

SEARCH AND DISCOVERY

Bose Condensates Produce Coherent Nonlinear Behavior

Because the atoms in a gaseous Bose condensate have nearly the same single-particle wavefunction, they can serve as sources of coherent atomic beams, or atom lasers. In analogy to an optical laser, the gain mechanism in the formation of a condensate of ultracold atoms is bosonic stimulation. (Bosonic stimulation occurs when N bosons are in a given state, and the transition rate into that state is proportional to $N+1$, so that the number of particles in that state is enhanced.)

Two new phenomena recently observed with Bose condensates of sodium atoms are based on matter-wave amplification—the buildup of highly directional “superradiant” pulses of matter waves, done by a group at MIT, and four-wave mixing, done by a group at the National Institute of Standards and Technology in Gaithersburg, Maryland.

In a recently published paper,¹ the MIT group led by Wolfgang Ketterle and David Pritchard, and also including Shin Inouye, Ananth Chikkatur, Dan Stamper-Kurn, and Joern Stenger, relates the observed directional Rayleigh scattering to the long coherence time of the condensate, which introduces strong correlations between successive Rayleigh scattering events. The MIT experiment combines the quantum coherence of a Bose condensed gas with quantum features in light scattering, producing collective atomic radiative effects. The optical properties of their elongated condensate differ dramatically from those of a cold, dense, thermal gas of atoms.

The coherence of the condensate gives rise to four-wave mixing or perhaps superradiance.

A few months ago, Lu Deng, Edward Hadley, Jesse Wen, Marek Trippenbach, Yehuda Band, Paul Julienne, John Simsarian, Kristian Helmerson, Steven Rolston, and William Phillips reported² the observation of coherent four-wave mixing in which three sodium matter waves of differing momenta mix to produce, by means of nonlinear atom–atom interactions, a fourth wave with a different momentum.

MIT superradiance experiment

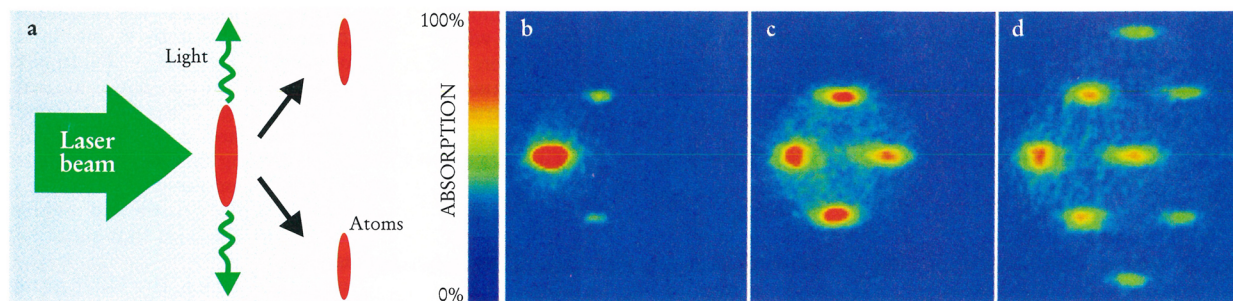
In describing the MIT experiment, Ketterle told us, “When a condensate has scattered light, an imprint is left in the form of long-lived excitations. This ‘memory’ accelerates the scattering of further photons into the same directions. It provides a gain mechanism for the generation of directed beams of atoms and light”—that is, directional Rayleigh scattering, unlike the ordinary variety, which is random. (Rayleigh scattering, in which a photon scatters off an atom or a molecule, is responsible for the blue sky.)

The MIT experimenters aimed a single off-resonant laser pulse (light detuned from the atomic resonance line) perpendicular to the long axis of an elongated Bose condensate that had been prepared in a magnetic trap. (See the figure below.) To probe the momentum distribution of scattered atoms,

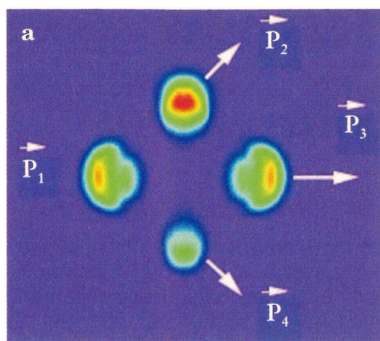
the experimenters turned off the magnetic trap just after the light pulse, and imaged the ballistically expanding cloud after a 20 ms time of flight. “It was late in the night,” recalls Ketterle. “We saw beams of atoms shooting out of the condensate. In five to ten minutes, we concluded we had a new phenomenon. It was really a surprise.”

At first the experimenters just studied the atoms. However, when they set up a detector to observe light, they found that collective scattering led to photons being scattered predominantly along the axial direction, and atoms being scattered at 45° with respect to the laser beam. When the experimenters illuminated the condensate with a single weak laser beam perpendicular to the condensate’s long axis, the condensate randomly scattered light in all directions, with the well-known dipolar pattern—ordinary Rayleigh scattering. But when a certain threshold intensity was reached, the condensate produced two highly directional beams of light. Because of the long coherence time of the condensate, the threshold intensity was as low as 1 mW/cm².

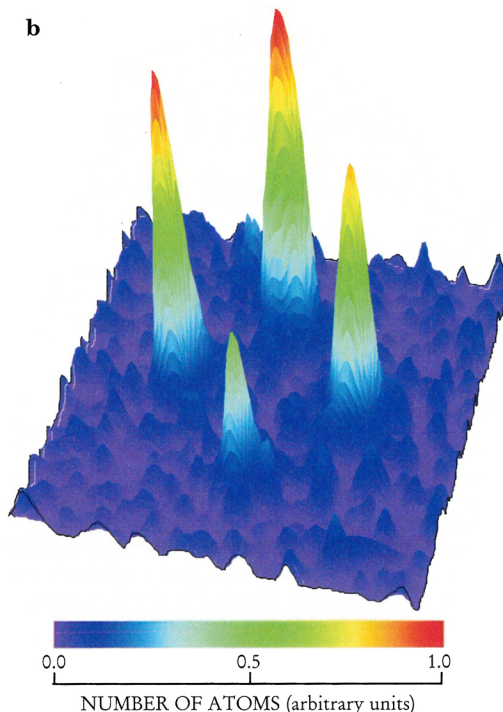
Ketterle, Pritchard, and their colleagues suggest that their new phenomenon is analogous to the concept of superradiance discussed by Robert Dicke in 1954, prior to the invention of the laser. Dicke showed that, in a system of incoherently excited two-level atoms contained in a small volume, the atoms would couple together through overlapping radiation fields. He predicted that a spontaneous emission



HIGHLY DIRECTIONAL RAYLEIGH SCATTERING. (a) A single off-resonant laser beam illuminates an elongated condensate. Collective scattering leads to photons scattered along the axial direction and atoms at 45°. (b), (c), and (d) Absorption images after 20 ms time of flight show atomic momentum distribution after condensate is exposed to a laser pulse of 35, 75, and 100 μ s, respectively. During expansion the aspect ratio changes so that the vertical elongation in (a) changes to horizontal in the other images. The additional momentum peaks are attributed to a sequential scattering process in which atoms undergo repeated superradiant scattering and populate a regular arrangement of final momentum states. (Adapted from ref. 1.)



NUMERICAL SIMULATION and experimental results for four-wave mixing. The experimenters start with three overlapping wavepackets with momenta $\mathbf{P}_1$, $\mathbf{P}_2$, and $\mathbf{P}_3$, and then a fourth wavepacket with momentum $\mathbf{P}_4$ is created. (a) Calculated two-dimensional atomic distribution after 1.8 ms. (Adapted from ref. 2.) (b) False-color image of the experimental atomic distribution showing the fourth (small peak) wavepacket generated by the four-wave mixing. (Courtesy of National Institute of Standards and Technology.)



from any one atom would tend to capture oscillations in all the other atoms, to produce a very large and almost totally coherent macroscopic polarization. So the system could evolve into a coherent superposition and emit, after a certain delay, what Dicke called a superradiant burst. Says Pritchard, "In Dicke superradiance, an oscillating coherence of internal states builds up and radiates. In our experiment, the moving density grating involves a superposition of translational states."

Treating the gain mechanism for Rayleigh scattering semiclassically, the MIT group finds that because light propagates at a velocity ten orders of magnitude greater than the recoil velocity of the sodium atoms, when the condensate scatters a photon, the recoiling atoms remain within the volume of the condensate long after the photons have left, and they affect subsequent scattering events. The moving atoms interfere with the condensate at rest to form a moving matter-wave grating, which diffracts the laser beam into the same direction as the earlier photons. This diffraction is a self-amplifying process because every diffracted photon creates another recoiling atom that increases the amplitude of the matter-wave grating. For an anisotropic Bose condensate, the gain is largest when the light is emitted along its longest axis. The semiclassical analysis predicts a buildup of highly anisotropic Rayleigh scattering from a nonspherical sample of atoms.

Very recently, Pierre Meystre and

Michael G. Moore (University of Arizona) have developed a full quantum mechanical theory to explain the MIT results, and in particular, they have shown that the observed fluctuations are quantum fluctuations. According to Meystre and Moore, the directional dependence of the Rayleigh scattering rate and depletion of the condensate lead to mode competition, which is ultimately responsible for the observed superradiance dynamics.

The MIT team finds that superradiance ends when all of the atoms in the condensate have been transferred to higher order recoiling beams.

NIST four-wave mixing

In 1961, shortly after the laser was developed, Peter Franken and his collaborators generated optical harmonics in a nonlinear medium (one in which the refractive index depends on the intensity of the light). Subsequently, experimenters produced multiwave mixing of several optical fields in a nonlinear medium and observed new phenomena, including optical phase conjugation by four-wave mixing. Almost four decades later, with the advent of the matter-wave laser (PHYSICS TODAY, March 1997, page 17, and April 1999, page 17), the NIST team has done an analogous experiment with matter waves, in which three sodium matter waves with different momenta collided to produce a fourth wave—that is, four-wave mixing.²

In 1995, Meystre and his collaborators had suggested producing four-

wave mixing using condensates prepared in different electronic states to enhance the nonlinearity. The NIST team found such preparation wasn't necessary, Phillips told us, because sufficient nonlinearity was already present in the ground state condensates they'd made. The NIST experimenters created three overlapping wavepackets with momenta $\mathbf{P}_n$ ($n = 1, 2, 3$) and observed the creation of the fourth wavepacket $\mathbf{P}_4$. Starting with a sodium condensate, the team used Bragg diffraction of atoms from a moving optical standing wave to create nearly simultaneously the three overlapping wavepackets of the required momenta. As the wavepackets separate, the interaction between the atoms, described by a nonlinear term in the Schrödinger equation, produces an additional,

fourth wavepacket that satisfies the condition $\mathbf{P}_4 = \mathbf{P}_1 - \mathbf{P}_2 + \mathbf{P}_3$ (see the figure on this page) and also conserves energy and particle number.

The four-wave mixing can be viewed in a frame of reference moving with velocity v such that the three input momenta have the same magnitude and two are counterpropagating. Then you can think of the mixing occurring in two steps. In the first step, condensates 1 and 2 (or 2 and 3) produce interference fringes (periodic variations in the density of the condensate). In the second step, condensate 3 (or 1) is Bragg reflected by those fringes to form condensate 4, at a 90° angle with respect to the incident direction. The four-wave mixing process can also be viewed as the annihilation of momentum states $\mathbf{P}_1$ and $\mathbf{P}_3$, the amplification of momentum state $\mathbf{P}_2$ and creation of state $\mathbf{P}_4 = \mathbf{P}_1 - \mathbf{P}_2 + \mathbf{P}_3$. In part (b) of the figure on this page, one sees a false-color image of the fourth (small peak) wavepacket generated by the four-wave mixing process. The largest peak, $\mathbf{P}_2$, is the one that got amplified, explains Phillips, and the two middle-sized ones "are the ones that sacrificed themselves."

Now, says Phillips, the NIST group would like to look at quantum correlations between the amplified wave and the fourth wave.

Comparisons

The NIST and MIT experiments both rely on a density grating formed by the interference of two matter waves. At

NIST, another matter wave is diffracted by the grating, whereas at MIT, light is diffracted by the grating. The superradiance reported by MIT is initiated spontaneously and depends only on light interacting with atoms,

whereas the four-wave mixing reported by NIST is purely a stimulated process and depends on interactions between atoms. Both effects depend on the mixing of four waves—four matter waves at NIST, and two matter waves and

two electromagnetic waves at MIT.

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References

1. S. Inouye *et al.*, *Science* **285**, 571 (1999).
2. L. Deng *et al.*, *Nature* **398**, 218 (1999).

Alpha Radiation Can Damage DNA Even when It Misses the Cell Nucleus

The biggest source of alpha radiation in our everyday lives is radon gas, which seeps out of the ground to accumulate in buildings and enter our lungs—with the potential to kill. Based on the average domestic radon concentration, the US Environmental Protection Agency has estimated that radon could cause up to 23 000 lung cancer deaths in the US each year.

But EPA's estimate was derived from epidemiological studies of uranium miners, who inhale much more radon than the typical house-dweller. For the rest of us, the average indoor radioactivity of 48 microbecquerels per cubic meter corresponds to most cells in the lining of the lung being traversed by an alpha particle either once or, more likely, never. Because it's far from clear that the risks associated with low doses can be accurately extrapolated from the existing data on high doses (see Jaworowski's article on page 24), it is vitally important that we be able to determine the cancer-inducing effect of small fluxes of alpha particles.

Death and mutability

Cells turn cancerous when their reproduction and growth, programmed by irreparably damaged DNA, get out of control. Because DNA resides in the cell nucleus, it's natural to presume that an alpha particle has to score a direct hit on the nucleus to induce DNA damage.

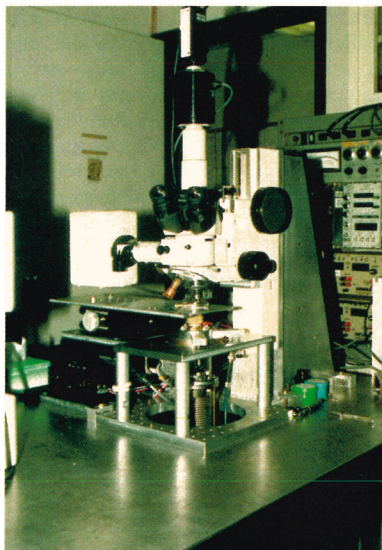
This conventional wisdom began to unravel seven years ago when Harvard University's Hatsumi Nagasawa and John Little irradiated cells with low fluxes of alphas.¹ From the level of genetic damage that ensued, the two researchers inferred that the cross section for genetic damage was much bigger than the cell nucleus. Indeed, their results implied that genetic damage could be induced in unirradiated neighboring cells—a phenomenon they dubbed the bystander effect. Direct proof of the bystander effect came in 1997 from Bruce Lehnert and Edwin Goodwin at Los Alamos National Laboratory.² Now, from Columbia University's Tom Hei and his coworkers comes direct evidence of a similar kind of effect: Alphas can hit a cell's cytoplasm, miss its nucleus, and still damage its DNA.³

An alpha-particle microbeam that can precisely irradiate specific parts of cells is being used to investigate radiation-induced genetic mutations.

To the physicist, investigating what happens when an alpha particle hits or misses a cell nucleus may seem simple: Shoot an alpha at an appropriate spot in the cell (the nucleus or the surrounding cytoplasm), and then assess the damage. The trouble is, the mutation frequency—even for direct hits on the nucleus—is extremely low. Only by precisely irradiating tens of thousands of cells can a picture be formed of the damage.

If you need statistics . . .

Thanks to its accuracy and sophisticated target acquisition mechanism, the microbeam at Columbia's Center for Radiological Research is just the



THE MICROBEAM at Columbia University's Center for Radiological Research. The alpha particles emerge upward from the tube beneath the microscope stage and strike their targets with micrometer precision (hence the term "microbeam"). Similar microbeams are installed at Texas A&M University and at the Gray Laboratory near London, England. (Courtesy of Tom Hei.)

tool for the job (see the picture on this page). Based on a 4 MeV Van de Graaff accelerator, it can fire single alphas with a spatial precision of 3.5 μm , which is sufficient to hit a single cell (30 μm across) while reliably avoiding its nucleus (10 μm across).

More impressive, perhaps, is the microbeam's automatic target acquisition system. Cell samples are placed in a string of dishes that are positioned one at a time beneath a digital camera. An image is taken of each batch of cells, whose nuclei and cytoplasm glow pink and red, respectively, thanks to the use of two special dyes (see the figure on page 20). Software automatically analyzes the image and identifies the position of each target. Next, the target coordinates are sent to the beam controller, which moves the dish to position the first target under the beam, opens the shutter, fires a predetermined exact number of alphas at the target, closes the shutter, and moves to the next target. When all the targets in a dish have been hit, the next dish takes its turn under the beam, and so on—all without human intervention. In that way, the Columbia microbeam can irradiate up to 15 000 cytoplasmic and nuclear targets per hour.

Human-hamster guinea pigs

As targets, Hei's team used human-hamster hybrid cells, which are made by fusing human fibroblasts and Chinese hamster ovary cells *in vitro*. Endowed with a full complement of hamster chromosomes, plus one copy of human chromosome 11, the hybrid cells are especially good at revealing a wide range of mutation. In the experiments, alpha particles were fired at the cytoplasm or nuclei of cells, and the degree of mutation was gauged by looking at a gene called *CD59*, which is located on human chromosome 11.

After expending more than 30 000 alphas, the Columbia researchers discovered that cytoplasmic irradiation does induce mutations in *CD59*. These mutations are patterned in the same way as naturally occurring spontaneous mutations, but take place at a three-times-higher rate. By contrast, the mutations induced by nuclear ir-