

able quasar absorption spectrum, one looks for evidence of a faint deuterium line slightly shifted from the prominent ^1H Lyman- α line. The intensities of the two absorption lines measure the relative abundance of the two hydrogen isotopes in the absorbing foreground cloud.

But one can be fooled. Suppose there is a smaller interloping hydrogen cloud along the line of sight between us and the principal absorbing cloud, and that the difference in Doppler redshifts between the two clouds happens to mimic the isotope shift. Thus the fainter ^1H Lyman- α line of the interloper can be mistaken for evidence of deuterium.

Just how likely such an unfortunate interposition would be is a matter of some dispute among the experts. But it seems clear that an interloper would cause an overestimate, rather than an underestimate, of the deuterium abundance. Indeed when Songaila and company first reported their result, they treated it as an upper limit rather than an unambiguous abundance measurement. In any case, the best way to get around the interloper problem is to find deuterium absorption lines in the light from several different quasars in different parts of the sky. Tytler argues that the fact that his group's two sightings gave consistent results is strong evidence in favor of the lower value of the primordial deuterium abundance.

Both the lower and higher deuterium-abundance results pose problems. If one believes the Songaila result, one has to explain where all that primordial deuterium has disappeared to. There is very little deuterium in our Galaxy and Solar System, and the standard theories of galactic and stellar evolution cannot account for the swallowing up of so much primordial deuterium.

On the other hand, Songaila's result is somewhat more consistent with the measured abundance of ^4He than is Tytler's. In the theory of Big Bang nucleosynthesis, knowing the fractional abundance of any one of the four minority primordial species fixes the other three. So measuring all four raises issues of consistency.

^4He is by far the most abundant, accounting for more than 20% of all the primordial baryonic mass. Nonetheless, it is easier, for several reasons, to get at Ω_b by measuring the deuterium abundance: First of all, deuterium, unlike the heavier primordial species, is never liberated in astrophysical processes; it can only be destroyed. Because all the other nuclei can be created as well as destroyed by stars, it is difficult to know if what one is seeing is of primordial or more recent origin. Second, the strongest helium lines are too far in the ultraviolet to be redshifted into the visible at quasar distances. Even with the Hubble Space Telescope, which can look deep into the ultraviolet, one faces the difficulty that helium, unlike hydrogen, has two different ionization states contributing to the absorption spectrum. (See PHYSICS TODAY, October 1995, page 19.) Primordial ^7Li , for its part, is about a million times less abundant than deuterium. Finally, the theoretical abundance of deuterium is a much steeper function of Ω_b than are any of the other primordial abundances.

Dark matter

Even without the assumption that $\Omega_T \equiv \Omega_b + \Omega_{nb} = 1$, studies of galactic and intergalactic dynamics make it clear that a large fraction of the matter in the universe is not visible to us in any part of the electromagnetic spectrum. This dark matter would be some

mix of exotic nonbaryonic particles and cold, dead baryonic bodies and gases. Theorists and observers invoke primordial nucleosynthesis to elucidate this mix.

X-ray observations of hot gas in large clusters of galaxies indicate that such gas accounts for something like $30 \pm 20\%$ of the cluster masses. Tytler and colleague Scott Burles,² arguing that the baryonic/nonbaryonic mass ratio of large clusters should be close to that of the universe as a whole, use their Ω_b to conclude that Ω_T is less than 80%, not quite enough to "close" the universe without the help of a cosmological constant. Nonetheless, Tytler's measurements are more comforting to true believers in $\Omega_T = 1$ than Songaila's, which would dictate an upper limit on Ω_T of only about 20%.

Closer to home, the relatively high baryonic mass density implied by the Tytler group's low value for the primordial deuterium abundance lends some support to recent results from the MACHO collaboration. (See PHYSICS TODAY, March, page 9.) The collaboration looks for dark bodies of stellar and substellar mass in the halo of our Galaxy via the gravitational lensing effect they can have on background stars. Having now accumulated seven lensing events in the direction of the Large Magellanic Cloud, the MACHO collaboration estimates that such dark celestial bodies account for about half the mass of our Galactic halo.

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Quantitative BEC Results Reported at DAMOP Meeting

Now that the fanfare of simply creating a Bose-Einstein condensate in a dilute atomic gas has died down (see the "Reference Frame" column by Daniel Kleppner on page 11), the leading research groups are proceeding in earnest to map out the properties of their condensates. Four experimental groups reported their latest results in invited talks at a session on Bose-Einstein condensation (BEC) at the meeting of the American Physical Society's Division of Atomic and Molecular Physics (DAMOP) held in Ann Arbor in May.

The Colorado researchers led by Eric Cornell and Carl Wieman have used their time-average orbiting potential (TOP) trap, which produced the first condensate in rubidium-87, to

A new trap, larger condensates, collective oscillations, interaction effects and nondestructive observations: A few groups have achieved a lot of results a year after the creation of dilute gaseous Bose-Einstein condensates.

study collective excitations of their condensate, including the effects of interactions between atoms.¹

The MIT researchers led by Wolfgang Ketterle have devised a new trap geometry for their sodium-atom condensates.² The new design allows them to form even larger condensates than before—containing as many as 5×10^6 atoms. In addition they have been able to study their condensates

in situ, including the repeated observation of a single condensate, a technique that will enable them to study how an individual condensate evolves.³ (See figure on page 19.)

The researchers led by Randall Hulet at Rice University have improved the optics used to study their system of lithium-7 atoms. The group can now image the lithium clouds with better resolution than before; at DAMOP Hulet reported preliminary data that shows evidence of a phase transition at which a small fraction of the lithium atoms condense. The current experiments (as yet unpublished) indicate condensates of no more than a few thousand atoms, whereas previous results published by the group, which

were less direct and harder to interpret, had suggested much larger condensates might be present.⁴

The fourth group of experimental BEC researchers invited to talk at DAMOP was that of Daniel Kleppner and Thomas Greytak at MIT. Although they remain apparently just on the verge of demonstrating BEC in spin-polarized hydrogen, the techniques they have developed for observing the atoms within their trap have opened the door to a new method of ultrahigh-resolution spectroscopy of atomic hydrogen.⁵ By performing two-photon, Doppler-free spectroscopy on the evaporatively cooled hydrogen in their magnetic trap they resolve the 1S–2S line to a linewidth of 3 kHz, a value that was briefly a record. (Theodor Hänsch of the University of Munich, however, told PHYSICS TODAY that his group, using a different method, had recaptured the record with a linewidth of 1.4 kHz that was reported at a meeting in June.)

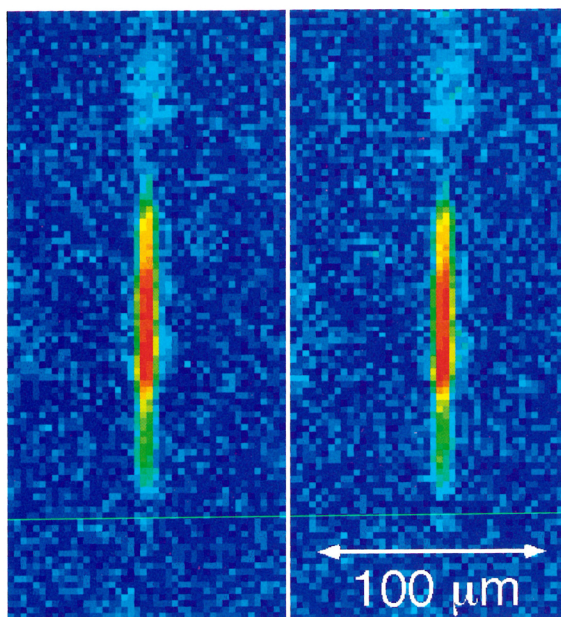
Cloverleaf trap

The new magnetic trap of Ketterle's group is called a cloverleaf trap because its main feature is an array of four coils arranged in a cloverleaf pattern around a fifth coil.² Two such arrays provide the trapping field. The central coil at each end provides a magnetic field that confines atoms along the axis of the trap, while the eight cloverleaves produce a quadrupole field that confines them in the transverse plane.

A trap with this configuration of field gradients is known as a Ioffe trap or a Ioffe–Pritchard trap, named after M. S. Ioffe, who first suggested it in the context of plasma physics, and David Pritchard, who independently suggested the design in 1983 for trapping neutral particles. Ioffe traps are widely used but the cloverleaf design is a new twist, suggested by Daniel Kurn, a graduate student in the MIT group. The cloverleaf design provides full optical access in the transverse plane.

The TOP trap design of the Colorado group⁶ (see PHYSICS TODAY, August 1995, page 17) can provide greater confinement along the axial direction, but a Ioffe trap can achieve much greater confinement in the transverse plane. Equipotentials in the Colorado trap have the form of spheres flattened along the axis of the trap. When first loaded with atoms cooled by magneto-optical trapping, the MIT cloverleaf trap also has a nearly spherical configuration, to match the initial cloud of atoms. Then the transverse, or radial, confinement is ramped up, compressing the atoms into a cigar-shaped cloud, which can then be evaporatively cooled.

The researchers produced pure condensates containing as many as



TWO IMAGES of the same sodium condensate taken one second apart using a nondestructive imaging technique. The cigar-shaped condensate, consisting of between 1 and 5 million atoms, is held in the cloverleaf trap and is about 120 μm long. About 100 such consecutive images of a single condensate may be possible before causing significant perturbation of the cloud. (Adapted from ref. 3, courtesy of Marc-Oliver Mewes.)

5×10^6 atoms, ten times more than they had achieved with their old laser-plugged quadrupole trap.⁷ (See PHYSICS TODAY, March 1996, page 18.) The clouds were initially imaged by first turning off the trapping fields, letting the atoms fly apart and imaging the absorption of a laser beam shone through the cloud.

According to theory the condensate fraction should vary with temperature, T , as

$$N_0/N = 1 - (T/T_c)^3$$

where N_0 is the number of condensate atoms and N is the total number of atoms present. Within uncertainties, the MIT data fitted that curve below a condensate fraction of about $1/2$. The Colorado researchers also performed such studies with their trap and obtained similar results. Neither group was able to get accurate data for large condensate fractions because it was not possible to measure the temperature accurately.

The effect of interactions

Although one of the desirable features of the dilute alkali condensates is their weak interactions—as compared with, say, liquid helium—there is still an interaction between the atoms in the atom clouds; the gases are not ideal. The dilute atomic condensates have a well-developed mean-field theory that theorists have been busy analyzing for precisely the conditions that occur in the traps. The interactions of both ^{87}Rb and Na correspond to an effective repulsion between the atoms. This results in a pressure in the Bose condensate—a potential energy term that is proportional to the density of the atom cloud.

For a noninteracting gas, the con-

densate would have a density profile proportional to the ground state wavefunction (squared) of a single atom in the trap. For a gas with a repulsive interaction, however, the repulsion between the atoms increases the size of the ground state and gives it a parabolic shape for large numbers of atoms. Indeed, the MIT group sees a condensate 20 times larger in the axial direction than the ideal gas ground state.

The relative interaction strength is proportional to N_0 and to the trap frequency, ω . Thus by varying N_0 and ω one can control the relative interaction strength between the atoms.

Both groups studied the effect of the interaction. The MIT group varied the number of condensate atoms, while the Colorado researchers also varied their trap's confinement. The MIT group found that the mean interaction energy per atom varied as $N_0^{2/5}$, as expected. Preliminary results of the Colorado group found approximate agreement with the equivalent relation between mean interaction energy and relative interaction strength.

Collective excitations

To study the collective dynamics of their condensates, both groups perturbed their atom clouds and observed the resulting oscillations.^{1,8} (See figure on page 20.)

The Colorado group applied two different perturbations.¹ The “ $m = 0$ ” perturbation preserved the axial symmetry of the trap but varied the transverse potentials as in a breathing mode. The “ $m = 2$ ” perturbation distorted the trap into an ellipse in the transverse plane, with the major axis of the ellipse rotating at the perturba-

tion frequency.

For an ideal gas, the normal modes of oscillation occur at integer multiples of the trap frequencies. For a gas at the density of the condensate, however, the interactions between atoms modify this picture. The Colorado group found that the $m = 0$ breathing mode excited an oscillation at about $1.84\nu_r$, where ν_r is the radial trap frequency. With this oscillation the axial and radial dimension of the Rb condensate oscillated approximately out of phase. The $m = 2$ mode oscillated freely at $1.43\nu_r$. For this oscillation the axial width of the cloud was unchanging, as would occur if the cloud were elliptical and rotating in the transverse plane. By varying the number of atoms in the condensates and the trap frequencies, the Colorado researchers could adjust the effective interaction strength. When they did so, the oscillation frequencies varied as predicted by various mean-field theory analyses. On the other hand, when they studied clouds just above the transition point, at $T \approx 1.3T_c$, the oscillation occurred at $2.0\nu_r$ and could be excited by either the $m = 0$ or the $m = 2$ drive.

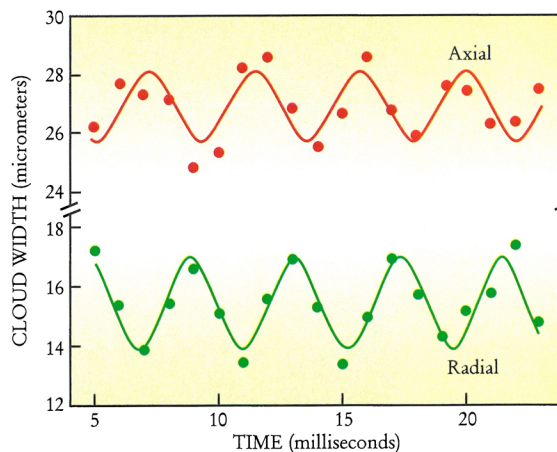
The MIT researchers also performed a number of experiments on collective excitations of their sodium condensate.⁸ For a cigar-shaped condensate with a large aspect ratio in the high-density regime, the mean-field theory predicts modes at $\sqrt{5}/2\nu_z = 1.58\nu_z$ and at $2\nu_r$. The group observed oscillations at $1.56\nu_z$ and $2.04\nu_r$.

Perhaps the most interesting effect occurred when the MIT researchers applied a large drive amplitude to their condensates. Then, the time-of-flight images displayed "striations" parallel to the radial direction. More work is needed to understand what causes this apparent interference effect.

Nondestructive imaging

The above results of the Colorado and MIT groups were obtained by releasing a cloud from its trapping field and allowing it to expand ballistically, thereby destroying it. To obtain information on the evolution of a cloud requires accurately recreating the same initial conditions many times with slight variations in the period of evolution on each run. At the densities and condensate sizes achieved by the MIT group, attempting to image a condensate *in situ* with near-resonant light would not work because the cloud would attenuate the probe beam by a factor on the order of e^{-300} !

A part of the solution is to detune the laser to far off-resonance, which greatly reduces the absorptive effect of the cloud but increases the effect of dispersion—the atom cloud deflects



RADIAL breathing mode oscillation of a rubidium condensate of about 4500 atoms. The oscillation is excited by perturbing the radial trapping fields close to the oscillation frequency for 50 ms. Each data point is from a separate cycle of condensate formation, excitation, evolution in the unperturbed trap and free expansion of the cloud. (Adapted from ref. 1.)

light similar to a glass sphere. A further trick is the technique of dark ground imaging, which allows one to image only the scattered light. The trick is that the lens that focuses the scattered light to form an image also focuses the unscattered component of the probe beam to a point in the Fourier plane. Blocking that light with a small opaque spot allows one to image only the scattered light.

Applying this technique with light far off-resonance, the MIT researchers successfully imaged their condensates *in situ* within their trap.³ The nondestructive nature of the method was demonstrated by taking repeated images of a single condensate. For example, two 500 ms exposures taken one second apart show that the condensate is not greatly disrupted despite scattering on the order of 5×10^6 photons. (See figure on page 19.)

Resolving lithium

The researchers led by Hulet at Rice University use a trap composed of permanent magnets so they are unable to lower the fields and let their condensates expand; they can only perform imaging of the condensate *in situ*.⁴ In their previous results, they reported achieving clouds of ^7Li sufficiently small, cold and dense to be degenerate and containing many thousands of atoms, but although this was reported as evidence for BEC, little more could be said with certainty. At the DAMOP meeting, Hulet reported the preliminary results achieved after improvements to the resolution of the optics system. The researchers were now able to obtain profiles of their clouds' optical density. Above the computed phase transition, the profiles fit to classical Maxwell-Boltzmann distributions with a Gaussian radius of about $30 \mu\text{m}$. But below the transition a peak with about a $5 \mu\text{m}$ Gaussian radius appeared. Hulet showed that these distributions fit to a Bose-Ein-

stein distribution function with up to a few thousand atoms in the condensate. Hulet notes, however, that there are "subtleties to the imaging and analysis" and estimates the accuracy of his group's measured condensate numbers to be good to only about a factor of two.

The Rice researchers also performed some dark-field imaging. From these data, they deduced that the condensate fraction never grew beyond about 15% of the total atoms present and never exceeded a few thousand atoms. Such results would sit well with theorists, who compute that a ground state condensate of ^7Li atoms in the Rice trap should be stable only up to about 1300–1500 atoms. (See PHYSICS TODAY, March 1996, page 18.) Larger ground state condensates are predicted to be rendered unstable by the effective attraction between the ^7Li atoms.

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