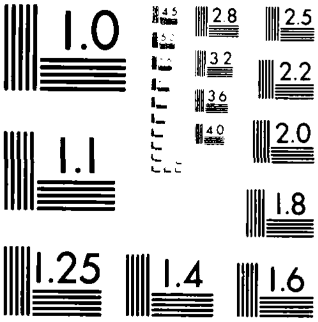
AD-A149 215 EXPERIMENTAL AND THEORETICAL STUDIES OF LASER COOLING 1/1
AND EMITTANCE CONTR..(U) HUGHES RESEARCH LABS MALIBU CA
R A MCFARLANE ET AL. OCT 84 AFOSR-TR-84-1163
UNCLASSIFIED F49620-82-C-0004 F/G 20/8 NL

END
FILMED
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

(4)

AFOSR-TR- 84-1183

# EXPERIMENTAL AND THEORETICAL STUDIES OF LASER COOLING AND EMITTANCE CONTROL OF NEUTRAL BEAMS

R.A. McFarlane, D.G. Steel, R.S. Turley, J.F. Lam, and A.J. Palmer

Hughes Research Laboratories
3011 Malibu Canyon Road
Malibu, CA 90265

OCTOBER 1984

F49620-82-C-0004
Annual Report
1 June 1983 through 30 September 1984

DIRECTOR OF PHYSICAL AND GEOPHYSICAL SCIENCES
Air Force Office of Scientific Research
Building 410
Bolling AFB, DC 20332

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

## REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: [illegible] se; distribution [illegible].

4. PERFORMING ORGANIZATION REPORT NUMBER(S):

5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- [illegible]1163

6a. NAME OF PERFORMING ORGANIZATION: Hughes Research Laboratories

6b. OFFICE SYMBOL *(If applicable)*:

7a. NAME OF MONITORING ORGANIZATION: AFOSR/NP

6c. ADDRESS *(City, State and ZIP Code)*:
3011 Malibu Canyon Road
Malibu, CA 90265

7b. ADDRESS *(City, State and ZIP Code)*: Bolling AFB, DC 20332

8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Air Force Office of Scientific Research

8b. OFFICE SYMBOL *(If applicable)*:

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F49620-82-C-0004

8c. ADDRESS *(City, State and ZIP Code)*:
Building 410
Bolling AFB, DC 20332

10. SOURCE OF FUNDING NOS.

| PROGRAM ELEMENT NO. | PROJECT NO. | TASK NO. | WORK UNIT NO. |
|---|---|---|---|
| 61102F | 2301 | A7 | |

11. TITLE *(Include Security Classification)*: (See cover)

12. PERSONAL AUTHOR(S): R.A. McFarlane, D.G. Steel, R.S. Turley, J.F. Lam and A.J. Palmer

13a. TYPE OF REPORT: Annual Report

13b. TIME COVERED: FROM 1/6/83 TO 9/30/84

14. DATE OF REPORT *(Yr., Mo., Day)*: October 1984

15. PAGE COUNT: 15

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

| FIELD | GROUP | SUB. GR. |
|---|---|---|
| | | |
| | | |

18. SUBJECT TERMS *(Continue on reverse if necessary and identify by block number)*:

19. ABSTRACT *(Continue on reverse if necessary and identify by block number)*

Experimental and theoretical progress has been made in the areas of experimental observation of the Optical Stern-Gerlach Effect (OSGE), resonant two-photon ionization of neutral hydrogen, and a theoretical study of $\pi$-pulse cooling. In the OSGE studies, we have improved our spatial resolution, the spatial beam profile monitor, magnetic substate selection, the size of the interaction region, the signal-to-noise ration, and our computer codes for acquiring and analyzing the data. In the resonant two-photon ionization of neutral hydrogen we have sucessfully produced a neutral hydrogen beam with a density of $\sim 10^{12}$ cm$^{-3}$ and are progressing on the development of the VUV source.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☒ DTIC USERS ☐

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: ~~R.A. McFarlane~~ Henry Pugh

22b. TELEPHONE NUMBER *(Include Area Code)*: ~~317-5445~~ (202) 767-4908

22c. OFFICE SYMBOL: NP

DD FORM 1473, 83 APR EDITION OF 1 JAN 73 IS OBSOLETE.

This report covers the progress made on contract number F49620-82-C-0004 in the period from 1 June 1983 to 31 September 1984. The principal investigator is R.A. McFarlane. The experimental effort during this reporting period has been the work of R.A. McFarlane, D.G. Steel, and R.S. Turley. J.F. Lam and A.J. Palmer were responsible for the theoretical studies. J. Shuler contributed to the overall laboratory support.

## A. OPTICAL STERN-GERLACH EFFECT (OSGE)

A considerble amount of attention to experimental detail is required in order to be able to see evidence of the optical Stern-Gerlach effect (OSGE). Careful attention must be paid to correctly preparing the atomic beam before the interaction region, to having an adequately small interaction time, and to being able to precisely measure the transverse position of the atoms downstream from the standing wave interaction. During this report peiod, significant progress has been made in all of these areas. In addition, one of the authors (R.S.T.) attended the Workshop on Controlling Atoms held in Storrs, Connecticut (University of Connecticut, 30 May-1 June 1984) in which ideas on the cooling and trapping of neutral atoms were exchanged and developed. A summary of the workshop and the accompanying meeting of the Division of Electron and Atomic Physics of the American Physical Society is included as Appendix A. Our ability to acquire and understand the laboratory data was enhanced by developing computer codes for calculating the predicted OSGE distributions and for an improved analysis of the acquired data. Specific accomplishments in our experimental effort are outlined below.

### 1. Spatial Resolution

The ultimate limit of how well we are able to resolve the details of the OSGE transverse momentum distribution is determined by the spatial collimation of the sodium beam. In this period we were able to reduce the spatial extent of the beam from 280 μm to 175 μm (equivalent to about 6 photon recoils) by realigning the system and changing the arrangement of the collimation slits. The significance of this reduction is illustrated in Figure 1 which is a plot of the calculated OSGE spatial distribution at the spatial beam profile monitor (SBPM) resulting from sodium beams of the two different widths and a standing wave laser power of 50 mW.

### 2. Spatial Beam Profile Monitor

The transverse momentum distribution of the sodium beam is inferred from the position of the sodium atoms downstream from the standing wave interaction region. Since the longitudinal velocity of the atoms is known and the transverse velocity is initially zero, the transverse momentum ($p_t$) is given by $p_t p_\ell x_t/d$, where $p_\ell$ is the longitudinal momentum, $x_t$ is the transverse position measured at the spatial beam profile monitor (SBPM), and d is the distance from the standing wave interaction region to the SBPM.

The SBPM consists of a focused laser beam reflected from a mirror driven by a stabilized scanning galvanometer. The resulting atomic beam fluorescence is monitored as a function of the driving voltage applied to the scanning mirror. The relationship between $x_t$ and the applied galvanometer voltage has been accurately measured to permit a precise determination of the transverse momentum. The SBPM resolution was improved by careful alignment of the mirror and the focusing optics. It appears that the system resolution is presently limited more by the width of the sodium beam than the intrinsic resolution of the SBPM.

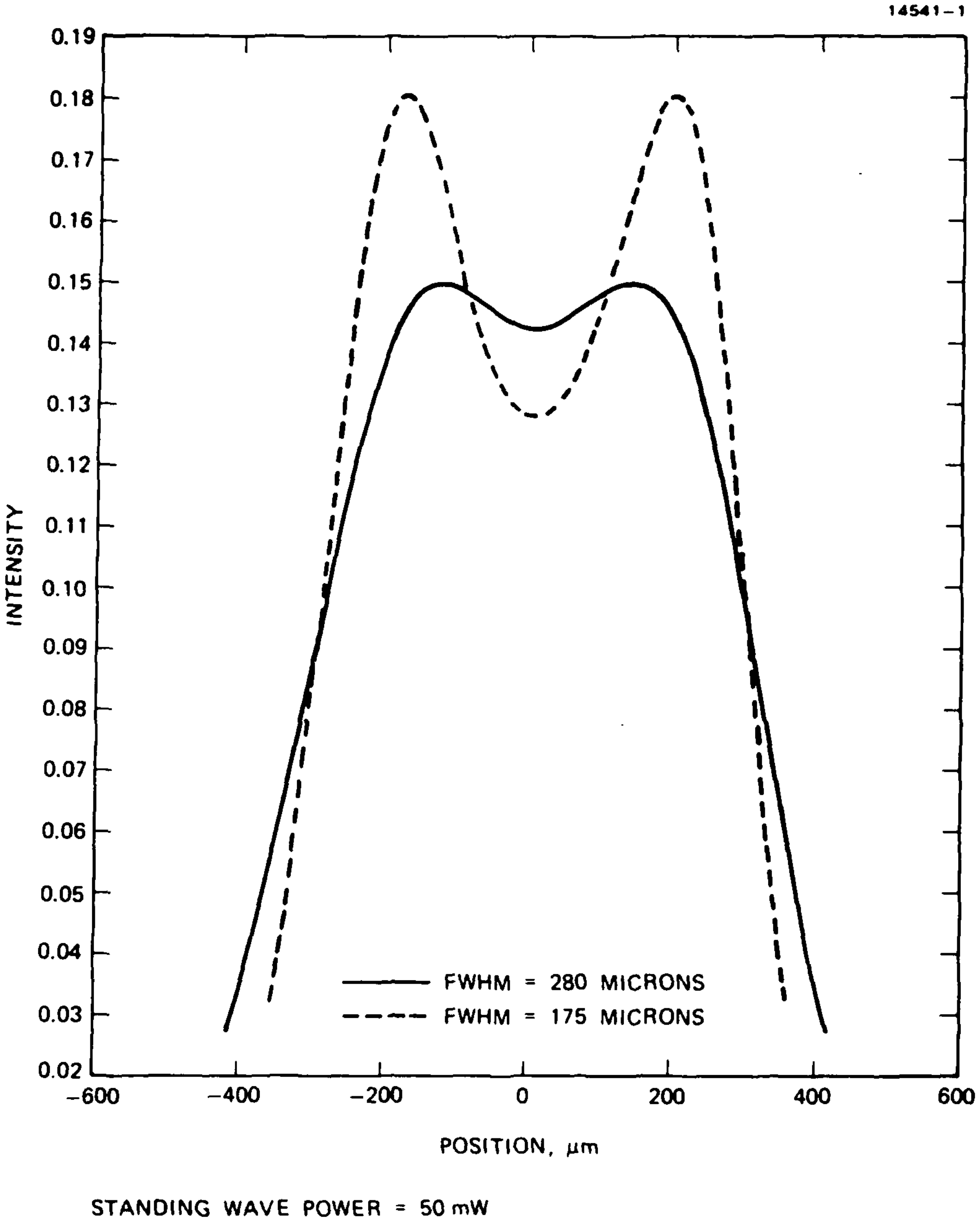


Figure 1. Plot of the theoretical spatial beam profile monitor signal resulting from sodium beams with widths of 280 μm FWHM (solid line) and 175 μm FHWM (dashed line). The calculation used a standing wave laser power of 50 mW.

## 3. Magnetic Pumping

Calculations of the OSGE effect have been carried out assuming a two-state system. To realize a two-state system experimentally with the sodium $D_2$ transition, it is necessary to optically pump the atoms into a stretched hyperfine configuration so that only one dipole transition is allowed. Further, the magnetic field direction defining the quantization axis in the pump region must be aligned with the field in the standing wave region so that the atoms remain in the stretched configuration during the standing wave interaction.

The magnetic fields from the sets of Helmholtz coils were mapped out in both the pumping and interaction regions. Optimum current settings were determined to cancel the earth's field (and other stray laboratory fields) and to establish a quantization axis in the correct direction.

Good state selection requires excellent and consistent circular polarization of both the pump and standing wave beams. We have improved our techniques for achieving and verifying the polarization of both beams to better than 1%. The improvement comes from an optical arrangement where perfect circular polarization results in a zero signal in the detector. Our old technique relied on measuring a uniform intensity in the circularly polarized beam after it passed through a linear polarizer which was rotated. Thus, the new error signal is measured relative to a zero background intensity rather than a very bright one.

The degree of magnetic substate selection was verified by monitoring the intensity and polarization of the fluorescence signal in the standing wave region. For perfect optical pumping into a stretched state, the fluorescence signal perpendicular to the probe beam should be linearly polarized. The polarization without optical pumping is expected to be elliptical. We found nearly complete optical pumping.

## 4. Interaction Region

In order to see the diffractive OSGE effects it is necessary that the interaction time of the atoms with the standing wave be less than the atomic spontaneous emission lifetime. In our case, this limits the size of the interaction region to about 10 μm. We have decreased our standing wave focal spot size by the addition of a beam expanding telescope to the system. The focus has been mapped out with a precision translator and a pinhole aperture and was found to have a width of 7 μm FWHM. We have also added an alignment aperture to the system to enable us to line up the atomic beam with the focal spot.

## 5. Signal to Noise

Our measurement technique involves the detection of a small signal on top of a relatively large background. Even with phase sensitive detection and signal averaging, our previous signal-to-noise ratio was only about three or four to one. We have increased this by a factor of three to ten by means of improved alignment, better optical and electrical shielding, enhanced averaging techniques, and better laser stability (permitting longer averaging times).

## 6. Computer Codes

Two computer programs have been developed to aid in acquiring and understanding the OSGE data. The first code calculates the expected SBPM intensity as a function of position, standing wave intensity, standing wave spot size, and atomic beam size. It has been very useful in understanding the fundamental limits of the measurement system, how different misalignments affect the results, and what kinds of signals we should be looking for.

The second program is used for analyzing the data from our TN-1710 signal averager on a VAX 11/780 computer. It has been significantly improved to provide for finding peaks and widths of arbitrary line shapes, for calculating statistical uncertainties and correlations of fit parameters, for generating improved hardcopy and graphic display of the data and fits, and for faster and more convenient transfer of data from the TN-1710 to the VAX.

## B. RESONANT TWO-PHOTON IONIZATION OF NEUTRAL HYDROGEN ($\lambda$=1216Å)

On internal IR&D funds, HRL is constructing a high density neutral hydrogen beam and a narrowband tunable VUV source. This part of the program has been running behind schedule due to limited space at the labs. Currently, the space problem is nearing resolution by the addition of 270 $ft^2$ to the current lab. Laboratory construction is scheduled to be completed by the end of January, 1985. Measurements with the hydrogen and sodium beams will be temporarily suspended until this construction is completed.

At present, construction of the neutral hydrogen beam has resulted in a demonstrated neutral beam current of 0.1 to 1.0 Amps. This corresponds to a density of $10^{12}$ $cm^{-3}$. The neutral hydrogen detector is platinum-coated Kapton. Due to the high hydrogen flux, we have demonstrated a saturation behavior which may lead to a direct measurement of the $H_2$ desorption rate. Because this represents a problem for our current measurements we are developing an alternate beam flux measurement procedure based on a quadrupole mass spectrometer.

The development of the VUV source is progressing. The pulsed dye amplifiers have been acquired and the purchase order for the YAG laser has been issued. The YAG laser is scheduled to be delivered near the end of November. The mercury heatpipe construction has been completed, along with the VUV calorimeter and a dc hydrogen discharge tube for frequency stabilization.

## C. THEORY OF QUANTUM MECHANICAL TRANSPORT IN THE PRESENCE OF RADIATION FIELDS

The study of recoil effects in the presence of radiation fields necessitates the development of an appropriate equation that describes both the internal and the external evolution of the atoms.

### 1. Dressed Atom Theory

An atom loses its distinct identity in the presence of a strong radiation field whose intensity is of the order of the saturation intensity. In this instance, the system must be considered as a coherent linear combination of photon and atomic states known as a dressed atom. We have constructed a full dressed atom picture where the radiation is present as a traveling wave and as a standing wave, including the effect of atomic recoil. For a single traveling wave, the dressed states are the elements of an infinite set of independent pair states, but for a standing wave the dressed states are sets of coupled triplets. Under conditions where the laser detuning from resonance is much larger than the natural linewidth, a complete decoupling of the sets of triplets occurs.

The dressed states have been used to derive the master equations. Included are correlations between stimulated and spontaneously emitted photons. These equations represent the physical situation of an atom acted upon by a standing wave while spontaneously emitting photons. The master equations were obtained by introducing bilinear combinations of the amplitudes for a two-level system. Atomic recoil was included by introducing the Wigner distribution; it was assumed that the photon momentum is much smaller than the atomic momentum.

### 2. Effect of the Atomic Angular Momentum

We have extended our analysis by taking into account the angular momentum of the internal atomic structure. This calculation brings the theory closer to reality than previously published theories. In real atoms the states are labeled both by the principle quantum number and by angular momentum quantum numbers (which could be specified in either the LS or JJ coupling schemes). The analysis technique used is based on the irreducible tensor representation of the density operator. This method involves the expansion of the wave function as a linear superposition of states of definite angular momentum. Having done this, we again constructed the generalized master equations using the same approach outlined in Section C.1. These equations include an additional observable, the Zeeman coherence, which is responsible for the interference between the two orthogonal polarization components of the radiation field.

## D. PI-PULSE COOLING THEORY

The theoretical work on pi-pulse cooling culminated in the presentation of a paper at a meeting of the Optical Society of America and the preparation of a preliminary paper for publication. The abstract of the OSA presentation is included as Appendix B.

# APPENDIX A

## Summary of DEAP Meeting

R. S. Turley

May 28– June 1, 1984

This report is a brief summary of the annual meeting of the Division of Electron and Atomic Physics of the American Physical Society held at the University of Connecticutt from May 30– June 1, 1984. I have also included a report of the accompanying Workshop on Controlling Atoms which preceded the conference.

The Workshop on Controlling Atoms consisted of three sessions of about five half hour papers each. The first session was on the subject of forces on atoms. Bill Phillips at NBS discussed their work on atomic beam cooling. They have succeeded in slowing a thermal beam of [illegible] dium atoms to an observed velocity at least as slow as 30 meters/second. Phil Mosko[illegible] scussed the work that Pritchard, Gould, and himself have been doing at M.I.T. on diffraction [illegible] neutral sodium beam by a near-resonant standing wave. They have seen good qualitative agreement with theory and have a resolution comparable to the recoil of a single photon. The rest of the disc[illegible] focussed on the ultimate physical limits on radiation cooling.

The second session of the workshop dealt with trapping of neutral atoms. Various schemes for confining cooled neutral atoms to volumns of the order a cm$^3$ were discussed along with their advantages and disadvantages. The traps were all composed of static magnetic fields, laser fields, or some combination of the two. In general the traps were not very deep, being unable to hold atoms with temperatures above the order of 1 Kelvin. The magnetic traps have the possible disadvantage of disturbing the energy levels of the neutral atoms. Laser traps heat up the trapped atoms, thus requiring similataneous cooling. Pritchard proposed a novel scheme of taking advantage of characteristics of both schemes to similtaneously trap and cool atoms down to temperatures of $10^{-6}$ Kelvin. Interest in trapped neutrals involves collective effects at this temperature and high resolution spectroscopy.

The final session of the workshop dealt with the subject of trapping of ions. Trapping of ions is technically much easier than the trapping of neutral atoms. Results of frequency standards based on laser-cooled and trapped ions, observed plasma waves in ion traps, and high resolution spectroscopy of trapped ions were presented. Several cooling and trapping schemes for ions were also presented.

I attended five sessions of the DEAP meeting dealing with photon interactions and quantum optics, atomic and molecular collisions at low energy, Rydberg states, cooling and trapping of atoms and ions, and laser spectroscopy. I also attended the poster session but saw little of interest.

One interesting talk in the first session was some work done at M.I.T. by Feld's group to resolve why the predicted coherent ringing is seen in some superfluorescence experiments but not others. They showed that experiments which did not observe ringing probably failed to do so because they were similtaneously sampling the output from regions illuminated by very different laser intensities. Another interesting series of talks by Shore, Eberly, and Wódkievwicz dealt with a new method of including incoherent fluctuations in quantum optics calculations.

The session on atomic and molecular collisions at low energy included a talk by Gaebe, Borge, and Wing on measurements of ionization cross sections in collisions between sodium Rydberg atoms. They explained the importance of this study to such applications as Rydberg masers and cutting down on the dark noise in Rydberg infrared and RF detectors. They measured a cross section of about five times the geometric area of the atoms as predicted by theory. Pritchard and his group reported some results of rotationally inelastic collisions in a supersonic jet. The first talk was a report of measurements of the collision rate as a function of angular momentum in the initial and final states of the lithium atoms used. Data were fit to the formula

$$\text{Rate} = \alpha \frac{l(l+1)^{\gamma} e^{l(l+1)}}{j^*(j^*+1)}$$

In the above, $\alpha$ is a proportionality constant, $l$ the angular momentum quantum number, $\gamma$ an empirical constant related to the impulsive amount of angular momentum transfered, and $j^*$ the maximum amount of angular momentum transferred in the collision. The fit to the above formula was not as good as it was in the earlier sodium data collected by the same group. Additionally, the group explained previously reported velocity dependence of rotationally inelastic collisions in sodium atoms in terms of a hard ellipse model which seemed to explain the data quite well.

The session on Rydberg atoms involved a number of interesting talks. Palfrey and Lundeen reported some measurements made on the high $L$ fine structure of helium Rydberg states. They were looking for manifestations of the predicted long-range (non-classical) Kelsey-Spruch forces. These forces were not observed at the level predicted by the simplest estimates. Hulet and Kleppner reported on work with "circular" Rydberg states (states with $|m| = l = n - 1$). These states have very long lifetimes since the only allowed decay transition is to the next lower $n$ state. Even this decay mode can be greatly suppressed by confining the atoms between two conducting plates spaced by $< \lambda/2$. Freeman, Bloomfield, and Bokor reported some observed "planetary" behavior in highly excited two-electron Ba atoms. The planetary atoms were detected by detecting $Ba^{++}$ ions after autoionization. One of the interesting features they noted was a vibrational spectrum of the two planetary electrons and the core. The same group also studied the probability of autoionization rates of two-electron atoms as a function of core size. The found the rate to be a constant independant of the size of the core. A group at Princeton reported some interesting results where they managed to localize a Rydberg electron away from the corresponding nucleus. A group from Los Alamos reported on several measurements they have made on hydrogen in the VUV spectral region. The high energy photons were obtained by using a UV laser pulse which was doppler shifted to the blue in the rest frame of 800 MeV hydrogen atoms obtained from the LAMPF accelerator.

The session on cooling and trapping of atoms and ions contained much of the same information which was presented during the workshop which preceded the conference. Prior presented some interesting work on the physics of trapped multiply charged ions. The possibility of containing the ions for extended periods of time permits the study of non-dipole transitions, total atomic binding energies, and quenched nuclear decays. Knight discussed some of the interesting astrophysical applications of ion spectroscopy. The low densities of astrophysical sources lead to an abundance of long lifetime metastable states which aren't seen on earth (since they are de-excited by collisions at higher densities). Knowledge of the lifetimes of these states gives a measure of the ion densities in astrophysical objects. Phillips talked about cooling and trapping of neutral ions in a nice summary of ideas which were discussed in and around the workshop. Nagourney illustrated part of the beauty of studying trapped ions by displaying a picture of a single trapped flourescing ion. Itano discussed some of the NBS frequency standard work being done with trapped ions. They are able to obtain frequency uncertainties of the order of 1 part in $10^{-13}$ using this technique.

The final session on laser spectroscopy had three sets of talks I found interesting. Rose and Gupta reported on some photoacoustic spectroscopy work. It can be used to investigate atoms molecules in hostile environments (plasmas, for instance), with high bandwidth, no boundary effects (e.g. in flames for instance), and with three dimensional spatial resolution. Prouden and Phillips reported in their laser cooling work at NBS in this session. They should an amazing picture of some sodium atoms being stopped and actually turning around. Lastly, the Los Alamos group reported on some of their spectroscopic studies in hydrogen which I have already mentioned.

In conclusion, I found the workshop and conference to be quite stimulating and interesting. The discussions in and outside of the workshop pointed out a number of important directions in which our laser cooling work here could go. I was encouraged during the conference at how nicely the work being done here at HRL will contribute to understandings in many of the topics of current research being pursued in this field.

# APPENDIX B

# Radiation Cooling with $\pi$-Pulses

A. J. Palmer and J. F. Lam

Hughes Research Laboratories
Malibu, Calif. 90265

## Abstract

Theoretical examination of radiation cooling by $\pi$-pulses reveals cooling rates, optimal power levels, and the need for zero-field dwell periods between the $\pi$-pulses.

# Radiation Cooling with $\pi$-Pulses*

A. J. Palmer and J. F. Lam

Hughes Research Laboratories
Malibu, Calif. 90265

Radiation cooling of a velocity distribution of two-level atoms by a train of $\pi$-pulses is examined theoretically through the use of the density matrix and quantum transport equations. The quantum transport equations are obtained from the Schrodinger equation by using the Wigner distribution function to take into account the effect of the laser field on the center-of-mass motion of the resonant atoms. In this manner, the effects of photon recoil appears as a convective derivative in momentum space. In essence, these equations are the quantum generalization of the classical Boltzmann equation. We have integrated the quantum transport equations for a train of alternate, oppositely-directed and oppositely-detuned $\pi$-pulses acting on an initial Maxwellian velocity distribution of two-level atoms homogeneously distributed in space. The results

confirm that a properly chosen zero field dwell period between the $\pi$-pulses produces the desired re-phasing of the state vectors by selectively maintaining good coherence of the atomic state with the $\pi$-pulse train on one side of the distribution only. Cooling rates comparable the c.w. cooling rate for the case of a power-broadened line are predicted.

- Work supported in part by AFOSR contract F49620-82-C-0004.