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13. ABSTRACT (Maximum 200 words)

We have made important progress in experiments and theory of laser cooling of neutral atoms. In addition, our understanding of quantum effects in laser cooling is evolving very rapidly, and this has enormous influence on how we view the subject. This change has impacted on both experimental and theoretical work.

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to

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AUGUST 1991 to JULY 1992

I. EXPERIMENTAL PROGRESS

A. Rb rf Experiments. In our laser cooling experiments in Rb the rms kinetic energy of the atoms can easily be less than the amplitude of the sinusoidal potential created by the light shifts in an optical standing wave. The atomic kinetic energy typically corresponds to <0.1 MHz, whereas the light shift (height of the potential hills) for typical laser parameters is 0.8 MHz. Thus the atoms must be channeled between the nodal planes of the optical standing wave. Since the deBroglie wavelength of these atoms is ≅ 250 nm, and the channels are $\lambda/2$ = 390 nm wide, their motion is clearly quantum mechanical. Laser cooling is then viewed as an optical pumping process that drives atoms toward the lowest quantum state of motion.

Thus it seems attractive to use rf transitions to excite atoms to higher vibrational levels of the sinusoidal potential wells and look for resonant effects on the velocity distribution. We have therefore built rf coils whose B field is oriented to induce $\Delta m = \pm 1$ transitions in the interaction region. Such rf transitions can not simply excite atoms to different levels within the same potential well because the rf field can not change the motion of the atom (that is, the transition matrix elements do not couple the mutually orthogonal vibrational levels). But transitions that change m can change the atomic motion because of the small differences of the shape of the potentials of the different m states.

The width of such transitions is determined by the coherence lifetime of the coupled states, and that is limited by the optical pumping rate γ_p that depends on the laser parameters. However, atoms excited in a cycling transition are almost sure to return to their original state, and preserve most of the coherence present before the excitation. Therefore the width is considerably less than γ_p, and may well be less than $\gamma_p/10$.

An rf-induced transition that would reduce the population of the lowest-lying n states would broaden and lower the peak of our measured spatial distribution. We observed such reduced peak heights, and resonant effects are quite evident in our data. But the positions of the peaks do not correspond to the calculated intervals and do not shift with laser parameters as expected.

B. Cooling With Diffuse Light One of the most important limitations of applications of the atomic beam slowing methods developed in previous years has been the presence of the slowing laser beam in the interaction region of many experiments. In 1991 the MIT group reported experiments with beam slowing using diffuse light. In this case the diffuse light can be produced by illuminating the inside surface of a pipe made from highly reflective, but diffuse, material. We have been studying the subject and working on implementation of the technique in our laboratory.

Compensation of the changing Doppler shift is achieved through the angular dependence of the Doppler shift embodied in $\omega_D = -\mathbf{k}\cdot\mathbf{v}$. Atoms interact with counterpropagating light from a cone of different angle, closer to the velocity direction, until they have decelerated to near $v = \delta/k$. Much below this velocity, there is no angle for which the Doppler effect can shift the light into resonance, and deceleration becomes very inefficient. The range of velocities for which a given frequency of light produces effective slowing is a significant fraction of the velocity, typically $v/3$ as long as $\mathbf{k}\cdot\mathbf{v} >$ few γ. Thus effective slowing over the thermal velocity range can be achieved by light of a few closely-spaced frequencies, and a series of diode lasers is ideal for production of such light. We are preparing for such experiments in Rb. In our initial experiments, we have observed only the very smallest hint of beam slowing, and that signal may be an artifact.

An important byproduct of these experiments has been the discovery velocity dependent optical pumping that covers a wide but controllable range of velocities. For example, we can optically pump atoms in the upper half of the velocity distribution of a thermal beam into one hfs state, leaving the other hfs state populated by only slower atoms. The effective temperature of this remaining population is < 1/4 of the oven temperature. This corresponds to a supersonic beam with much lower than thermal energy, and may be a very useful technique for a variety of experiments.

<u>C. Helium Cooling Experiments</u> We have used our home-built LNA laser to collimate a beam of helium metastables (He*) with a variety of polarization configurations. In all cases we have found that the degree of collimation (residual velocity spread) is much worse than anticipated based on our semiclassical notions. We are therefore slowly coming to the conclusion that the laser cooling mechanism for He* is governed by quantum processes. Using a mixed semiclassical and quantum viewpoint, we can say that the capture velocity of the force γ_p/k is comparable to the atomic recoil velocity $\hbar k/M$, and in this domain, the damping force picture is not correct.

Experiments to test the quantum nature of the cooling process must be done in a proper magnetic environment, and to this end we have developed and extended the mechanical Hanle effect to calibrate the local magnetic field. We can now reliably measure and map the field directly along the atomic beam path to a few mGauss in just an hour or so.

<u>D. Laser Beam Profile Flattening.</u> Most lasers work in the fundamental TEM_{00} mode that has a characteristic Gaussian spatial profile. A number of experiments require a flat spatial beam profile and thus the problem of creating a flat beam profile in an efficient manner is of importance. We have demonstrated a relatively simple approach that has the favorable features of being efficient as well as low cost.

We exploit the angular dependence of the transmission characteristic of a solid etalon to tailor the spatial profile as desired. For a diverging laser beam, we get the familiar bull's-eye pattern similar to Newton's rings. In the simplest case, we can choose the center of the ring pattern to be dark, and thus have a minimum of transmission. The transmission rises to unity at the first bright ring some distance from the center and corresponding to a particular angle. By matching a diverging (or converging) laser beam's Gaussian profile to this curve, it is clear that the intensity at the center of the Gaussian will be reduced, and that there is a point on the side where it will be unity. Proper choice of the parameters can make this central region almost perfectly flat.

This system has several obvious advantages over previous beam profile flattening methods. First, it makes optimum use of the available power and still achieves extraordinary uniformity. Second, it is easily adjustable for beams of different sizes. The angular divergence is simply adjusted with a small Galilean telescope. No centering of the beam is needed. Third, its cost is much lower than that of most available Gaussian filters.

We have measured the flattened beam profiles produced this way for several different laser and etalon parameters. In all cases, the data is in excellent agreement with the calculated curves. We found that typically 40% of the laser beam power could be in the top-hat shaped profile produced this way.

II. THEORETICAL PROGRESS

A. Introduction. One common aspect of much of the past year's progress has been the evolution toward quantizing the atomic center of mass motion or external coordinates. In the past we described the motion of atoms in a perfectly classical way, assuming they had arbitrary position and momentum, and assuming we could know both of these quantities simultaneously. We used the Wigner distribution in classical phase space to describe the state of an atomic sample, and classical mechanics to describe its evolution in time and space. Now this description seems to be outmoded.

The new theoretical approach requires a different explanation of laser cooling than that of a damping force competing with momentum diffusion because stationary quantum states rather than classical trajectories are involved. Optical pumping and spontaneous emission deplete the more energetic quantum states faster than the low energy states because the transition rates are asymmetric in kinetic energy. Thus laser cooling becomes an optical pumping process among external states of motion as well as internal atomic states.

To set the stage for these discussions, we consider atomic position and motion as quantum mechanical variables, replete with wave packet spreading and non-commuting operators. We think of a deBroglie wave field occupying allowed states of a region of space which may have a spatially varying potential that defines modes of the field. However, atoms are not all bosons so there will be cases where occupation of a particular mode of the deBroglie wave field can be done by only a single atom.

In analogy with optics, we claim that occupation of particular modes of this field can result in spatial interference, and we then see that the entire field of atom interferometry emerges as a subset of this way of thinking. Atoms can only "interfere" if they occupy both the same internal and external states, and thus are indistinguishable. "Parts of an atom", i.e., atoms whose internal state is a superposition of eigenstates, certainly have some overlap and can thus interfere. In this same picture, Ramsey oscillations, spin and photon echoes, and quantum beats are simply interference in the time domain rather than in space.

<u>B. Rb Theory</u> The motion of Rb atoms in our cooling experiments is surely dominated by quantum effects. Also, the recoil velocity $\hbar k/M$ for Rb from 780 nm light is 6 mm/s, certainly not negligibly small compared with their 2 cm/s velocity (see above), so use of the Fokker-Planck Equation to describe the evolution of the momentum distribution is not appropriate.

In order to provide a more appropriate description of laser cooling in this quantum domain, we have extended the quantum band structure calculation of Castin and Dalibard from the simple $J = 1/2$ case to higher angular momentum states that correspond with our experiments in Rb. The atoms move in a manifold of sinusoidal potentials that arise from the light shifts of the ground states in the optical standing wave. These are not equal for all ground states because of the different optical coupling strengths between the ground and excited states of different magnetic quantum number m. The results of these calculations were presented at the 1992 Chicago DAMOP meeting and are now being prepared for publication.

To simulate the experimental conditions, we project free particle states for transverse motion of the beam onto the density matrix before and as the cooling evolves. At low intensities, where the amplitude of the periodic light shift potential is small, the quantum and semiclassical results approach agreement. As the intensity increases, there are differences that we attribute to quantum effects.

<u>C. He theory</u> We have developed a computer code for the calculation of momentum distributions of laser cooled atoms using a Monte Carlo simulation of the quantum evolution equations of the atomic wavefunction. The program is based on the wave-function approximation to dissipative processes in quantum optics, a theory

formulated only recently by Dalibard et al., and in a slightly different form by Zoller et al.

The program is especially useful for application to metastable helium, where the semiclassical treatment of laser cooling breaks down and a quantal description is more appropriate. This breakdown arises because the natural linewidth γ of the 2P state is close to the recoil shift. Since the optical excitation rate γ_p is typically $\gamma/10$ or less, the velocity capture range γ_p/k becomes comparable to the recoil velocity $\hbar k/M$. For He*, $(\gamma/k)/(\hbar k/M) = \gamma/\gamma_R$ is only about 20, so $\gamma_p/k \sim 1$.

We have formulated the theory for an atomic wavefunction expanded on a basis of both internal (electronic) and external (momentum) states appropriate for one-dimensional laser cooling. We have not made approximations such as low excitation rate to keep the range of applications as wide as possible. We have used our program for Doppler cooling, polarization gradient cooling, and magnetically induced laser cooling in 1-D optical molasses for the angular momenta appropriate for He*.

ABSTRACTS SUBMITTED TO CONFERENCES

1. "Search for Quantization of Atomic Motion in a Standing Wave Light Field" (with R. Gupta, S. Padua, C. Xie, H. Batelaan, T. Bergeman), Bull. Am. Phys. Soc., 37, 1139 (1992), J1 41.

2. "Experiments in Laser Cooling Metastable He" (with M. Widmer, T. Chuang, and E. Vredenbregt), Bull. Am. Phys. Soc., 37, 1126 (1992), G4 6.

3. "Improvements to an LNA Laser for Experiments in a Metastable He Beam" (with M. Widmer, T. Chuang, and E. Vredenbregt), Bull. Am. Phys. Soc., 37, 1116 (1992), F1 57.

4. "Quantum Calculations for 1-D Laser Cooling" (T. Bergeman), Bull. Am. Phys. Soc. 37, 1139 (1992) J1 40.

5. "Measurement of Diffuse Reflection Coefficient" (S. Padua, H. Batelaan) Bull. Am. Phys. Soc. 37, 1127 (1992) G4 11.

6. "Diffuse Slowing of Rubidium" (with H. Batelaan, S. Padua, R. Gupta, C. Xie) Albuquerque Meeting of the O.S.A., 1992.

7. "Laser Cooling of Triplet Metastable Helium", (with E. Vredenbregt, M. Widmer, and M. Bellanca) Albuquerque Meeting of the O.S.A., 1992.

8. "Motional Quantization of Laser Cooled Atoms," (with R. Gupta, S. Padua, C. Xie, H. Batelaan, and T. Bergeman), ICAP 1992.

9. "Experiments in Laser Cooling Metastable He," (with M. Widmer, M. Bellanca, Ti Chuang, E. Vredenbregt), ICAP 1992.

10. "Beam Profile Flattening for Gaussian Beams," (with C. Xie and R. Gupta), Albuquerque meeting of the OSA, Sept., 1992.

PAPERS IN PREPARATION

1. "Quantum Theories of Laser Cooling" (with T. Bergeman, E. Vredenbregt, and M. Doery).

2. "Simple and Flexible Laser Beam Profile Flattening Scheme" (with R. Gupta and C. Xie).

3. "Laser Cooling and Trapping" (with P. van der Straten) A major review paper invited by Physics Reports.

4. "Slow Supersonic Beams by Optical Pumping with Diffuse Light" (with H. Batelaan and S. Padua)

Abstract Submitted

for the May 1992 Meeting of the

Division of Atomic, Molecular, and Optical Physics

20-22 May 1992

Physical Review
Analytic Subject Index
Number:

Bulletin Subject Heading
in which paper should be placed:
Laser Cooling

Search for Quantization of Atomic Motion in a Standing Wave Light Field† R. GUPTA, S. PADUA*, C. XIE, H.BATELAAN, T.BERGEMAN, AND H.METCALF, SUNY Stony Brook-- Sub-Doppler laser cooling can readily reduce atomic kinetic energies to < 0.2 MHz ($\approx$10 μK), less than the light shifts in a weak standing wave. Such atoms are readily confined in the $\lambda/2$ space between the planes of the standing wave, but have a deBroglie wavelength $\approx\lambda/10$ or more. Thus their motion is quantized by the light field. We are seeking evidence for these states by rf spectroscopy, and have observed resonant effects in the 1-D cooling of a thermal Rb beam [1] by a transverse optical molasses. In magnetically induced cooling, there is no polarization gradient so that atoms are not rapidly optically driven between sublevels, and are therefore optically pumped into well defined states whose quantized motion can be calculated. We continue to seek a simple comparison between our calculations and observed resonances.

† Supported by NSF, ONR, and AFOSR
* Supported by C.A.P.E.S., Brazil

1. R. Gupta et al., Proceeding of the CXVIII Fermi School

Submitted by Harold Metcalf

Signature, APS Life Member

( ) Prefer Poster Session
( ) Prefer Standard Session
(X) No Preference

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Abstract Submitted

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Physical Review
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Bulletin Subject Heading
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Laser cooling

Experiments in Laser Cooling Metastable He† M. WIDMER, T. CHUANG*, E. VREDENBREGT, AND H. METCALF, SUNY Stony Brook -- We have designed, built, tested, and used a source of triplet metastable helium (He*) that produces ≈10E14 atoms/s-sr for use in laser cooling experiments. We have successfully collimated the beam to near the Doppler limit with λ = 1.083 μm light from a diode laser pumped LNA laser on the J = 1 → 2 transition. We have used the mechanical Hanle effect on the J = 1 → 1 transition [1] to map and calibrate the magnetic field in our interaction region. We are studying magnetically induced sub-Doppler cooling in the simplest possible transition scheme which is J = 1 → 0. Results from both cooling and field mapping will be presented.

† Supported by NSF, ONR, and AFOSR.

* Present Address: Fibertek Corp., Herndon, VA 22070

1. R. Kaiser et al., Z. Phys. D 18, 17 (1991).

Submitted by Harold Metcalf

Signature, APS Life Member

( ) Prefer Poster Session
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20-22 May 1992

Physical Review
Analytic Subject Index
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Bulletin Subject Heading
in which paper should be placed:
Tunable Solid State Lasers

Improvements to an LNA Laser for Experiments in a Metastable He Beam† M. WIDMER, T. CHUANG, E. VREDENBREGT, AND H. METCALF, SUNY Stony Brook -- We have made considerable improvements in the utility of our LNA laser for pumping metastable helium (He*) at λ = 1.083 μm [1]. We have installed a new locking circuit that provides better long term stability, and have locked the laser to a saturated absorption signal. The He* cell that generates this signal is placed in Helmholtz coils so the optical transition frequencies, and hence the laser, can be easily and reliably Zeeman tuned on the 0.1 MHz scale. The laser spectral width is ≃ 0.2 MHz. More efficient coupling of the light from two 500 mW SDL30 diode laser arrays has provided stronger excitation of the LNA crystal resulting in more overall power and efficiency. We presently produce more than 25 mW of single-frequency light tuned at the He* line that can be stable to 0.1 MHz for hours.

† Supported by NSF, ONR, and AFOSR.

* Present Address: Fibertek Corp., Herndon, VA 22070

[1] Ti Chuang and H. Metcalf, Appl. Opt. 30, 2495 (1991).

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(X) Prefer Poster Session
( ) Prefer Standard Session
( ) No Preference

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Abstract Submitted

for the Chicago **Meeting of**

American Physical Society, DAMOP

20-22 May, 1992
Date

Physical Review
Analytic Subject Index
Number 2.80.Pj

Bulletin Subject Heading
in which Paper should be placed
Atom Cooling

Quantum Calculations for 1D Laser Cooling.* T. BERGEMAN, SUNY, Stony Brook.--- The approach of Castin and Dalibard[1] is used to simulate 1D magnetically induced laser cooling (MILC)[2] using a basis of quantum states in the periodic light shift potential. At low intensity, excited states may be eliminated from the density matrix equations. Because of rapid optical pumping by the two σ^+ laser beams, for $F=2\rightarrow3$ (Rb), only $M_F=2$ and 3 sublevels are included. For optimum laser intensity and detuning, cooling is evident with 10-15 periodic (Bloch) states for each M_F sublevel, of which 5-10 are below the maxima of the periodic potential. Population accumulates in the lowest quantum states from a combination of recoil-induced momentum diffusion, precession in the transverse magnetic field, and optical pumping. With optimum parameters, 1/3 to 1/2 the population over the basis set goes to the lowest quantum state, while the total population in all basis states declines to 1/2 to 3/4 the original value in 50 μsec. In contrast with semi-classical "Sisyphus" cooling, tunneling here allows cooling to continue in the population below the potential maxima, for moderate values of the potential amplitude.
*Supported by the NSF, ONR, and AFOSR.
1. Castin and Dalibard, Europhys. Lett. 14, 761 (1991).
2. Sheehy et al., Phys. Rev. Lett. 64, 858 (1990).

(x) Prefer Poster Session
( ) Prefer Standard Session
( ) No Preference

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Abstract Submitted

for the May 1992 Meeting of the

Division of Atomic, Molecular, and Optical Physics

20-22 May 1992

Physical Review
Analytic Subject Index
Number:

Bulletin Subject Heading
in which paper should be placed:
Laser Cooling

Measurement of Diffuse Reflection Coefficient†, S. PADUA*, H. BATELAAN, SUNY Stony Brook, NY 11790 -- Use of diffuse light for deceleration of a sodium beam has been studied and demonstrated [1], and we are preparing for such experiments with diode lasers in Rb. Diode lasers offer distinct advantages for such experiments for many reasons; e.g., it's easy to have many different frequencies present simultaneously. To evaluate the effect of our machining of the diffuse reflector Spectralon [2] we have developed a method to determine the diffuse reflection coefficient. We measure the power emitted from each end of a cylindrical hole when light is introduced through a small hole in its side and compare the results with a simple model. We have found that drilling a 6 mm diam hole results in an inner surface with reflectivity ≈99%, about as good as the manufacturer can provide. This result is corroborated by measuring the spatial distribution of light diffusing through the walls of the hollow Spectralon cylinder.

† Supported by NSF, ONR, and AFOSR
* Supported by C.A.P.E.S., Brazil

[1] W. Ketterle et al., preprint.
[2] Trademark of Labsphere Inc., North Sutton, NH

Submitted by Harold Metcalf

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( ) Prefer Standard Session
(X) No Preference

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Summary submitted
for the Albuquerque Meeting of the
Optical Society of America
20-25 September, 1992

Physical Review
Analytic Subject Index
Number: 32.80.Pj

Suggested title of session in
which paper should be placed:
Optical Trapping and Cooling

Diffuse Slowing of Rubidium H. Batelaan, S. Padua*, R. Gupta, C. Xie and H. Metcalf, SUNY Stony Brook— We will present measurements indicating slowing of Rubidium atoms with diffuse light, following the approach of Martin et al.[1]. We intend to slow as large a part of the velocity distribution of a thermal Rb beam as possible. The velocity capture range, which determines the part of the beam that will be slowed, depends on the total laser power. We use a measured laser power ranging from 10-20 mW in the interaction region and obtain a capture range of about 20m/s. The interaction region is a cylindrical hole of 10cm length drilled in the diffusely reflecting material Spectralon [2]. Two diode lasers tuned to excite the hyperfine ground states of Rb are used to slow the beam and compensate for optical pumping. Shining a third laser at an angle to the Rb beam after the interaction region gives the velocity distribution of the slowed beam by detection of the Doppler broadened fluorescence spectrum.

1. Martin, Ketterle and Pritchard, private communication (1991)
2. Labsphere, P.O.Box 70 North Sutton, NH 03260

Supported by NSF, ONR, AFOSR and *CAPES

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(X) Prefer Standard Session
( ) No Preference

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Abstract Submitted

for the Albuquerque Meeting of the

Optical Society of America

20-25 September 1992

Physical Review
Analytic Subject Index
Number: 32.80.Pj

Suggested Title of Session
in which paper should be placed:
Optical Trapping and Cooling

Laser Cooling of Triplet Metastable He (He*)†

E. VREDENBREGT, M. WIDMER, M. BELLANCA, H. METCALF, SUNY Stony Brook -- We are studying light forces on atoms in the regime where the atomic transition linewidth γ, and the recoil shift Ω are of comparable magnitude. We have developed a high-intensity, discharge-excited, cooled nozzle source that produces He*. One transition is driven by λ = 1.083 μm light from a 35 mW, home-made stabilized, diode laser-pumped LNA laser. Another is driven by λ = 389 nm light from an injection locked diode laser array that is frequency doubled (under development). For this transition, $\gamma/\Omega < 3$. We used the mechanical Hanle effect [1] to calibrate and map the magnetic field in the interaction region with an accuracy in the mG range. We employ the Monte Carlo wave function formalism [2] with quantization of the atomic momentum for comparisons with experimental atomic velocity distributions resulting from laser cooling, in various schemes among which is the simplest possible configuration for MILC, $J=1 \rightarrow J'=0$.

1. R. Kaiser et al., Z. Physik, D18, 17 (1991).
2. J. Dalibard et al., Phys. Rev. Lett. 68, 580 (1992).

† Supported by NSF, ONR and AFOSR.

Submitted by Harold Metcalf

Signature, OSA Member

(X) Prefer Poster Session
( ) Prefer Standard Session
( ) No Preference

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ICAP-92

MOTIONAL QUANTIZATION OF LASER COOLED ATOMS*

R. Gupta, S. Padua†, C. Xie, H. Batelaan, T. Bergeman, and H. Metcalf
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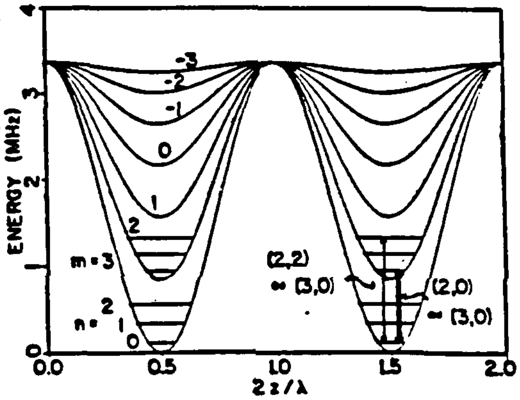
The extreme laser cooling achievable with polarization gradient optical molasses [1] or *Magnetically Induced Laser Cooling* [2] (MILC) yields mean energies of less than ~25 times the recoil energy, $E_R \equiv (\hbar k)^2/2M$ (3.9 kHz for Rb) and rms momenta of a few times $\hbar k$ ($k \equiv 2\pi/\lambda$). Such atoms have deBroglie wavelengths only a few times smaller than λ. When the optical excitation rate is small compared to the natural linewidth γ, the standing wave laser fields may be viewed as producing an effective sinusoidal potential of depth $U_O = 2\hbar\delta s/L \approx$ hundreds $\times E_R$. Here $L \equiv 1+(2\delta/\gamma)^2$, $\delta \equiv \omega_{laser}-\omega_{atom}$, and $s \equiv I/I_{sat} \equiv I\tau\lambda^3/\hbar c$ where I is the intensity of each laser beam. For $s = 0.85$ and $\delta = -2\gamma$ ($= -2\pi \times 12$ MHz for Rb) we find the depth of the periodic potential is 1.2 MHz, more than 15 times the observed rms energy of the cooled atoms. Thus they are confined between the standing wave nodes at intervals of $\lambda/2$. Since the atoms are confined to a space comparable to their deBroglie wavelengths, their motion is clearly quantum mechanical. We present evidence for such quantization of atomic motion by a standing wave, and our method of probing it is to induce rf transitions between the translational quantum states in the effective periodic potential [3].



The semiclassical theory of laser cooling that uses the Fokker-Planck equation to find the momentum distribution is inconsistent in the regime of these low temperatures. Castin and Dalibard [4] developed a fully quantum treatment of laser cooling for a $J = 1/2 \rightarrow 3/2$ atomic transition. We have applied their approach to MILC for the 5S → 5P cycling transition ($F = 3 \rightarrow 4$) in ^{85}Rb, and show some of the energy levels in Fig. 1 [5]. The quantum numbers used are $(m_F, n_{vibration})$.

In our experiments we use a thermal beam of natural Rb produced by an oven at T = 150°C with a horizontal slit aperture 0.1 mm high by 2 mm wide, and a vertical beam defining slit 0.1 mm wide by 2 mm high about 35 cm away [6]. The atoms emerge from the vertical slit in a horizontal fan-shaped beam and then interact with a pair of counterpropagating laser beams transverse to the atomic beam axis. Both laser beams have the same circular polarization and a magnetic field is applied perpendicular to the direction of the laser beams. The atomic beam profile is measured with a scanning platinum-tungsten hot wire, 25 μm in diameter, 1.3 m away from the region of interaction with the laser beam. The laser light is tuned near the 5S → 5P cycling transition of Rb at $\lambda = 780$ nm. The laser and atomic beams cross perpendicularly, so the Doppler shifts are small. The laser frequency is calibrated with a saturated absorption signal from an auxilliary Rb cell at room temperature.

A typical hot-wire scan of the atomic beam is shown in Fig. 2. An atom in the $m_F = 3$ sublevel experiences a potential of 1.8 MHz for the parameters of Fig. 2. The channeled atoms oscillate at a frequency $\omega_{vib}^2 = 8s\delta E_R/\hbar L$ of 185 kHz, and the rms velocity for the lowest quantum state is 2 cm/sec. Our measurements show that most of the atoms are cooled into the lowest quantum level.

The (3,0) → (3,n) transitions are forbidden in our model because there is no mechanism for the rf field to connect translational states since their wavefunctions are orthogonal. However, rf transitions can be driven between different m_F states, and Δm_F

= ±1 will be magnetic dipole allowed. Experiments were planned to excite the (m,n) = (3,0) → (2,2) transition as shown in Fig. 1. Since this transition has an effective Franck-Condon factor of only ~ 0.15, an rf field of 1 Gauss was chosen to obtain a transition during the flight of atoms through the laser beam.

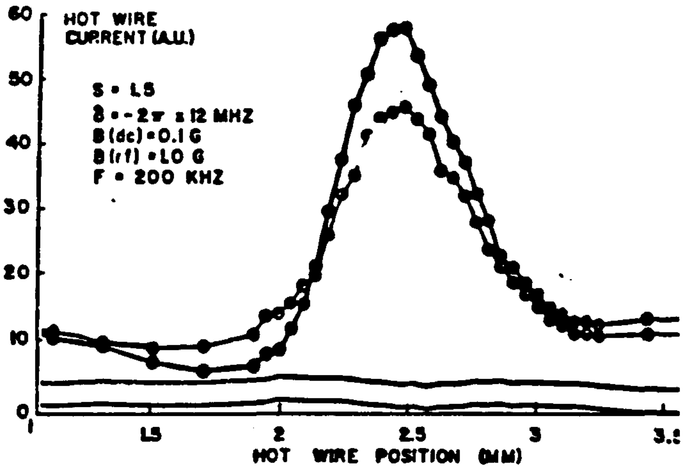


Figure 2

An rf-induced transition that would reduce the population of the lowest-lying n states would broaden and lower the measured peak of our spatial distribution. Figure 2 shows such a reduced peak height, and Fig. 3 shows how this reduction varies with rf frequency. The positions of the peaks in Fig. 3 do not correspond to the intervals shown in Fig. 1, and do not shift with laser parameters as expected.

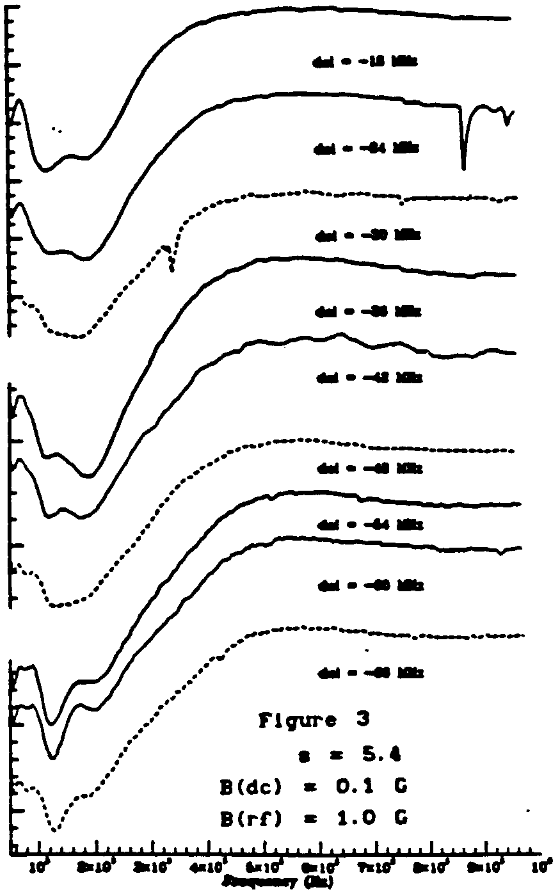


Figure 3

The expected width of these transitions is determined by the coherence lifetime of the coupled states, and that is limited by the optical excitation rate $\gamma_P = 4\gamma s/2L$, multiplied by the transition strength and branching ratio for decay into a different m_F state. The effective Q of the transitions is then given by the ratio $\omega_{vib}/\gamma_P = (16/3\gamma)(2\delta E_R L/\hbar s)^{1/2}$. For the parameters of Fig. 2, Q ~ 1 corresponds to a width consistent with Fig. 3.

We have observed a resonant effect caused by an rf magnetic field on the velocity distribution of atoms cooled with MILC . However, the simple picture that we are driving stationary states in a static periodic potential may be inappropriate for these experiments. We are currently working on improving the homogeniety of the optical field to improve the quality of our data and thereby provide a more reliable interpretation of these resonances.

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EXPERIMENTS IN LASER COOLING METASTABLE HE*

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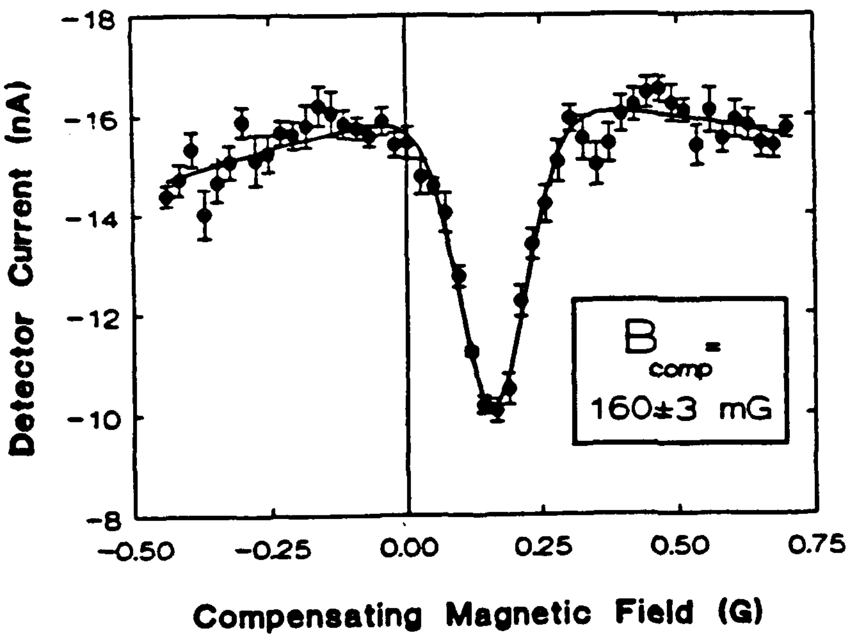
We are studying light forces on atoms in the regime where the atomic transition linewidth γ, and the recoil energy $E_R \equiv (\hbar k)^2/2M$ are of comparable size. To do this we have chosen two transitions from the triplet helium metastable 2^3S_1 state (He*), one at $\lambda = 1.083$ μm to the 2^3P manifold and the other at $\lambda = 389$ nm to the 3^3P manifold. The ratio $E_R/\hbar\gamma$ is ≈ 0.05 for the 2^3P state but 0.4 for the 3^3P state. Thus the infrared experiments will be in the ordinary domain of laser cooling where $E_R/\hbar\gamma \ll 1$ and can be used to characterize the apparatus, while the uv experiments will provide a test for various models of laser cooling in this domain.

We have built and tested a source of He* that produces $\approx 10^{14}$ atoms/s-sr. He* is produced in a dc discharge of a few hundred volts and a few mA through a 200 μm nozzle. The pressure behind the liquid-nitrogen-cooled nozzle is ~50 Torr, thus making a supersonic flow. A movable skimmer a few mm away admits the beam to a second, differentially pumped chamber, the interaction region. The average velocity of the atoms is 1400 m/s and the spread is ~17%. The beam travels 1.9 m to a chamber where we have two detectors for the He* atoms. One is simply a movable 75 μm diameter wire that emits electrons when struck by the 20 eV He*. The current is collected, amplified, and measured. We also let the beam impinge directly on the first of a pair of multichannel plates whose downstream amplified output electrons are accelerated to a phosphor screen, thus imaging the beam profile. The screen is viewed by an ordinary TV camera whose output is fed to a frame grabber in a PC and stored for later analysis.

The interaction region is surrounded by square Helmholtz coils to control the magnetic environment for the laser cooling experiments. We have used the mechanical Hanle effect on the $J = 1 \rightarrow 1$ and the $J = 1 \rightarrow 2$ transitions [1] to map and calibrate this field with an accuracy in the mG range. A typical mechanical Hanle effect signal is shown below.



Mechanical Hanle Effect signal for the $J = 1 \rightarrow 1$ transition with linearly polarized light parallel to $\vec{x}$, $\lambda = 1.08$ μm, and a magnetic field along $\vec{z}$.

The $\lambda = 1.083\ \mu m$ light is produced by a diode-pumped LNA laser that has been considerably improved since its original description [2]. We have installed a new locking circuit that provides better long-term stability and have locked the laser to a saturated absorption signal. The He* cell that generates this signal is placed in Helmholtz coils so the optical transition frequencies, and hence the laser, can be easily and reliably Zeeman tuned on the 0.1 MHz scale. The laser spectral width is $\approx$ 0.2 MHz. More efficient coupling of the light from two 500 mW SDL-30 Spectra-Diode Labs arrays has provided stronger excitation of the LNA crystal resulting in more overall power and efficiency. We presently produce more than 25 mW of single-frequency light tuned at the He* line that can be stable to 0.1 MHz for hours.

We are presently working on various methods of production of the 389 nm light for the uv experiments. We have successfully injection locked high-power diode laser arrays that operate near $\lambda = 778$ nm and have produced $\sim$ 100 mW of single mode light [3]. We plan to scale this system up to 500 mW arrays and frequency double this light with an appropriate crystal. We anticipate production of a few mW of uv with this scheme.

We have successfully collimated the He* beam to near the Doppler limit with $\lambda = 1.083\ \mu m$ light tuned to the $J = 1 \rightarrow 2$ transition. We are experimenting with polarization gradient and magnetically induced sub-Doppler cooling in the simplest possible transition scheme which is $J = 1 \rightarrow 0$.

We have developed a computer code for the Monte Carlo wave function formalism [4] to treat Doppler cooling, polarization gradient cooling, and magnetically induced cooling in 1-D optical molasses for the angular momenta appropriate for He*. Compared to the density matrix approach, this formalism uses much less storage space but comparable computer time. It provides sub-recoil resolution of the calculated momentum distribution function even when the atomic wavefunction is discretized on a one recoil spaced grid. We plan a detailed comparison of these two methods with the semiclassical theory for the case $E_R/\hbar\gamma \sim 1$.

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Physical Review
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Suggested title of session in
which paper should be placed:
Optical Instruments

Beam Profile Flattener For Gaussian Beams*. C. Xie, R. Gupta, and H. Metcalf, SUNY Stony Brook -- We report a novel technique to make a Gaussian laser beam profile spatially flat. We exploit the angular dependence of the transmission of an etalon to tailor the spatial profile to the desired form. A converging or diverging laser beam is transformed into the familiar ring pattern when it passes through an etalon, and the resulting angular filter function corresponds to a spatially dependent transmission that can be used to shape the beam's intensity profile. This can be done with the center spot or with one of the higher order rings. The latter usage works only in the radial direction but avoids feedback of the reflected light to the laser. The reflected light can then be used for laser diagnostics. A simple analysis shows why our method works so well, and how an etalon could be tuned to give the optimum results at all wavelengths. This technique has enormous advantages over other methods. We made measurements with a Sharp LT021 5 mW semiconductor laser at $\lambda=780$ nm. The solid etalon was 600 μm thick coated for $R = 30\%$ at $\lambda=800$ nm. The maximum power achieved in the spatially flat region is approximately 50% of the total power. All the results are in excellent agreement with the calculations.

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( ) Prefer Poster Session
( ) Prefer Standard Session
( ) No Preference

Submitted by Harold Metcalf

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