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6. AUTHOR(S)
Prof. Wolfgang Ketterle

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Research Laboratory of Electronics
Massachusetts Institute of Technology
77 Massachusetts Avenue
Cambridge, MA 02139

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13. ABSTRACT *(Maximum 200 words)*

Our long-term goals are twofold. First, to explore the new properties of gaseous Bose-Einstein condensates and advance our understanding of quantum gases. Second, we want to use Bose condensed gases as new atom sources of unprecedented brightness ("atom lasers") for precision atom optics and precision metrology.

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OFFICE OF NAVAL RESEARCH
END-OF-THE-YEAR REPORT
For the period 7/1/98 - 6/30/99

Experiments with Trapped Neutral Atoms

PI: Wolfgang Ketterle

Massachusetts Institute of Technology
Department of Physics and Research Laboratory of Electronics
77 Massachusetts Avenue
Cambridge, MA 02139
Phone: 617-253-6815
Fax: 617-253-4876
E-mail: KETTERLE@MIT.EDU

GRANT Number: N00014-96-1-0485
PR Number: 96PR02383-00
ONR Program Officer: Dr. Peter Reynolds

Long-term Research Objective:

Our long-term goals are twofold. First, to explore the new properties of gaseous Bose-Einstein condensates and advance our understanding of quantum gases. Second, we want to use Bose condensed gases as new atom sources of unprecedented brightness ("atom lasers") for precision atom optics and precision metrology.

S&T Objectives:

The goal is to characterize quantum-degenerate bosonic gases by studying their elementary excitations and their coherence properties. In parallel, we want to develop new techniques to manipulate and probe ultracold atomic matter.

Approach:

Ultralow temperatures are reached by applying first laser cooling and then evaporative cooling. The atomic samples are isolated using optical and magnetic traps. Excitations of Bose-Einstein condensates are created by perturbing the condensate, either by optical forces or magnetic forces.

S&T Completed:

1. Strongly enhanced inelastic collisions in a Bose-Einstein condensate near Feshbach resonances

The properties of Bose-Einstein condensed gases can be strongly altered by tuning an external magnetic field near a Feshbach resonance [1]. Feshbach resonances affect elastic collisions and lead to the observed modification of the scattering length [2]. However, we found that this is accompanied by a strong increase in the rate of inelastic collisions. The observed three-body loss rate increased by up to several orders of magnitude when the scattering length was tuned to both larger and smaller values than the off-resonant value [3]. These observations could not be explained by available theoretical treatments and have stimulated theoretical studies by several groups. The strong losses impose severe limitations for using Feshbach resonances to tune the properties of Bose-Einstein condensates.

2. Metastable Bose-Einstein condensates

In the previous year, we studied the equilibrium state of spinor condensates in an optical trap [4]. In contrast to magnetically trapped condensates, spinor condensates have the orientation of the spin as a degree of freedom, which can be described by a multi-component wavefunction (one for each magnetic sublevel). During the studies of the spinor ground states with total angular momentum F=1 we encountered two different types of metastability which we investigated in more detail [5]. In one case, a two-component condensate in the $m_F=+1$, 0 hyperfine states was stable in spin composition, but spontaneously formed a metastable spatial arrangement of spin domains. In the other, a single component $m_F=0$ condensate was metastable in spin composition with respect to the development of $m_F=+1$, -1 ground-state spin domains.

3. Quantum tunneling across spin domains in a Bose-Einstein condensate

The observation of metastable spin domains in optically trapped F=1 spinor Bose-Einstein condensates of sodium (previous section) raised the question of how thermal equilibrium would ultimately be achieved. Besides thermally activated processes, we observed quantum tunneling as an equilibration process. For the study of this process, spinor condensates were prepared which consisted of only two spin domains in the $m_F=0$ and $m_F=+1$ states. Those domains are immiscible due to their antiferromagnetic interaction. When a field gradient was added, it became energetically favorable for the two domains to change sides, and quantum tunneling was observed. A mean-field description of the tunneling process was developed and agreed well with the measurements [6].

4. Bragg spectroscopy of a Bose-Einstein condensate

The first evidence for Bose-Einstein condensation in dilute gases was obtained by a sudden narrowing of the velocity distribution as observed for ballistically expanding clouds of atoms. However, the dominant contribution to the observed momentum distribution of the expanding condensate was the released interaction energy (mean-field energy) resulting in momentum distributions much broader than the zero-point motion of the ground state of the harmonic trapping potential. Since the size of a trapped condensate with repulsive interactions is larger than the trap ground state, the in-situ momentum distribution should be considerably narrower than in the trap ground state. We could measure the momentum distribution of a trapped condensate with Doppler velocimetry using two-photon Bragg scattering. We observed that the momentum distribution was Heisenberg uncertainty limited by its finite size, i.e. the coherence length of the condensate was equal to its size [7].

5. Excitation of phonons in a Bose-Einstein condensate by light scattering

Light scattering imparts momentum to the condensate and creates an excitation (which can be a phonon or a free particle). A detailed study of the scattered light should therefore reveal a detailed picture of the Bose condensate similar to the case of superfluid helium where neutron scattering was used to obtain the spectrum of elementary excitations.

In the previous section, we showed how a condensate responds to a large momentum transfer, which lead to particle-like excitations. Light scattering at small angles does not impart enough momentum to the condensate to create a recoiling atom. Instead, it creates a sound wave by "optically imprinting" phonons into the gas. A sound wave is a collective excitation of all the atoms in the system and therefore requires that the atoms don't act as individual atoms, but show correlated motion. It has been predicted that this correlated motion results in much weaker light scattering than for free atoms. We found a significant decrease of the rate of light scattering in the phonon regime, providing dramatic evidence for the presence of correlated momentum excitations in the many-body condensate wavefunction [8].

6. Superradiant Rayleigh scattering from a Bose-Einstein condensate

We discovered a new phenomenon in the scattering of light by a condensate: highly directional, "superradiant" scattering of light and atoms [9]. This phenomenon is deeply rooted in the long coherence time of a condensate. 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 direction. It provides a gain mechanism for the generation of directed beams of atoms and light.

When a condensate was illuminated with a single weak laser beam, it randomly scattered light into all directions. However, above a certain threshold intensity, the condensate produced two highly directional beams of light. Such highly directional light scattering was accompanied by the production of highly directional beams of recoiling atoms. These beams of atoms were shown to build up by matter wave amplification. The condensate acted as an amplifier for a recoiling atom and "amplified" it to about a million atoms. The simultaneous superradiant emission of light and atoms emphasizes the symmetry between atom lasers and optical lasers.

7. A new BEC experiment

A major effort of our group is the design and construction of an improved source of Bose condensed atoms. The design includes an intense slow atomic beam, a glass trapping chamber and a tightly confining magnetic trap. In January '99, the first condensates were produced with about five million atoms in the condensate. A YAG laser with a rapidly scanning x/y deflector was implemented which will allow flexible manipulation and optical trapping of Bose condensates.

Impact / Navy Relevance:

Bose-Einstein condensates of dilute atomic gases are quantum degenerate gases, which have properties different form the quantum liquids helium-3 and helium-4. Therefore, it is now possible to study macroscopic quantum phenomena in a new regime.

Coherent atom sources based on Bose-Einstein condensation may replace conventional atomic beams in demanding applications such as atom interferometry, precision measurements, future atomic clocks (which provide the time and frequency standard), matter wave microscopy, and the creation of microscopic structures by direct-write lithography. The techniques, which we have developed, may improve future sensors for rotation based on matter-wave gyroscopes.

Planned Research Efforts:

We will study collective excitations with angular momentum. They will be excited by a scanning laser beam. We plan an experiment on superfluidity in a condensed Bose gas. The idea is to stir the gas with a scanning laser beam and show that there is no heating below a certain critical velocity.

References:

1. E. Tiesinga, B.J. Verhaar, and H.T.C. Stoof, Phys. Rev. A **47**, 4114 (1993).
2. S. Inouye, M.R. Andrews, J. Stenger, H.-J. Miesner, D.M. Stamper-Kurn, and W. Ketterle, Nature **392**, 151 (1998).

3. J. Stenger, S. Inouye, M.R. Andrews, H.-J. Miesner, D.M. Stamper-Kurn, and W. Ketterle, Phys. Rev. Lett. **82**, 2422 (1999).
4. J. Stenger, S. Inouye, D.M. Stamper-Kurn, H.-J. Miesner, A.P. Chikkatur, and W. Ketterle, Nature **396**, 345 (1998).
5. H.-J. Miesner, D.M. Stamper-Kurn, J. Stenger, S. Inouye, A.P. Chikktur, and W. Ketterle, Phys. Rev. Lett. **82**, 2228 (1999).
6. D.M. Stamper-Kurn, H.-J. Miesner, A.P. Chikkatur, S. Inouye, J. Stenger, and W. Ketterle, Phys. Rev. Lett. (1999), in press.
7. J. Stenger, S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, D.E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **82**, 4569 (1999).
8. D.M. Stamper-Kurn, A.P. Chikkatur, A. Görlitz, S. Inouye, S. Gupta, D.E. Pritchard, and W. Ketterle, Phys. Rev. Lett. (1999), submitted.
9. S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, J. Stenger, D.E. Pritchard, and W. Ketterle, Science (1999), in press.

Other Sponsored Science & Technology (besides ONR):

- "Basic Research in Electronics", Army Research Office, $ 97,050 for the period 1/98 - 1/01 (non-renewable)
- "Atomic Quantum Gases", NSF Career Program, $ 415,000 for the period 5/1/98 through 4/30/00
- "Packard Fellow in Science and Engineering", David and Lucile Packard Foundation, $ 575,000 for the period 9/24/1996 through 9/23/2001 (non-renewable)
- "Towards Precision Experiments with Bose-Einstein Condensates", NASA, $ 410,000 for the period 2/1/98 - 1/31/03
- "Atom Interferometry, atom optics and the atom laser", DURIP, Army Research Office, $ 117,000 for the period 3/01/99 – 12/31/99

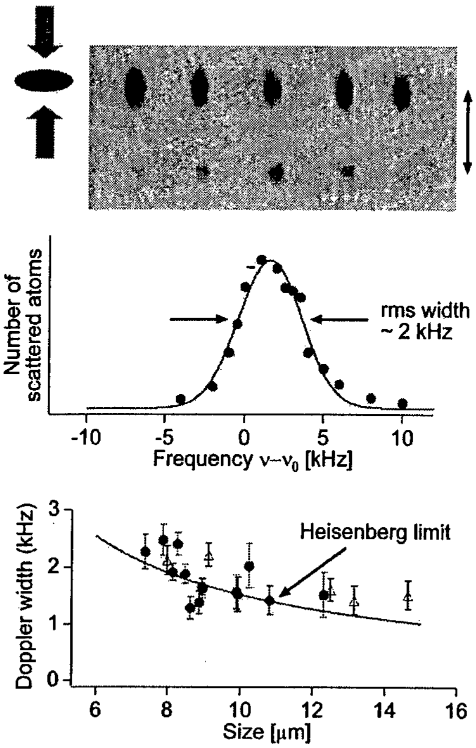

Figure caption: Bragg spectroscopy of a trapped condensate. A condensate was exposed to two counterpropagating laser beams. Atoms absorbed a photon from one beam and were stimulated to emit it by the other beam, resulting in the transfer of recoil momentum to the atoms, as observed in ballistic expansion using absorption imaging after 20 msec. time-of-flight (upper part). The number of Bragg scattered atoms showed a narrow resonance when the difference frequency between the two laser beams was varied (upper and middle part). The width of the resonance was studied for various radial sizes of the condensate. The solid line (lower part) compares the experimental results with the prediction for the momentum uncertainty due to the finite size. The agreement shows that the coherence length of a condensate is equal to its physical size, i.e. condensates are one “coherent matter wave”.

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Experiments with Trapped Neutral Atoms
PI: Wolfgang Ketterle

Massachusetts Institute of Technology
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Phone: 617-253-6815
Fax: 617-253-4876
E-mail: KETTERLE@MIT.EDU

GRANT Number: N00014-96-1-0485
PR Number: 96PR02383-00
ONR Program Officer: Dr. Peter Reynolds

Subcontractors:

None.

Technology Transfer:

Our current effort includes the development of new techniques to manipulate coherent atomic matter. There are potential technological applications in atomic clocks and metrology, but these are rather long-term prospects.

Journal publications appearing in print:

1. J. Stenger, S. Inouye, A.P. Chikkatur, D.M. Stamper-Kurn, D.E. Pritchard, and W. Ketterle:
   Bragg spectroscopy of a Bose-Einstein condensate.
   Phys. Rev. Lett. **82**, 4569–4573 (1999).
2. H.-J. Miesner, D.M. Stamper-Kurn, J. Stenger, S. Inouye, A.P. Chikkatur, and W. Ketterle:
   Observation of metastable states in spinor Bose-Einstein condensates.
   Phys. Rev. Lett. **82**, 2228-2231 (1999).
3. J. Stenger, S. Inouye, M.R. Andrews, H.-J. Miesner, D.M. Stamper-Kurn, and W. Ketterle:
   Strongly enhanced inelastic collisions in a Bose-Einstein condensate near Feshbach resonances.
   Phys. Rev. Lett. **82**, 2422–2425 (1999).
4. J. Stenger, D.M. Stamper-Kurn, M.R. Andrews, A.P. Chikkatur, S. Inouye, H.-J. Miesner, and W. Ketterle:
   Optically confined Bose-Einstein condensates.
   Proceedings of the Symposium on "Quantum Fluids and Solids" (QFS 98), Amherst, Massachusetts, June 9-14, 1998.
   J. Low Temp. Phys. **113**, 167-188 (1998).
5. J. Stenger, S. Inouye, D.M. Stamper-Kurn, H.-J. Miesner, A.P. Chikkatur, and W. Ketterle:
   Spin domains in ground state spinor Bose-Einstein condensates.
   Nature **396**, 345-348 (1998).

6. D.M. Stamper-Kurn, H.-J. Miesner, A.P. Chikkatur, S. Inouye, J. Stenger, and W. Ketterle:
   Reversible formation of a Bose-Einstein condensate.
   Phys. Rev. Lett. **81**, 2194-2197 (1998).
7. H.-J. Miesner and W. Ketterle:
   Bose-Einstein condensation in dilute atomic gases.
   Proceedings of the Symposium on "The Advancing Frontiers of Condensed Matter Science", Philadelphia, Oct. 13-14, 1997.
   Solid State Comm. **107**, 629-637 (1998).
8. D.M. Stamper-Kurn, H.-J. Miesner, S. Inouye, M.R. Andrews, and W. Ketterle:
   Collisionless and hydrodynamic excitations of a Bose-Einstein condensate.
   Phys. Rev. Lett. **81**, 500-503 (1998).
9. W. Ketterle:
   Optical Confinement of Bose-Einstein Condensates.
   Optics&Photonics News, December 1998, p. 42.
10. M. Naraschewski and D.M. Stamper-Kurn
    Analytical description of a trapped semi-ideal Bose gas at finite temperature.
    Physical Review A **58**, 2423-2426 (1998).

Formal technical reports released by your institution:
None

Presentations (indicate invited presentations):
Invited Presentations 7/1/98 – 6/30/99

1. *Making, probing and understanding Bose-Einstein condensates.*
   Four lectures at the Summer School on Bose-Einstein condensation in atomic gases, International School of Physics "Enrico Fermi", Varenna, Italy, July 7-18, 1998.
2. *Bose-Einstein condensation, atomic coherence and the atom laser.*
   Sixth European Conference on Atomic and Molecular Physics (ECAMP VI), Siena, Italy, 14-18 July 1998.
3. *Experiments with optically confined Bose-Einstein condensates.*
   Conference on "Trapped Charged Particles and Fundamental Physics", Monterey, Aug. 30 - Sept. 4, 1998 (Talk by H.-J. Miesner).
4. *New experiments with optically confined Bose-Einstein condensates.*
   European Research Conference on Quantum Optics, Castelvecchio Pascoli, Italy Sept 29 - Oct. 4, 1998 (Talk by H.-J. Miesner).
5. *Recent advances in Bose-Einstein condensation.*
   CLEO/Europe-EQEC'98, Glasgow, Scotland, Sept. 13-18, 1998.
6. *The new physics of optically trapped Bose-Einstein condensates.*
   Annual meeting of the section for atomic physics ad quantum electronics of the Dutch physical society, Lunteren, 5-6 November 1998.
7. *Spinor condensates and Bragg spectroscopy*
   Workshop on Bose-Einstein condensation and degenerate Fermi gases, JILA, Boulder, 2/10-2/12/1999.
8. *The Physics of Cold Atoms at Millikelvin, Microkelvin and Nanokelvin Temperatures.*
   Tutorial at the APS Centennial Meeting, Atlanta, 3/21-3/26/1999.

9. Spring meeting of the German Physical Society.
   (Talk by J. Stenger).
10. *Keeping the focus on Bose-Einstein condensates.*
    Fysica '99, Nederlandse Natuurkundige Vereniging, Delft, Netherlands, 4/14/1999.
11. *Recent Results on BEC: Quantum Tunneling, Bragg Spectroscopy and Superradiance.*
    1999 NASA/JPL International Conference on Fundamental Physics in Space.
    Washington DC, 4/29-5/1/1999.
12. *Dilute Bose-Einstein condensates - early predictions and recent experimental studies.*
    C.N. Yang Symposium, Stony Brook, 5/21-22/1999.
13. ICOLS, Innsbruck, Austria, 6/7-11/1999.
    (Talk by J. Stenger).

Total number of other presentations by group members: 32

Books or book chapters published:

1. H.-J. Miesner and W. Ketterle:
   Bose-Einstein condensation in dilute atomic gases and realization of an atom laser.
   (Article is a shortened version of the Solid State Comm. paper).
   SPIE Proceedings Vol. 3270, Methods for Ultrasensitive Detection, ed. B. L. Fearey, ISBN 0-8194-2709-8, pp. 107-115 (1998).
2. M.R. Andrews, D.S. Durfee, S. Inouye, D.M. Kurn, H.-J. Miesner, and W. Ketterle:
   Studies of Bose-Einstein condensates.
   (Article identical to the J. Low. Temp. Phys. paper).
   in: "Macroscopic Quantum Coherence", eds. E. Sassaroli, Y. Srivastava, J. Swain, and A. Widom (World Scientific, Singapore, 1998), pp. 38-52.
3. W. Ketterle:
   Atom laser.
   McGraw-Hill 1999 Yearbook of Science & Technology (McGraw-Hill, New York, 1998), pp. 43-46.

Patents (indicate status, e.g., filed, issued):

None

Honors, awards or prizes received during the reporting year:

- Shin Inouye, a graduate student, was selected as the winner of the 1999 Deutsch Award for Excellence in Experimental Physics. This award is given every other year to one graduate student at MIT.
- Dan Stamper-Kurn, was one of the 1998 winners of the New Focus Student Award of the Optical Society of America
- Wolfgang Ketterle was awarded the 1999 Fritz London Prize in Low Temperature Physics.
- Wolfgang Ketterle was elected a fellow of the American Academy of Arts and Sciences.

Number of Students Supported (minimum of 1/4of their support):

Post Doctoral: 0 Doctoral: [illegible] Masters: 0 Undergraduate: 0
3

Note: The salaries for the graduate students and postdocs involved in the current experiments are paid from AASERT awards, the Packard fellowship and the NSF grant (this is cost-effective due to different overhead charges).

9	Number of Papers Published in Refereed Journals Citing ONR Support
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45	Number of Presentations
1	Number of Degrees Granted (Jeff Gore)
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