The **RESEARCH LABORATORY *of* ELECTRONICS**
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
77 MASSACHUSETTS AVENUE
CAMBRIDGE, MASSACHUSETTS 02139-4307

18 July 1995

Dr. Peter J. Reynolds, Code 312AI
Scientific Officer
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5660

In accordance with the terms of the Office of Naval Research Grant No. N00014-94-1-0807, I am sending you the following material:

Type of Material:	Annual Technical Report Annual AASERT Evaluation Report
Title:	A Quantum Gas of Cold Lithium Atoms
Submitted by:	Prof. David E. Pritchard
Period Covered:	July 1, 1994 - June 30, 1995
Number of Copies:	Three plus form 298
Distribution:	ONR Distribution List (5)

Thank you. Please contact me if you have any questions or comments.

Mary S. Greene
RLE Financial Assistant
Room 36-437

cc: Prof. Pritchard (1)
A.F. Favaloro, E19-702
File (1)

OSP 61908

Enclosures

Accesion For		
NTIS CRA&I		☒
DTIC TAB		☐
Unannounced		☐
Justification		
By		
Distribution /		
Availability Codes		
Dist	Avail and / or Special	
A-1		

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
June 29, 1995

3. REPORT TYPE AND DATES COVERED
Interim, 7/1/94-6/30/95

4. TITLE AND SUBTITLE
Evaporative Cooling of Magnetically Trapped Neutral Atoms
[AASERT grant: A quantum gas of Cold lithium atoms]

5. FUNDING NUMBERS
N00014-94-1-0807
aasert940201

6. AUTHOR(S)
Wolfgang Ketterle and David E. Pritchard

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

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Office of Naval Research
Ballston Tower One
800 North Quincy Street
Arlington, VA 22217-5660

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The view, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy, or decision, unless so designated by other documentation.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited.

12b. DISTRIBUTION CODE

13.

Abstract:

We have observed evaporative cooling of sodium atoms trapped in a spherical quadrupole trap. A novel technique, rf induced evaporation, was used to reduce the temperature by a factor of twelve and increase the phase space density by more than two orders of magnitude. The elastic collision cross section of cold sodium atoms in the F=1, m_F=-1 hyperfine state was determined to be 6 10^{-12} cm^2 which implies a positive value of the scattering length. The increase in phase space was limited by trap loss due to Majorana flops in the center of the magnetic trap where the magnetic field goes through zero.

This trap loss is avoided in a novel hybrid trap employing magnetic fields and optical dipole forces. The magnetic field configuration is still the magnetic quadrupole, but the trap loss is suppressed by a tightly focused blue detuned laser beam which creates a repulsive AC Stark shift potential around the zero of the magnetic field. Evaporative cooling in this trap increased the phase space density by about five orders of magnitude, only a factor of 30 less than required to reach the phase transition to Bose-Einstein condensation.

14. SUBJECT TERMS
Evaporative cooling
Bose-Einstein condensation

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Evaporative cooling of magnetically trapped neutral atoms

Annual Report for AASERT grant
"A quantum gas of cold lithium atoms"
Period 7/1/94 to 6/30/95

PROFESSORS: Wolfgang Ketterle, David E. Pritchard

GRADUATE STUDENTS: Michael R. Andrews, Kendall B. Davis, Marc O. Mewes, Dallin Durfee

UNDERGRADUATE STUDENTS: Ilya Entin, Philip Hinz, Everest Huang, Stanley Thompson, Peter S. Yesley, Charles Sestok

Introduction

Cooling and trapping of neutral atoms offers exciting new possibilities. Many are related to the fact that the deBroglie wavelength increases with decreasing temperature T as $1/\sqrt{T}$. When the deBroglie wavelength is comparable to atomic dimensions (range of the interaction potential) collisions can no longer be treated classically and are dominated by a few partial waves. Dramatic effects are expected for even colder temperatures and higher densities, when the deBroglie wavelength becomes comparable to the interatomic spacing. In this case, the "atomic waves overlap" and a novel type of highly correlated quantum matter is predicted. In the case of bosonic atoms one expects the formation of a Bose condensate, a macroscopic population of a single quantum state [1], and phenomena similar to superconductivity or superfluidity; fermions would form a highly correlated Fermi sea.

Such strongly correlated atoms are predicted to exhibit unusual behavior in their interaction with light and in collisions. Furthermore, such samples of atoms have potential applications in the field of atom optics, such as the creation of microscopic structures by direct-write lithography or atom microscopy. With coherent atoms, one could realize the ultimate resolution in focusing atoms which is analogous to the diffraction limit in optics. A Bose condensate would also find application in metrology, improving frequency standards and atom interferometry.

The observation of degenerate quantum gases requires temperatures well below the recoil-limit (i.e. kinetic energies should be much less than the recoil energy due to the emission of a single photon). Although optical sub-recoil cooling is possible, it has severe limitations due to collisions of excited atoms and absorption of scattered light.

Our approach is to use evaporative cooling which does not involve light and therefore has no recoil limit to overcome. The cooling is accomplished by selectively removing atoms with the highest energy from the trap and then allowing the rest of the sample to rethermalize through elastic collisions. Unfortunately, this method requires high initial densities which could until recently only be prepared by cryogenic methods applicable solely to atomic hydrogen [2]. By using a combination of different cooling and trapping techniques involving lasers and magnetic fields we were able to obtain the high initial density and observe evaporative cooling. This closes the gap between optical cooling at relatively low density and collisional cooling. It frees evaporative cooling from the restrictions of a cryogenic environment by using laser cooling as the precooling stage.

The graduate students (Michael R. Andrews, Kendall B. Davis) and the undergraduate students (Philip Hinz, Everest Huang) supported by the AASERT grant have made essential contributions to the first demonstration of evaporative cooling in alkali atoms [3, 4] and to major improvements since then. They are now described in greater detail.

Elastic cross section of ultracold sodium atoms

The driving process for evaporative cooling is elastic collisions. We were able to deduce the elastic collision cross section by observing the thermalization of an atom cloud (Figure 1). For this, a non-thermal distribution was prepared by temporarily displacing the trap center along the symmetry axis resulting in an elongated cloud. Using absorption imaging, the relaxation of this anisotropic energy distribution was observed by recording the shape of the cloud as a function of time [5]. In principle, equilibration might happen due to the ergodic evolution of orbits in the trap independent of collisions. However, this effect was ruled out by showing that the equilibration time depended linearly on density.

From the thermalization time we derived the elastic cross section $\sigma = 6.0 \pm 3.0$ cm^{-12}. The measurement was performed at 200 μK, well below the temperature (1 mK) at which one expects d-wave contributions or a temperature dependence of the s-wave cross section. We can therefore deduce the scattering length $a = \pm(92 \pm 25)\ a_0$ using the relation $\sigma = 8\ \pi\, a^{\ 2}$. Recently, accurate calculations of the scattering length of cold sodium atoms have been performed. For sodium atoms in the F=1, m_F = -1 state the result was $56\ a_0 < a < 154\ a_0$ and, for an alternative choice of potentials $-36\ a_0 < a < 154\ a_0$ [6]. Thus those calculations could not rule out negative values of the scattering length which would result in an unstable Bose condensate. Our experimental result, together with the theoretical prediction, show that sodium in the F=1, m_F = -1 state has a large positive scattering length and is therefore an ideal choice for the pursuit of Bose Einstein condensation in alkali atoms.

Rf induced evaporative cooling of atoms

We want to reach the nK regime using evaporative cooling. Evaporative cooling is accomplished by repetitively removing the high energy "tail" of the thermal distribution of atoms in the trap [7]. The remaining atoms then cool collisionally as the high energy tail is repopulated. The essential condition for evaporative cooling is that the collision rate be sufficiently high for many collisions to occur within the lifetime of the atoms in the trap. Beside high initial density and long trapping times, evaporative cooling requires a method for selectively removing hot atoms from the trap. In rf induced evaporation, atoms are spinflipped to an untrapped state when they are in resonance with an applied rf field [8]. Since this resonance frequency is a function of magnetic field B, atoms are selectively removed at a specific value of B. In the case of transitions between magnetic sublevels m_F, the resonance frequency is $\omega_{rf} = |g|\ \mu_B\ B/\hbar$, where g is the g-factor and μ_B the Bohr magneton. Since the trapping potential is given by $m_F g \mu_B\ B(r)$, only atoms which have a total energy $E > \hbar\omega_{rf}\ |m_F|$ will evaporate, or in other words, application of rf radiation of frequency ω_{rf} creates a trap lip with a height of $\hbar\omega_{rf}\ |m_F|$. An advantage is that the "lip" exists over a large surface rather than a small saddle point region of the trap [2].

We observed temperature reduction by a factor of 12 and a simultaneous increase in density by a factor of 4.6 resulting in an increase in phase space density by a factor of 190. Evaporation was performed in such a way that the elastic collision rate, which is proportional to density times velocity, increased during evaporation. We are therefore already in the regime where evaporative cooling is self-accelerating. Indeed, one expects "run-away" evaporation when the number of collisions during a trapping time exceeds 25 [9]. With an estimated collision rate of 50/s in the compressed cloud we exceed this value by a factor of about 60. The cloud after evaporation had a temperature of 80 μK and a density of $2\ 10^{12}$ cm^{-3}. This phase space density is $2\ 10^{4}$ times smaller than required for Bose-Einstein condensation.

An optically plugged magnetic quadrupole trap

The limitation of our initial evaporative cooling experiments is an increased trap loss for small atom clouds. For the coldest temperatures achieved, the trapping time decreases from 30 s to a few seconds. This is due to Majorana flops, non-adiabatic transitions to an untrapped state which happen near the center of the trap where the magnetic field vanishes [10].

We have demonstrated a novel type of magnetic trap, which provides the tight confinement of a linear potential, but avoids trap loss due to non-adiabatic spin flips near zero magnetic field. The trap loss is suppressed by a tightly focused blue detuned laser beam which creates a repulsive AC Stark shift potential around the zero of the magnetic field (see Fig. 3). One concern when using light forces to manipulate atoms is the heating generated by photon scattering. However, due to the far-off resonant detuning, photon scattering rates are less than 0.01/s.

Rf induced evaporation in this trap increased the phase space density by about five orders of magnitude, only a factor of 30 less than the phase transition to Bose-Einstein condensation. In the 1000 G/cm gradient, the size of the atom cloud approached our resolution limit of 10 μm. Adiabatic expansiŏn is non-trivial, because the magnetic center has to be kept aligned with the optical plug. Work into this direction is in progress.

REFERENCES:

1. K. Huang, *Statistical Mechanics*, second edition (Wiley, New York, 1987).
2. N. Masuhara *et al.*, Phys. Rev. Lett. **61**, 935 (1988).
3. K.B. Davis, M.-O. Mewes, M.A. Joffe, M.R. Andrews, and W. Ketterle, Phys. Rev. Lett. **74**, 5202 (1995).
4. K.B. Davis, M.O. Mewes, M.A. Joffe, and W. Ketterle, in *Fourteenth International Conference on Atomic Physics*, Boulder, Colorado, 1994, Book of Abstracts, 1-M3.
5. C.R. Monroe, E.A. Cornell, C.A. Sackett, C.J. Myatt, and C.E. Wieman, Phys. Rev. Lett. **70**, 414 (1993).
6. A.J. Moerdijk and B.J. Verhaar, Phys. Rev. Lett. **73**, 518 (1994).
7. H.F. Hess, Phys. Rev. B **34**, 3476 (1986).

8. D.E. Pritchard, K. Helmerson, and A.G. Martin, in *Atomic Physics 11*, edited by S. Haroche, J.C. Gay, and G. Grynberg, Proceedings of the 11th International Conference on Atomic Physics (World Scientific, Singapore, 1989) p. 179.

9. K.B. Davis, M.-O. Mewes, and W. Ketterle, Appl. Phys. B **60**, 155 (1995).

10. T.H. Bergeman, P. McNicholl, J. Kycia, H. Metcalf, and N.L. Balazs, J. Opt. Soc. Am. B **6**, 2249 (1989).

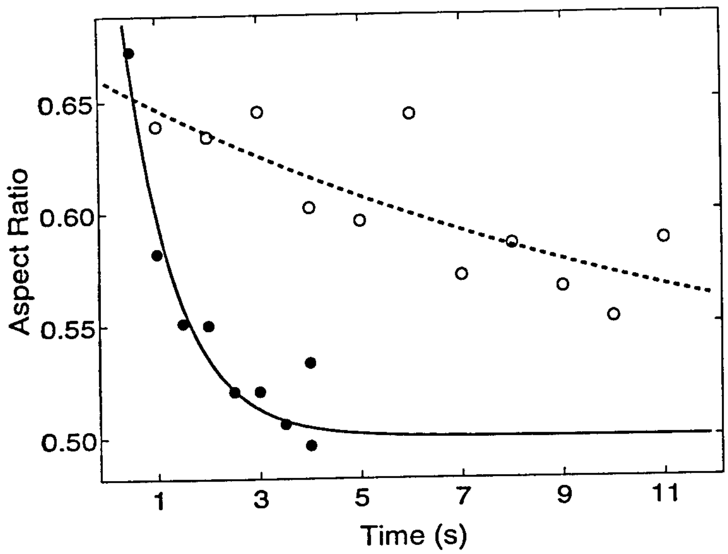

FIGURE 1: Thermal relaxation of an atom cloud after one-dimensional heating. The figure shows the aspect ratio of the cloud versus time for two different initial (peak) densities (solid circles: 5 10^{10} cm^{-3}, open circles: 4 $10^{-9}cm^{-3}$). The lines represent simple exponential fits with time constants of 1.0 s and 13 s, respectively.

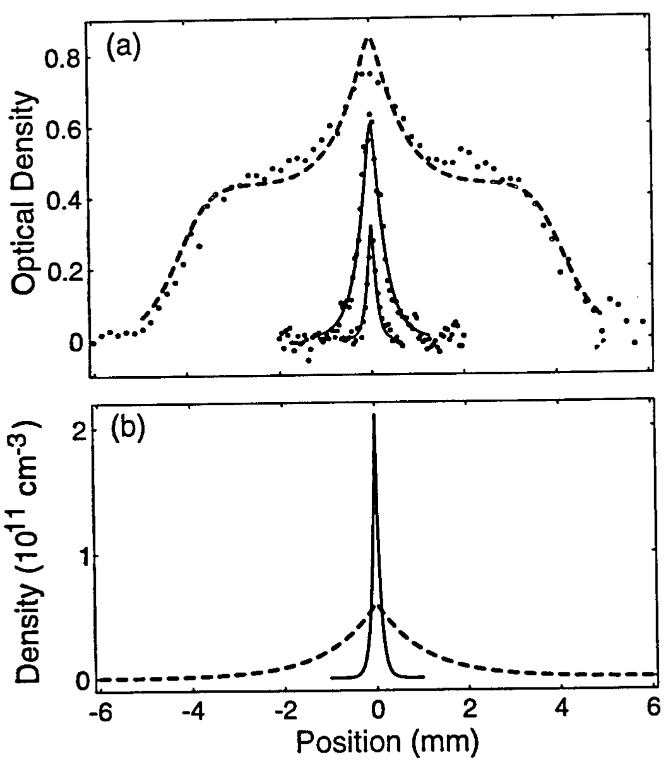

FIGURE 2: Optical density (a) and density (b) before and after evaporative cooling. The initial temperature was reduced by a factor of twelve. At the same time, the density increased, despite the loss in the number of trapped atoms.

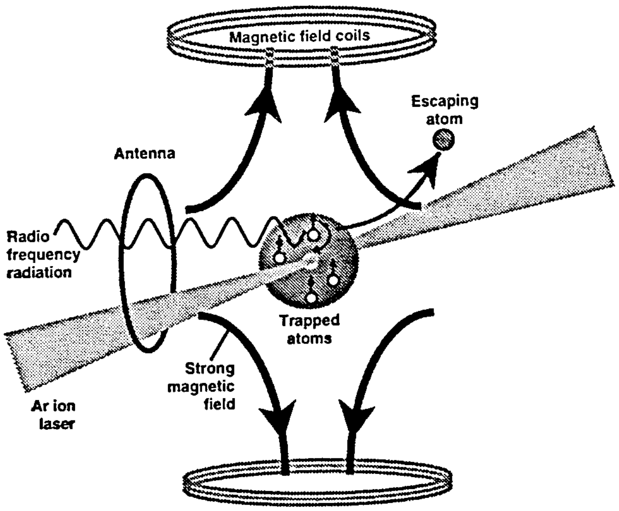

FIGURE 3: Experimental setup for forced evaporation. Neutral atoms are magnetically trapped. Radio-frequency radiation is tuned into resonance with the most energetic atoms in the thermal distribution. These atoms are spin-flipped to an untrapped state and ejected from the trap. The temperature of the remaining atoms is reduced by collisional thermalization. Trap loss due to Majorana flops in the center of the trap is avoided by repelling the atoms with a focused Ar ion laser beam - the Ar ion laser is "plugging the hole" due to Majorana flops.

RECENT PUBLICATIONS:

K.B. Davis, M.-O. Mewes, M.A. Joffe, M.R. Andrews, and W. Ketterle:
Evaporative Cooling of Sodium Atoms.
Phys. Rev. Lett. **74**, 5202 (1995).

K.B. Davis, M.-O. Mewes, and W. Ketterle:
An analytical model for evaporative cooling of atoms.
Appl. Phys. B **60**, 155 (1995).

CONFERENCE CONTRIBUTIONS WITH PUBLISHED ABSTRACTS

K.B. Davis, M.-O. Mewes, M.A. Joffe, M.R. Andrews, and W. Ketterle:
Evaporative Cooling of Sodium Atoms.
Research conference on Bose-Einstein condensation, Mont Ste. Odile, June 1995, Book of Abstracts, p. 53.

W. Ketterle:
Evaporative cooling of magnetically trapped sodium.
Bull. Am. Phys. Soc. **40**, 1269 (1995).

W. Ketterle:
Cooling and trapping of neutral atoms.
The Future of Spectroscopy: From Astronomy to Biology. Quebec, Sept. 1994, National Research Council Canada, Book of Abstracts, p. 34.

K.B. Davis, M-O. Mewes, M.A. Andrews, and W. Ketterle:
Transfer of laser-cooled atoms into a magnetic trap.
in: OSA Annual Meeting, Dallas, 1994, Program p.135, Abstract WPP3.

K.B. Davis, M-O. Mewes, P. Yesley, M.A. Joffe, D.E. Pritchard, and W. Ketterle:
A spin-flip Zeeman slower for the production of intense slow sodium beams.
in: OSA Annual Meeting, Dallas, 1994, Program p.135, Abstract WPP4.

K.B. Davis, M-O. Mewes, M.A. Joffe, and W. Ketterle:
Evaporative cooling of sodium atoms.
14th International Conference on Atomic Physics (ICAP) 1994, Boulder, Colorado, Book of Abstracts, Paper 1M-3.

W. Ketterle, K.B. Davis, M.A. Joffe, M.-O. Mewes, and D.E. Pritchard:
Dark cold atoms at high densities.
International Quantum Electronics Conference (IQEC), Anaheim, California 1994.
1994 Technical Digest Series, Vol. 9 (Optical Society of America, Washington, D.C., 1994) p. 236.

THESIS (Graduate)
Kendall B. Davis, "Evaporative cooling of sodium atoms", Ph.D. thesis, Dept. of Physics, MIT, 1995.

Stanley H. Thompson, Jr., "Radio Frequency Induced Evaporative Cooling of Magnetically trapped Neutral Sodium Atoms", B.S. thesis, Dept. of Physics, MIT, 1995.

Ilya A. Entin, "Magnetic trapping of Neutral Sodium Atoms", B.S. thesis, Dept. of Physics, MIT, 1995.

GRANT NUMBER: N00014-94-1-0807

FORM A2-2

AUGMENTATION AWARDS FOR SCIENCE & ENGINEERING RESEARCH TRAINING (AASERT)
REPORTING FORM

The Department of Defense (DOD) requires certain information to evaluate the effectiveness of the AASERT program. By accepting this Grant Modification, which bestows the AASERT funds, the Grantee agrees to provide the information requested below to the Government's technical point of contact by each annual anniversary of the AASERT award date.

1. Grantee identification data: (R & T and Grant numbers found on Page 1 of Grant)

a. Massachusetts Institute of Technology
University Name

b. N00014-94-1-0807
Grant Number

c. aasert940201
R & T Number

d. Prof. David E. Pritchard
P.I. Name
Prof. Wolfgang Ketterle
Co - P.I.

e. From: 7/94 To: 6/95
AASERT Reporting Period

NOTE: Grant to which AASERT award is attached is referred to hereafter as "Parent Agreement."

2. Total funding of the Parent Agreement and the number of full-time equivalent graduate students (FTEGS) supported by the Parent Agreement during the 12-month period prior to the AASERT award date.

a. Funding: $ 190,000

b. Number FTEGS: 2

3. Total funding of the Parent Agreement and the number of FTEGS supported by the Parent Agreement during the current 12-month reporting period.

a. Funding: $ 130,000

b. Number FTEGS: 1

4. Total AASERT funding and the number of FTEGS and undergraduate students (UGS) supported by AASERT funds during the current 12-month reporting period.

a. Funding: $ 55,011

b. Number FTEGS: 1.5

c. Number UGS: 1

VERIFICATION STATEMENT: I hereby verify that all students supported by the AASERT award are U.S. citizens.

Wolfgang Ketterle
Principal Investigator

6-27-95
Date

GRANT NUMBER: N00014-94-1-0807

ATTACHMENT NUMBER 2

REPORTS AND REPORT DISTRIBUTION

REPORT TYPES

(a) Performance (Technical) Report(s) (Include letter report(s))
FREQUENCY: As required.

(b) Final Technical Report, issued at completion of Grant.

(c) Final Financial Status Report (SF 269)

(d) University Research Initiative (URI)-Augmentation Awards for Science & Engineering Research Training (AASERT) Report (Use attached Form A2-2)

REPORT DISTRIBUTION

ADDRESSEE	REPORT TYPES	NUMBER OF COPIES
Scientific Officer: Peter J. Reynolds Code 312AI Office of Naval Research 800 North Quincy Street Arlington, Virginia 22217-5660	(a) & (b) (d)	3 1
Administrative Grants Officer Office of Naval Research Resident Representative ONR MIT 495 Summer Street Room 103 Boston MA 02210-2109	(a) & (b) & (c)	1
Director, Naval Research Laboratory Attn: Code 2627 Washington, DC 20375	(a) & (b)	1
Defense Technical Information Center Building 5, Cameron Station Alexandria, Virginia 22304-6145	(a) & (b)	2
ONR Code: 11SP Attn: AASERT/92 800 N. Quincy St. Arlington, Virginia 22217-5660	(d)	1

If the Scientific Officer directs, the Grantee shall make additional distribution of technical reports in accordance with a supplemental distribution list provided by the Scientific Officer. The supplemental distribution list shall not exceed 250 addressees.