Laboratory. He has over ten years of experience in the areas of atom/ion trapping, laser cooling, and high-resolution laser spectroscopy. Together with David Vieira and collaborators, Xinxin has demonstrated the trapping of a record number of radioactive atoms and observed the first beta-decay asymmetry spectrum from magnetically trapped polarized atoms. His current research interests are application of laser cooling and trapping to fundamental and applied physics.

