Chapter 2. Basic Atomic Physics

Academic and Research Staff

Professor Daniel Kleppner, Professor David E. Pritchard, Dr. Alexander G. Martin, Dr. Min Xiao

Visiting Scientists

Theodore W. Ducas[1]

Graduate Students

Vanderlei S. Bagnato, Kevin R. Boyce, Pin Peter Chang, Eric A. Cornell, Chris R. Ekstrom, Thomas R. Gentile, Kristian Helmerson, Long Hsu, Barbara J. Hughey, Chun-Ho Iu, Michael M. Kash, David W. Keith, Peter J. Martin, Peter McGill, Warren Moskowitz, Bruce G. Oldaker, Scott Paine, Eric L. Raab, Brian Stewart, Ke-Xun Sun, Richard E. Stoner, Robert M. Weisskoff, George R. Welch

Undergraduate Students

Deborah Kuchnir, Joseph Landry, Debra Lew, Andy H. Miklich, James Schwonek, Genevieve Sparagna, Quentin Turchette, Garth Zeglin

2.1   Rydberg Atoms in a Magnetic Field

Sponsor

Project Staff

Michael M. Kash,[2] George R. Welch, Chun-Ho Iu, Long Hsu, Professor Daniel Kleppner

A Rydberg atom in a strong magnetic field constitutes a prototype two-dimensional nonseparable problem. It is one of the simplest experimentally-realizable quantum systems for which there is no general solution. In addition, this system is uniquely suited to studying the manifestations of chaos in quantum mechanics for it is among the very small number of systems whose classical motion displays chaos and whose quantum properties can be studied both experimentally and theoretically.

We are carrying out a study of Rydberg states of lithium in a strong magnetic field. The experiment employs two dye lasers to excite an atomic beam of lithium inside of a superconducting solenoid. The first laser drives the two-photon $2S \rightarrow 3S$ transition; the second laser excites the atom to a Rydberg state. A central goal of this work is to obtain much higher resolution than previously possible. We have achieved this by using stabilized c.w. dye lasers and by carefully collimating the atomic beam to remove effects of motional electric fields and Doppler broadening. In addition to achieving high resolution, the experiment achieves high absolute accuracy in energy and field. The wavelength of the exciting laser is measured by careful comparison with an iodine absorption spectrum. The magnetic field is determined by exciting $|\Delta m| = 1$ transitions and observing the paramagnetic splitting of the n = 21 manifold.[3] The linewidth is slightly less

---

[1] Wellesley College.

[2] Received Ph.D. from MIT in August 1988; Presently on the faculty of Lake Forest College.

[3] M.M. Kash, G.R. Welch, C. Iu, and D. Kleppner, *Spectrochemica Acta A* 45:57 (1989).
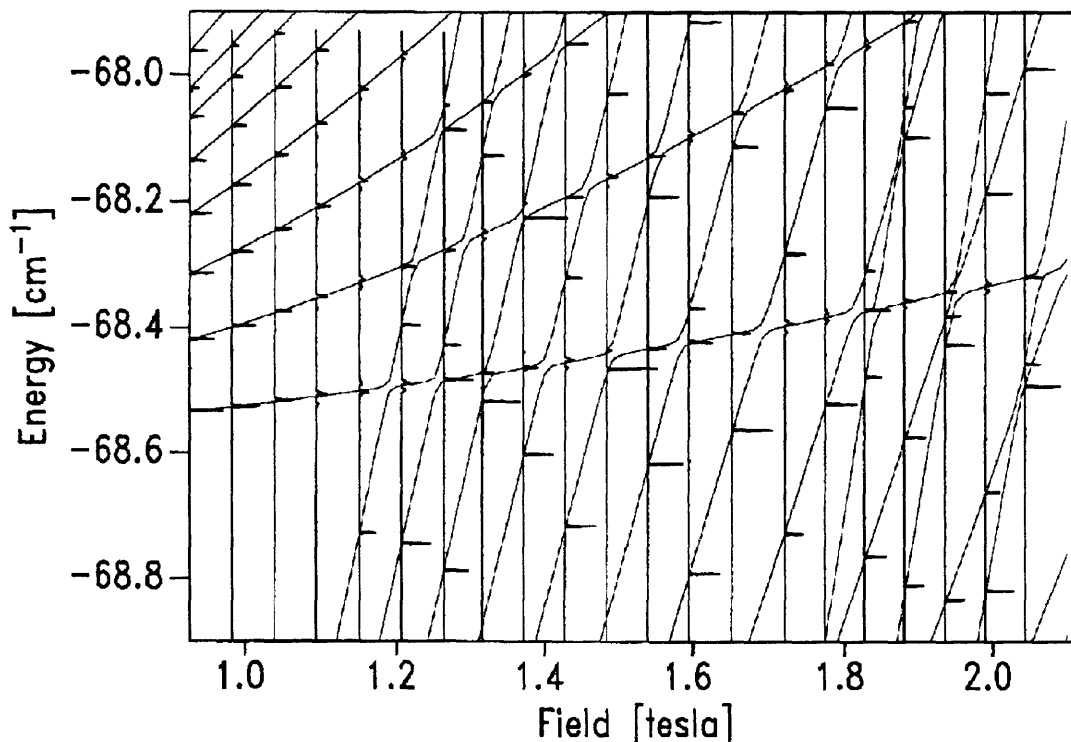
Figure 1. Experimental and calculated energy level map of lithium in a regime where accurate calculations are possible.

than $10^{-3}cm^{-1}$. The energy accuracy is approximately equal to this line width. The magnetic field can be determined to $\pm 10^{-3}T$ at fields up to 6T.

We have carried out a series of studies in regions of energy and field extending from areas in which accurate quantum calculations are possible to areas where there are no quantum calculations and in which the classical motion is completely chaotic. Figure 1 shows results from one of the former regions. In addition to the gross features of the interacting levels, the data reveal numerous level anticrossings which are of particular interest. The size of these anticrossings is a manifestation of the non-separability of the Hamiltonian caused by the lithium core.[4] We have measured the sizes of a sequence of anticrossings between levels from n=24,25

and n=39,40. The data are in excellent agreement with calculations based on our model of the lithium core.

In regions with sufficiently high energy and magnetic field, the classical trajectories of the electron become chaotic.[5] Although the manifestations of classical chaos in quantum systems are far from understood, it is generally accepted that energy level statistics provide an important signature of chaotic behavior. In particular, the energy level statistics for a non-separable system with regular classical motion are expected to be Poisson-like, while in areas of chaotic classical motion the statistics are expected to resemble those of ensembles of eigenvalues of random matrices. This behavior has been characterized as "universal" for all quantum systems.[6] However, to our knowledge, pre-

---

4 M.L. Zimmerman, M.M. Kash, and G.R. Welch, *J. de Phys. Col. C2* 43:113 (1982).

5 D. Delande and J.C. Gay, *Phys. Rev. Lett.* 57:2006 (1986).

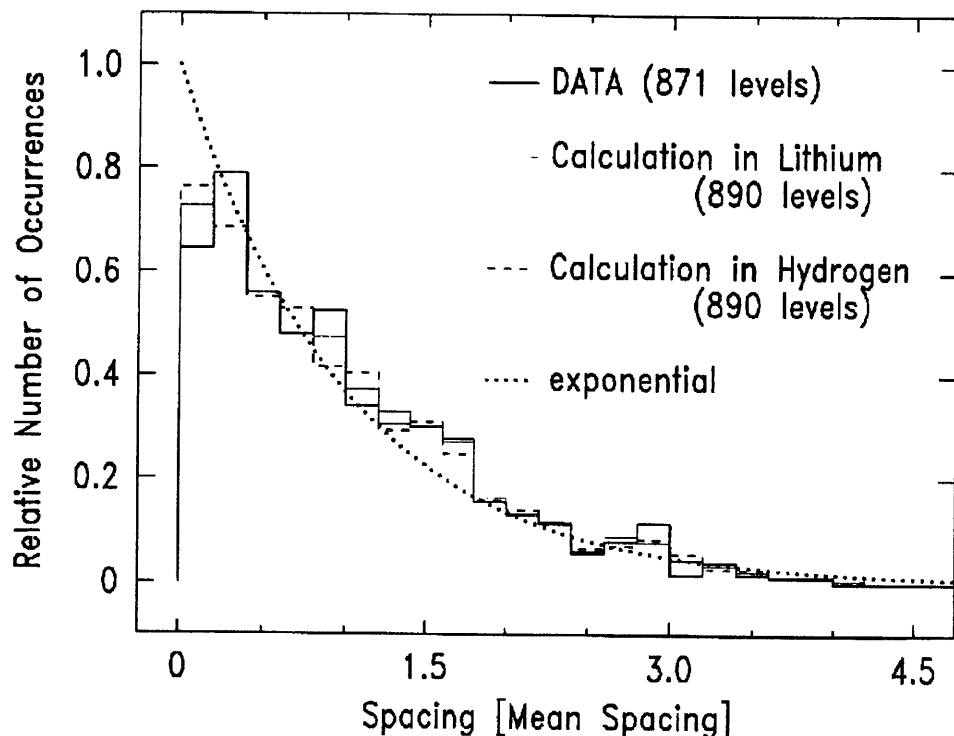6 O. Bohigas, M.J. Giannoni, and C. Schmit, *Phys. Rev. Lett.* 52:1 (1984).

Figure 2. Adjacent energy level spacing histogram for lithium in a regime of regular classical motion. The exponential behavior characteristic of Poisson-like statistics is evident.

vious to this work the Poisson-like behavior of regular motion has not been demonstrated experimentally.

The classical dynamics of an atom in a magnetic field change smoothly from regular to chaotic.[7] We have observed the Poisson-like behavior predicted in the regular regime.[8] This observation requires accurate measurement of the energies of a large number of fully resolved spectral lines. A commonly used measure of the randomness of spectra is the adjacent-neighbor spacing distribution. The spacings between adjacent levels are computed and plotted as a histogram. Figure 2 shows the result for 871 levels measured in the regular regime, along with an exponential curve which is the Poisson prediction. Although the agreement is not perfect, the

discrepancy can be traced to the near-degeneracy of the zero-magnetic field levels, and is well understood. In addition, we have investigated long range correlations in the spectrum which are not apparent in the nearest neighbor distribution. Our analysis indicates that these correlations can be simply related to the underlying quantum structure of the system.[9]

We have also carried out an initial exploration of the positive energy regime. This particular area is of interest due to the lack of any quantum solutions, and because its classical behavior is completely chaotic. The Rydberg spectrum of a one-electron atom consists of a series of terms characterized by a principle quantum number n that converges to a series limit as $n \to \infty$: above this

[7] G. Wunner, U. Woelk, I. Zech, G. Zeller, T. Ertl, F. Geyer, W. Schweitzer, and H. Rudder, *Phys. Rev. Lett.* 57:3261 (1986).

[8] G.R. Welch, M.M. Kash, C. Iu, L. Hsu, and D. Kleppner, *Phys. Rev. Lett.* 62:893 (1989).
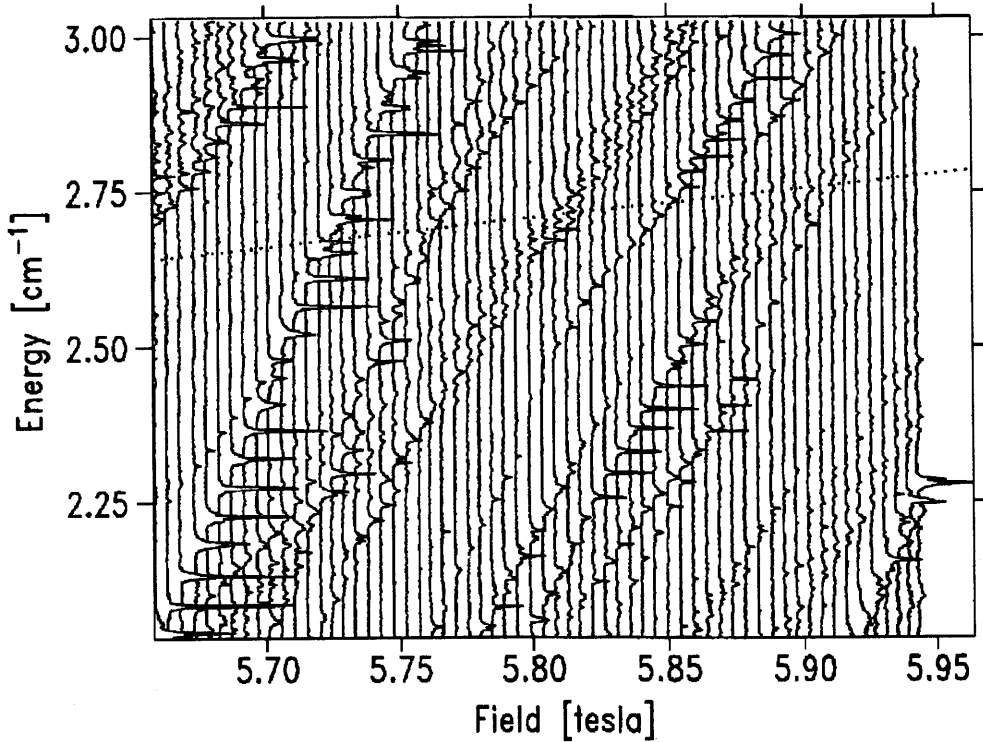
[9] Ibid.

Figure 3. Positive energy spectra showing evolution of "auto-ionizing levels." Energy is measured relative to the zero-field ionization limit.

ionization limit, there are no bound states. In a uniform magnetic field, however, the electron's transverse motion is confined and ionization can only occur if the electron leaves along the field. We have discovered groups of resonances above the ionization limit whose widths give information about the rate of ionization. Some of these "auto-ionizing" resonances are found to be extremely sharp. This is surprising because the dynamical time scale in a strong magnetic field is set by the cyclotron period $T_c = 2\pi m/eB$, but we have observed resonances whose widths indicate a lifetime as great as $10^4 T_c$. Figure 3 shows the behavior of these resonances in a magnetic field of 6 tesla. These results are unexpected because the classical motion in this regime is chaotic and the trajectories appear to lose all "memory" of their initial conditions in a time of approximately T_c. Understanding the origin and structure of these states is a principal goal of the next stage of our research.
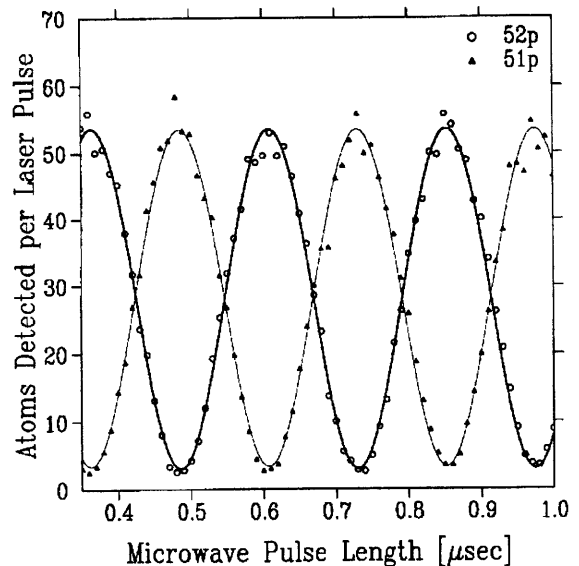

Figure 4. Two-photon Rabi oscillation of the 52p→51p transition. The horizontal axis represents the interaction time of the atoms with the microwave radiation, which is controlled by a microwave switch. The vertical axis is the number of atoms detected per laser pulse by the two respective channels.

2.2 Microwave Quantum Optics

Sponsors

Joint Services Electronics Program
(Contracts DAAL03-86-K-0001
and DAAL03-89-C-0002)

Project Staff

Theodore W. Ducas, Thomas R. Gentile, Barbara J. Hughey, Professor Daniel Kleppner

We are investigating atom-field dynamics in an experimental study of the interaction of microwave fields with highly excited (Rydberg) states of calcium. During the past year, we have completed a study of the dynamics of two-photon transitions — two-photon "Rabi oscillations" — and a high resolution study of several series of Rydberg states of calcium by one- and two-photon microwave spectroscopy. In addition, we have made substantial progress towards the final goal of this research; a study of the effect of a microwave cavity on the evolution of an atomic two-level system interacting with the vacuum field, and other fields, in a high-Q cavity.

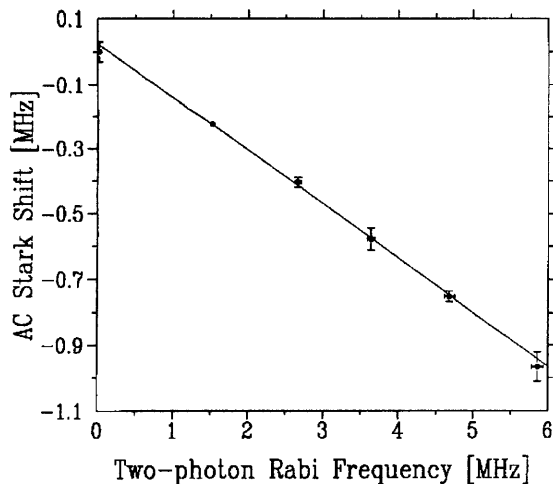Our experiment employs an atomic beam of calcium that is excited to a Rydberg state by

Figure 5. The AC Stark shift of the two-photon 52p→51p transition measured in terms of the two-photon Rabi frequency. When expressed in these variables, theory predicts a linear relation.

three-step pulsed laser excitation. Singlet states of calcium are used to avoid complexities of fine and hyperfine structure. By tuning the wavelength of the final laser, nearly any 4snp Rydberg state can be excited.

Our studies involve microwave transitions between two Rydberg states induced in a waveguide or a cavity. After the atoms pass through the interaction region they enter a field ionization detector where the two states can be separately measured with high resolution and discrimination.

2.2.1 Rabi Oscillations

We use the term "Rabi oscillations" to describe the coherent evolution of an atomic system in a near resonant electromagnetic field in the absence of significant damping mechanisms. We have studied one- and two-photon Rabi oscillations and a number related coherent effects. The experiments include measurements of the dependence of the one- and two-photon oscillation frequencies on microwave power and detuning from resonance. We have used the off-resonant behavior of the two-photon oscillation frequency to measure the AC Stark shift. (The AC Stark shift is the shift of atomic levels under the influence of a strong radiation field). In addition, we have studied the effect of Zeeman splitting on one-photon Rabi oscillations and on the free evolution of the magnetic sublevels.

Figure 4 shows the two-photon Rabi oscillation of the transition 52p→51p. We have carried out a detailed study of the AC Stark shift of this transition. To interpret the AC Stark shift, it is essential to know the field amplitude, but measuring it precisely is a formidable task. We have overcome the problem by using the Rabi frequency to calibrate the field. Results are shown in figure 5.

2.2.2 High-Resolution Microwave Spectroscopy

We have determined the energy dependence of the quantum defects of six series of Rydberg states by measuring transition fre-
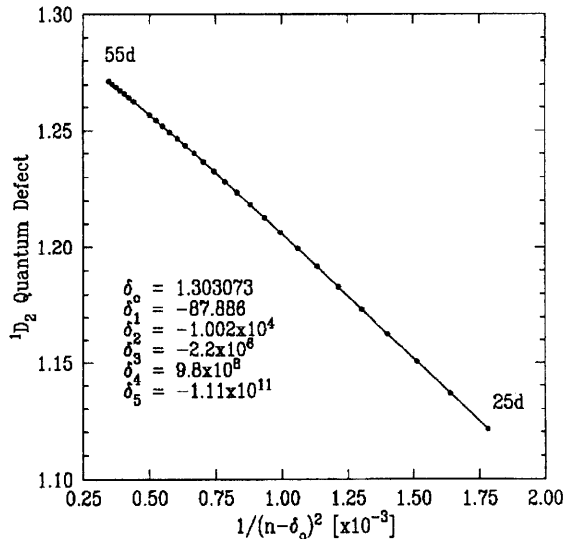
Figure 6. The quantum defects of the $^1D_2$ series in calcium. To display their small energy dependence the defects are plotted against $1/(n-\delta_0)^2$ which is the first approximation to the energy of a Rydberg atoms.

quencies from 4snp $^1P_1$ states to the following final states: 4sns $^1S_0$, 4sn'd $^1D_2$, 4sns $^3S_1$, 4sn'd ^3D_J(J = 1 and J = 2), and 4s(n-1)p $^1P_1$ (two-photon). We have also measured the frequencies of 4sns $^1S_0 \rightarrow$ 4s(n − 1)s $^1S_0$ and 4sns $^1S_0 \rightarrow$ 4snp $^3P_1$ transitions, for a total of 126 transitions with principal quantum numbers in the range 23-55. In addition, we have studied transitions with n as high as 74 as a diagnostic of stray electric fields. Figure 6 shows results for the 4snd $^1D_2$ series. To evaluate the quantum defect of a number of final states from measurements of transition frequencies, the quantum defect of the initial states must be separately determined. The $^1P_1$ quantum defects were measured by fitting the energy dependence of a series of two-photon np $\rightarrow$ (n−1)p $^1P_1$ transition frequencies. These quantum defects were used in conjunction with the measurement of the np $\rightarrow$ n'd transition frequencies to determine the 4snd $^1D_2$ quantum defects.

2.2.3 Atom-Photon Interactions in a Superconducting Microwave Cavity

A cavity tuned to an atomic transition can drastically modify the absorption and emission rates for that transition from its free space values. For a sufficiently long damping time (high Q), the atom and cavity will periodically exchange energy. Our goal is to study this regime of spontaneous oscillatory behavior.

The experiment employs a cylindrical superconducting cavity operated in the TM_{010} mode at 35 GHz. Because the electric field of this mode has a constant amplitude along the atomic beam, the atom-field interaction does not vary as the atoms traverse the cavity. We prepare an atomic beam of calcium Rydberg atoms inside the cavity and we probe the time evolution of the system by using Stark switching techniques to mistune the atomic transition.

A key element of the experiment is the use of a split cavity which allows us to apply the Stark-switching electric field. In principle, splitting the cavity lengthwise should not significantly degrade the Q because currents in the TM_{010} mode are parallel to the plane of the seam. However, in practice there is a small leakage of power from the seam which limits the Q. For our studies we need Q > 10^7. To achieve this we use a niobium cavity with a choke groove to suppress the leakage. (Without the choke groove, the Q obtained in a split cavity is limited to ~ $2x10^5$.) By electrically isolating the cavity halves, we can apply a small electric field inside the cavity which Stark tunes the transition frequency away from the cavity resonance, thus inhibiting the atomic transition and "freezing" the system evolution. This method allows us to vary the atom-cavity interaction time from zero to the full transit time. The split cavity design also allows us to tune the cavity over a large range without significant degradation of the Q. The tuning is accomplished by varying the spacing between the halves. The maximum Q we have obtained is 4 x 10^7; a Q > 10^7 has been maintained while tuning over a range of 150 MHz. We believe the Q is limited by residual losses through the crack.
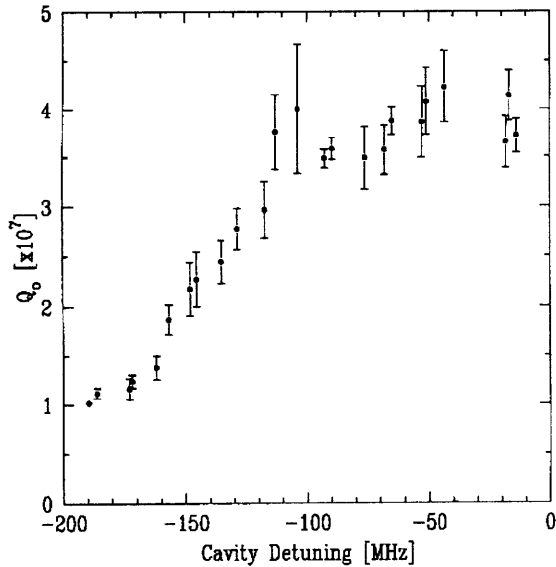
Figure 7. Unloaded Q of the TM_{010} mode of the niobium split cavity as a function of cavity detuning.

Figure 7 shows the dependence of the Q of the superconducting niobium cavity on the cavity detuning. The detuning is measured relative to the frequency obtained when the cavity halves are pushed tightly together. The cavity detuning is proportional to the size of the gap between the halves with a slope of 3.6 MHz/μm. This cavity has been cooled to 1.6 K in our atomic beam apparatus. Work is in progress to observe the oscillatory exchange of energy between a single calcium atom and the cavity.

2.3 Millimeter-Wave Measurement of the Rydberg Constant

Sponsors

Project Staff

Pin P. Chang, Scott Paine, James Schwonek, Professor Daniel Kleppner

The Rydberg constant plays a prominent role in the table of fundamental constants as a primary atomic unit of length. A series of recent experiments have determined R to nearly one part in 10^{10}. The fundamental limitation to these measurements is not the precision of the experiment but the accuracy of the wavelength standard. It is generally recognized that optical wavelengths cannot be compared to a precision greater than 1 part in 10^{10}. One consequence is that length is now defined in terms of the distance traveled by light in a fixed time interval rather than in terms of a certain number of optical wavelengths. Thus, wavelength measurements of R appear to have reached a natural barrier.

We are attempting to advance the precision of R by measuring it in frequency units. (The specific quantity we shall measure is cR). We shall accomplish this by measuring millimeter wave transitions between Rydberg states of hydrogen. Because the frequency of millimeter radiation can be measured to the full precision of modern atomic clocks, the experiment is not limited by metrological standards.

Our experiment has three goals: 1) to reevaluate R; 2) to measure the Lamb shift; and 3) to calibrate the precise frequency of the spectrum of hydrogen. Because our measurements involve high angular momentum states for which the Lamb shift is extremely small, a comparison of our results with optical measurements can yield an improved value of the Lamb shift. Calibrating the precise frequency allows an independent check of optical frequency metrology as it starts to advance.

We are determining the Rydberg constant by measuring the frequency of the n = 29→n = 30 "circular" transition in atomic hydrogen. Our goal is accuracy of 1 part in 10^{11}, a full order of magnitude improvement over the present state of the art.[10] The transition frequency, 256 GHz, allows us to use established techniques to phase lock our millimeter-wave source directly to a cesium primary frequency standard.

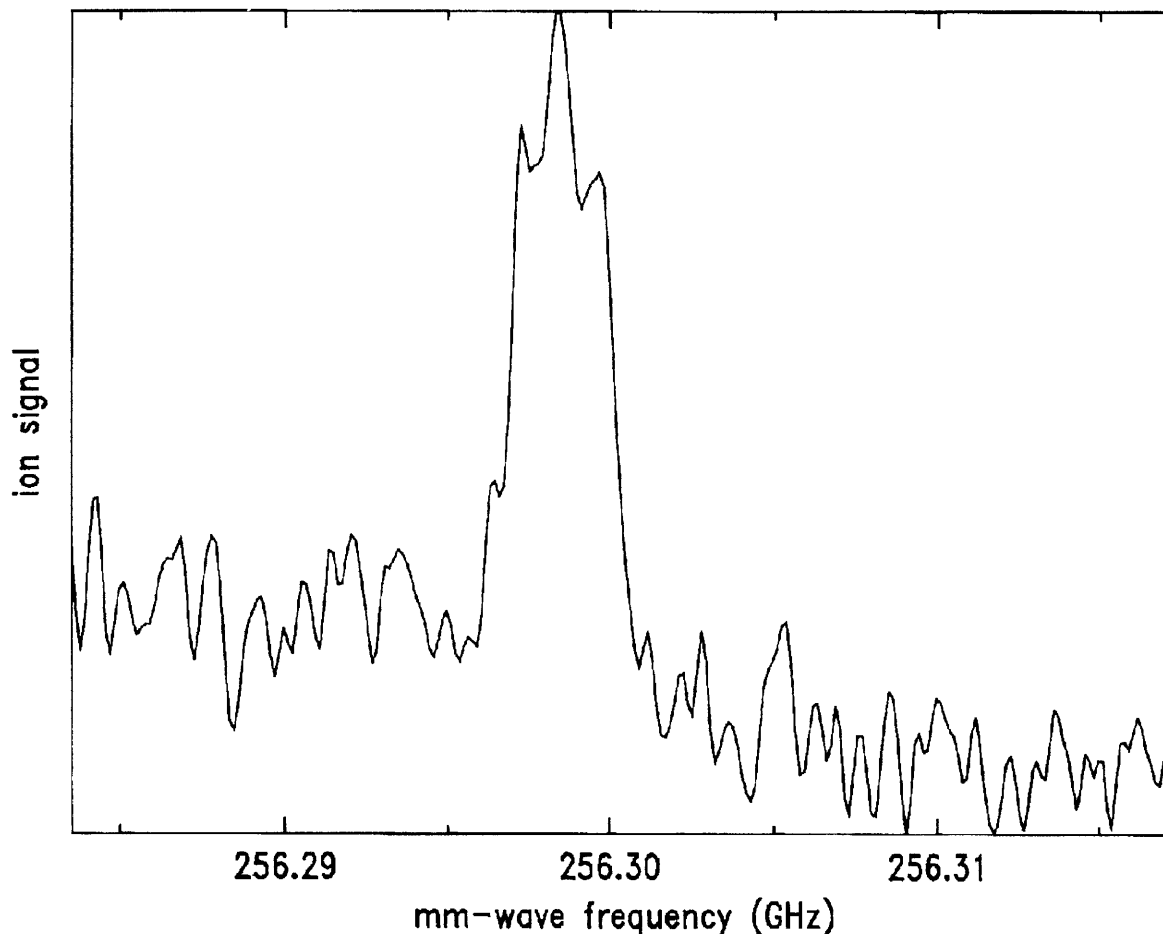[10] F. Biraben et al., PRL 62:621 (1989); P. Zhao et al., PRL 58:1293 (1987).

Figure 8. Millimeter-wave transition from (n, n1, m) = (29, 14, 0) to (30, 14, 1). The n = 29 state is populated by a two-step pulsed laser excitation. The n = 30 state is detected by electric field ionization.

We have completed construction of an atomic beam apparatus with a cold (10K−80K) atomic hydrogen source. An upgraded version of our pulsed UV + VUV laser system excites Rydberg states by two-photon absorption via the 2p state. With a new millimeter wave source and quasioptical system, we have observed transitions between low-m Rydberg states (figure 8). We have excited the circular (m = n-1) states which will be used in our measurement, using the crossed-fields method of Delande and Gay (figure 9).[11]

The next steps are to increase the yield of circular state atoms, to improve our data

acquisition system, and to construct the interaction region for performing high resolution separated-field millimeter-wave spectroscopy.

Publications

Haroche, S., and D. Kleppner, "Cavity Quantum Electrodynamics," *Physics Today*, 42:24 (1989).

Kash, M.M., G.R. Welch, C.-H.Iu, and D. Kleppner, "Diamagagnetic Structure of Lithium, n ~ 21," *Spectrochemica Acta* 45A:57 (1989).

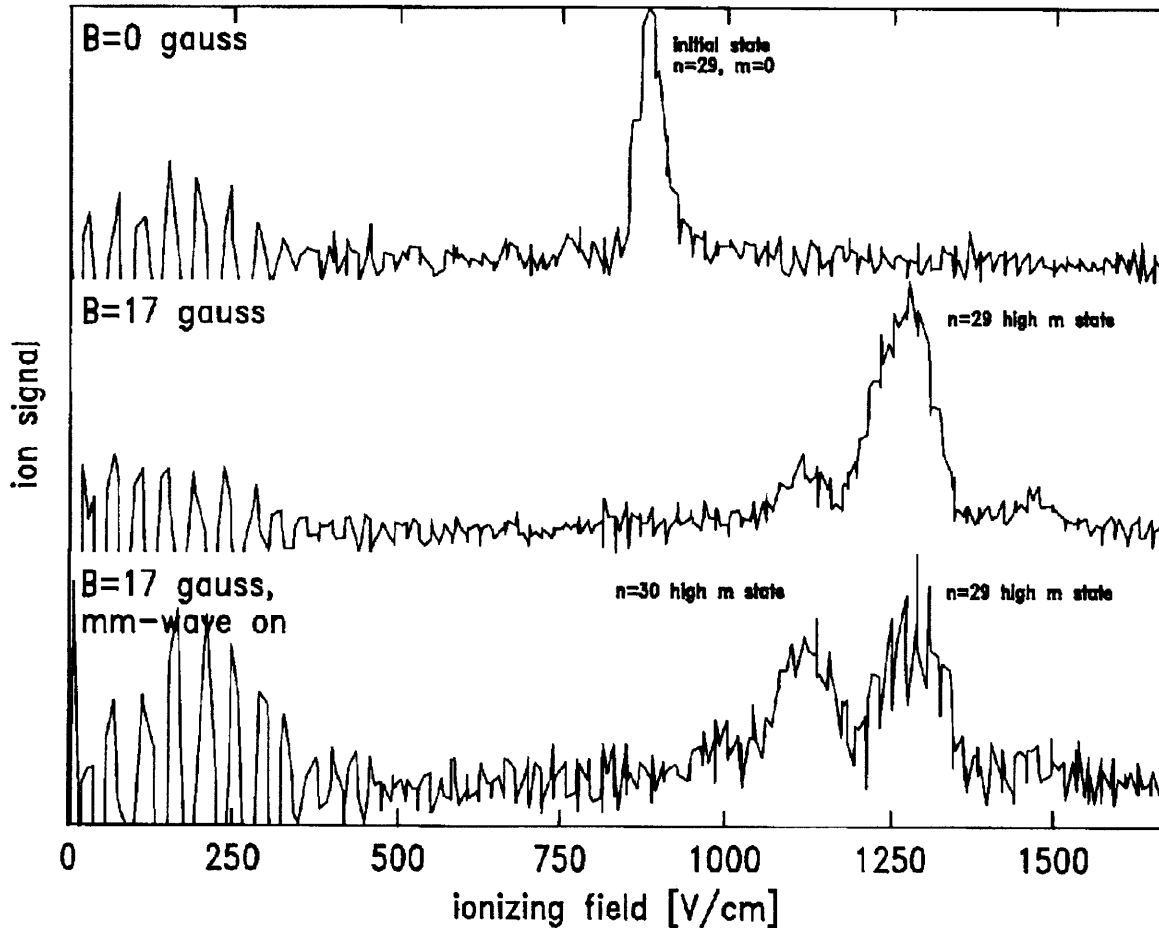[11] D. Delande and J.C. Gay. *Europhys. Lett.* 5:303 (1988).

Figure 9. Transfer of H atoms from a laser-excited n = 29, m = 0 state to the m = 28 state by the crossed-fields method. The atoms are excited in an electric field; the electric field is then reduced to zero in the presence of a perpendicular magnetic field, transferring the atoms to the m = 28 circular state. The various states are distinguished by the electric field at which they ionize. In the last trace, 256 GHz radiation transfers some of the atoms to the n = 30, m = 29 state.

Kleppner, D., "A Future for Hydrogen," *Proceedings of the 11th International Conference on Atomic Physics,* Paris, 1988, to be published.

Kleppner, D., "Trapped Atomic Hydrogen," *Proceedings of the Symposium on Hydrogen,* Pisa, Italy, 1988, to be published.

Kleppner, D., "Frontiers of Atomic Physics," In *Physics in a Technological World,* ed. A.P. French, 347. New York: American Institute of Physics, 1988.

Kleppner, D. "Niels Bohr and Atomic Physics Today," In *Niels Bohr: Physics and the World,* eds. H. Feschbach, T. Matsui and A. Oleson, 45. Harwood, 1988.

Welch, G.R., M.M. Kash, C.-H. Iu, L. Hsu, and D. Kleppner, "Positive Energy Structure of the Rydberg Diamagnetic Spectrum," submitted to *Phys. Rev. Letts.*

Welch, G.R., M.M. Kash, C.-H. Iu, L. Hsu, and D. Kleppner, "Experimental Study of Energy Level Statistics in a Regime of Regular Classical Motion," *Phys. Rev. Lett.* 62:893 (1989).

MIT Thesis

Kash, M.M., *Rydberg Atom Diamagnetism.* Ph.D. diss., Dept. of Physics, MIT, 1988.

2.4 Precision Mass Spectroscopy of Ions

Sponsors

Project Staff

Professor David E. Pritchard, Kevin R. Boyce, Eric A. Cornell, Deborah Kuchnir, and Robert M. Weisskoff

We are developing an experiment to determine the mass of individual atomic and molecular ions with precisions of 10^{-11}. This capability will allow us to do a variety of experiments which address issues of both fundamental and applied physics:

- The $^3H^+-^3He^+$ mass difference is important in ongoing experiments to measure the electron neutrino rest mass.

- Excitation and binding energies of typical atomic and molecular ions can be determined by "weighing" the small decrease in energy: $\Delta m = E_{bind}/c^2$.

- Experiments that weigh γ-rays can be used in a new method to determine Avogadro's number, N_A, a key fundamental constant.
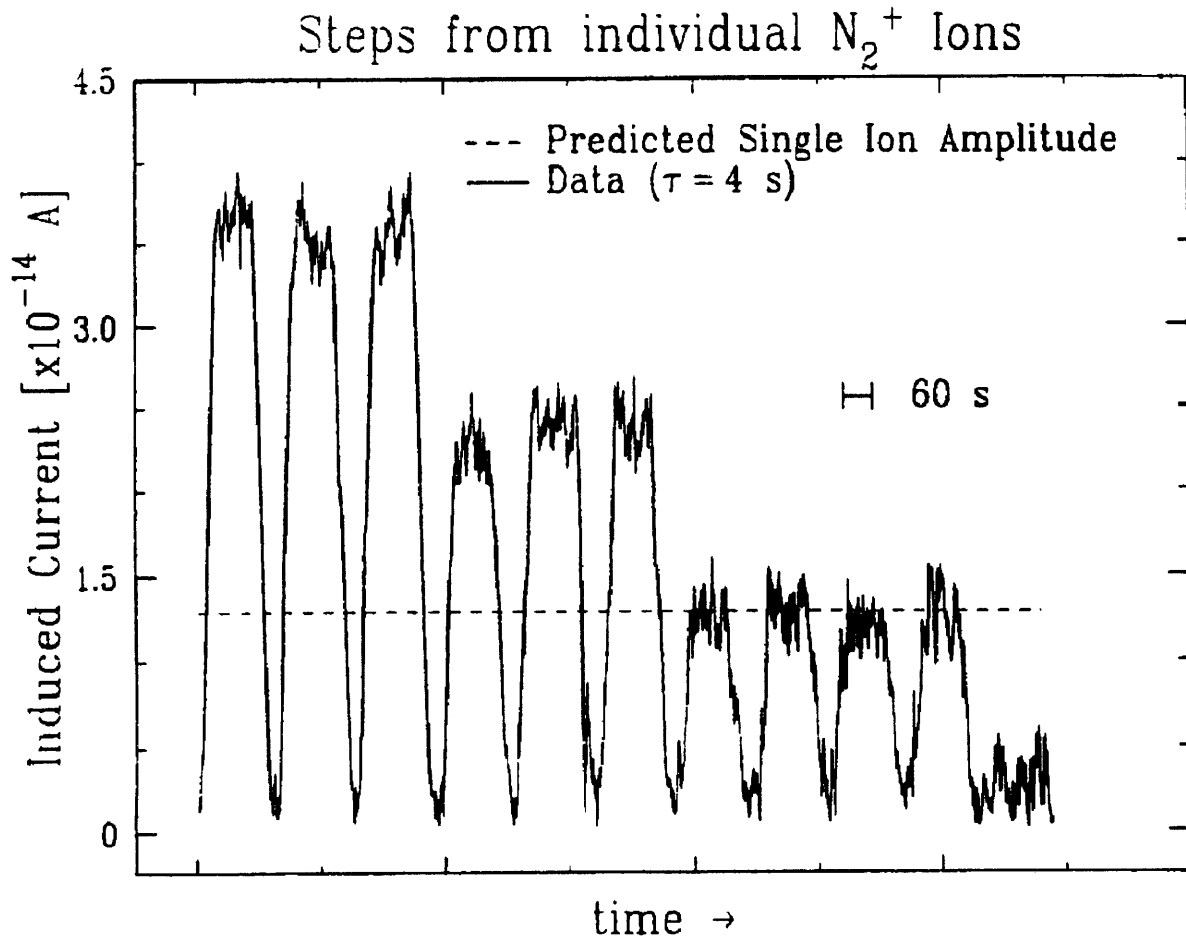

Figure 10. Steps in the axial signal as one ion after another is expelled from the trap. The ions were driven to 20% of the trap size.

- Traditional applications of mass spectroscopy should benefit from the several orders of magnitude improvement in both accuracy and sensitivity which our approach offers over conventional techniques.

Our experimental approach is to make ion cyclotron resonance measurements on a single molecular or atomic ion in a Penning trap, which consists of highly uniform magnetic field with axial confinement provided by weaker electric fields. Ions are monitored via the currents they induce in the trap electrodes as the ions oscillate along magnetic field lines. Working with only a single ion is essential: space charge from other ions would lead to undesired frequency shifts.

This year, we succeeded in isolating a single N_2^+ ion in our trap and measuring its cyclotron frequency. The induced current, 10^{-14} amps r.m.s. at 160 kHz, is detected by an rf SQUID coupled to the trap by a high-Q superconducting circuit.[12] In figure 10, the trapping voltage is adjusted every two minutes to bring the remaining ions close to an electrode. Sometimes an ion hits the
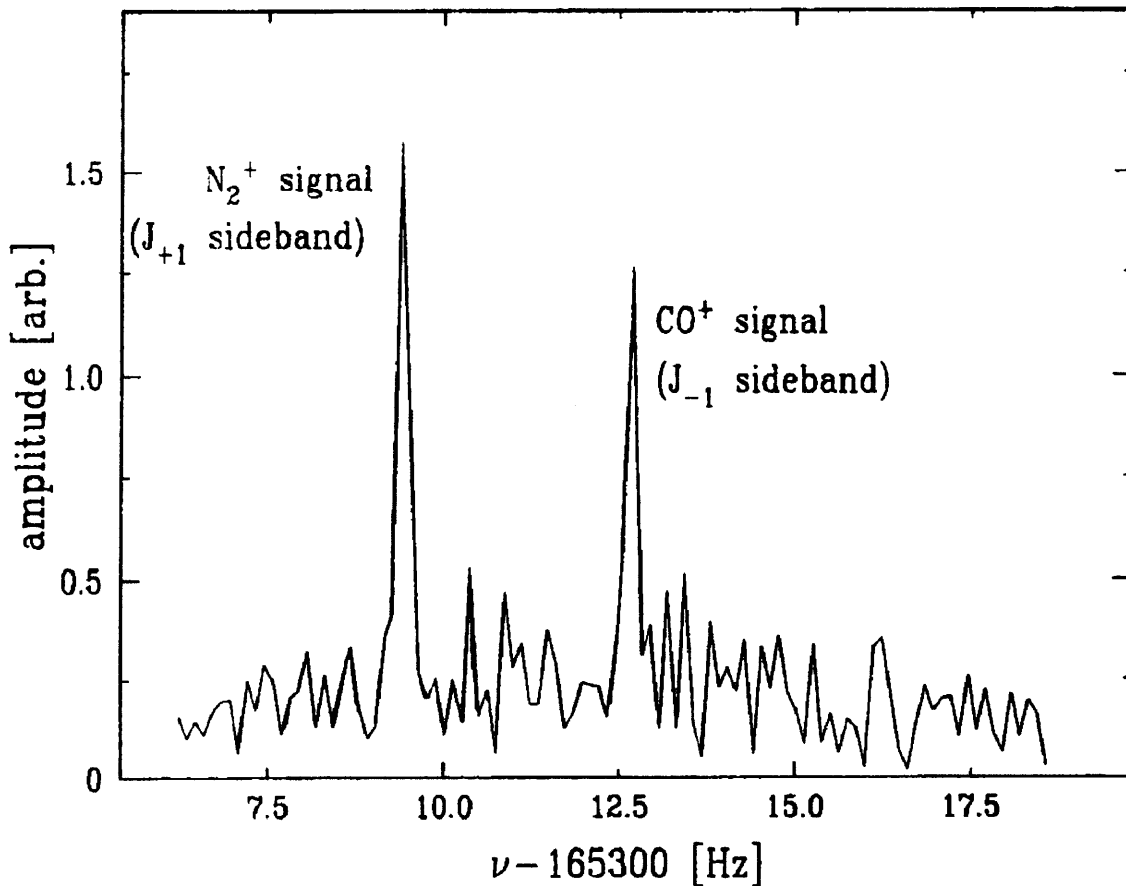
Axial Ring–down Signal from an Ion Pair

Figure 11. For each plotted point, the following experiment is performed: the ion is pulsed into a cyclotron orbit of known initial phase, then allowed to evolve "in the dark." After time t, a π-pulse is applied, bringing the ion's cyclotron action and accumulated phase into the axial mode. As the ion's axial motion rings down, its phase is detected. The appropriate multiple of 360 degrees is added, and a line is fitted to the points. The slope of the line is the offset from the frequency generator to the trap cyclotron frequency.

---

[12] R.M. Weisskoff, G.P. Lafyatis et al., *J. Appl. Phys.* 63:4599 (1988).

electrode and is neutralized, causing a reduction in detected ion signal by an amount corresponding to the signal from a single ion.

We have demonstrated techniques for driving, cooling, and measuring the frequencies of all three normal modes of Penning trap motion. Thus we can manipulate the ion position reproducibly to within 20 microns of the center of the trap, and correct for electrostatic shifts in the cyclotron frequency to great accuracy. We use a π-pulse method to coherently swap the phase and action of the cyclotron and the axial modes. Thus, although we detect directly only the axial motion, we determine the cyclotron frequency by measuring how much phase accumulates in the cyclotron motion in a known time interval (figure 11).

Working with N_2^+ and CO^+ ions, we have attained a precision of about 2×10^{-9} in a five minute measuring time. Precision is currently limited by magnetic field imperfections and temporal instabilities. Progress in these areas should bring our mass measurement precision into the 10^{-10} range. Achieving our longer range goal of 10^{-11} precision requires either dramatic improvements in field stability, or else simultaneous comparison of two different ions (with two ions, the ion-ion perturbations are calculable and also very similar for each ion and, hence, do not introduce significant uncertainty in the mass ratio).

Figure 12 shows the signal from a single CO^+ ion and a single N_2^+ ion simultaneously trapped. In the coming year, we hope to develop techniques for making precision resonance measurements on both ions at the same time.

2.5   Atom Interferometry

Sponsors

Project Staff

Chris R. Ekstrom, David Keith, Bruce G. Oldaker, Quentin Turchette, Garth Zeglin, Professor David E. Pritchard

We are beginning to construct an atom interferometer (a device which interferes atom waves). We plan to use fabricated metal transmission gratings as optical elements for the matter waves. Atom interferometers should be useful in studies of atomic properties, tests of basic quantum physics, metrology, and perhaps ultimately as devices to make ultra-small structures using atom holograms.

The major advance in 1988 was the demonstration of the diffraction of sodium atoms by transmission through a fabricated grating structure (figure 13).[13] This was the first reported diffraction of atoms by a fabricated device. The grating was an array of 0.2μm-period slits formed in a gold foil; upon transmission through this array the Na atoms in our seeded supersonic beam were diffracted through angles of $\sim 10^{-4}$ rad. This discovery gives us reliable devices with which to manipulate atom waves and should lead directly to the demonstration of the first atom interferometer.

During the last half year, our efforts have been directed at the construction of an atom interferometer using these transmission gratings. The interferometer will consist of three diffraction gratings spaced ~ 0.65 m apart in our existing atomic beam machine, the maximum separation of the beams will be $\sim 60\mu$m. The first two gratings separate and redirect the atom beam forming an inference pattern in the atom flux at the third grating, which acts like a mask to sample this pattern (figure 14). A principal technical obstacle is the mechanical vibrations of our machine which will blur the inference pattern. After investigating the character of the vibration

---

13 D.W. Keith, M.L. Schattenburg, H.I. Smith, and D.E. Pritchard, *Phys. Rev. Lett. B* 61:1580 (1988).
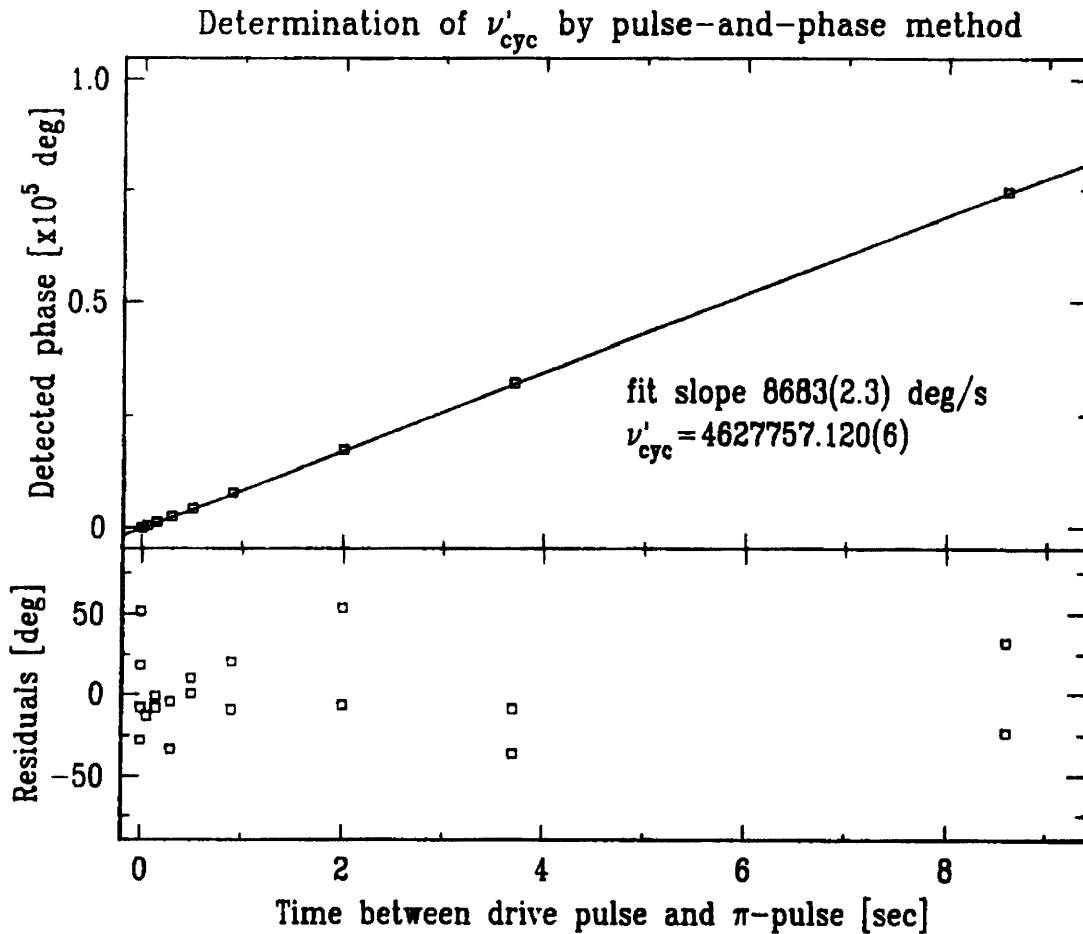
Determination of ν'_{cyc} by pulse-and-phase method

fit slope 8683(2.3) deg/s
$\nu'_{cyc} = 4627757.120(6)$

Figure 12. The signal from a single N_2^+ ion and a single CO^+ ion where magnetron orbits are separated by about 0.5 mm. After the ions are pulsed to about 20% of the trap size, their ring-down motion is modulated at 15 Hz. Although the axial frequencies of the two ions differ by 33 Hz, the first sidebands are only 3 Hz apart, well within the detector bandwidth.
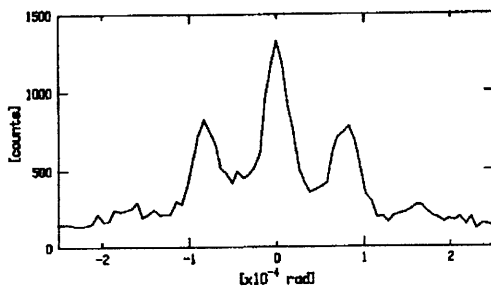

Figure 13. Angular diffraction pattern of sodium atoms after passage through a transmission x-ray grating with 0.2 μm period.

we have decided to attack the problem by establishing a laser interferometer using transmission gratings on the same translation stages as the matter wave gratings. We will use the signal from the optical interferometer to actively stabilize the platforms.

The fact that the gratings were made (for soft x-ray spectroscopy) at RLE's Submicron Structures Laboratory offers the possibility of collaborative efforts to improve our grating technology. One possibility is that by making the lines in our gratings thin enough (while maintaining the same period) we could tilt the grating so that a beam impinging on the surface at a grazing angle was still transmitted. Using a grating at grazing incidence increases its dispersive power due to the foreshortening of the grating period seen by the incident beam. The Submicron Structures Laboratory has made 200 nm period Cr gratings in which the 100 nm wide lines are only $\sim$ 5 nm thick.
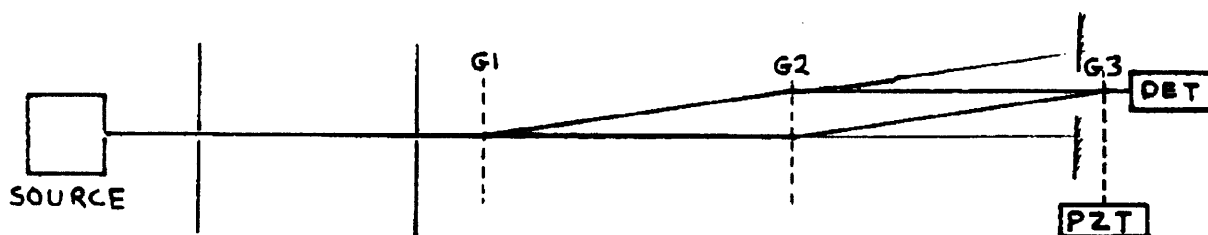
Figure 14. If a collimated atomic beam is diffracted by gratings G1 and G2, the two paths shown interfere at G3 to produce a spatially modulated intensity pattern which can be detected by moving G3 and measuring the intensity transmitted to the detector.

We should be able to tilt these gratings to an angle of 1/5 and thus get diffraction to five times larger angles. We are also investigating the possibility of using grazing incidence reflection gratings for atom optics.

Interferometers measure the difference in the phase accumulated by particles travelling between two points by spatially separated paths. Thus an interferometer is sensitive to length changes caused by absolute rotation or relative mechanical displacements of its parts, and to energy shifts caused by electromagnetic or gravitational interactions. To date, interferometers have been made for photons, electrons and neutrons. For almost all purposes, atoms would be better for matter wave interferometers than neutrons: atoms are far more sensitive to electromagnetic interaction, they are available with ~ 10 times shorter wavelengths, and from cheap compact sources (neutrons come from reactors). The fluxes available in atomic beams are 10^8 times larger than those for neutrons; high fluxes would enable an atomic interferometer to make use of the fringe splitting techniques developed for optical interferometers. An atomic interferometer is intrinsically 10^5 times more sensitive to mechanical displacement than an optical interferometer. Since atoms travel many times slower than light, atomic interferometers are 10^{10} more sensitive to rotations than laser gyros. Atomic interferometers could be used to make precise measurements of atomic properties as well as to make fundamental tests in physics including Berry's phase, and the phase shift on rotation of bosons and fermions.

2.6 Traps for Neutral Atoms

Project Staff

Alexander G. Martin, Kristian Helmerson, Dr. Min Xiao, Ke-Xun Sun, Genevieve Sparagna, Professor David E. Pritchard

Now that we have trapped large numbers of neutral atoms, we plan to cool them to microkelvin temperatures. The objective — a dense sample of ultra cold atoms — promises to open up new and exciting areas of physics. The lack of interaction of the trapped atoms with any confining walls, their low velocities due to their reduced thermal motion, and the possibility of indefinitely long interaction times makes such samples of trapped atoms ideal for high resolution spectroscopy and for use as atomic frequency standards. High density samples of ultra-cold atoms also promise to open up new areas of research in the study of both interatomic collisions and collective effects, such as Bose condensation.

This past year, we have concentrated on radio frequency resonance experiments on magnetically trapped neutral atoms. (We are the only group in the world which has done

such experiments.) rf resonance of trapped atoms is valuable for at least three reasons: 1) as a high resolution diagnostic of the atoms' individual and collective behavior; 2) as a tool to selectively manipulate the magnetic quantum states of the trapped atoms; and 3) potentially for ultra-high resolution spectroscopy of isolated atomic systems.

Following the successful demonstration of rf induced transitions on trapped neutral atoms,[14] we proceeded to increase the number ($\sim 2 \times 10^{10}$) and confinement time ($\tau_{1/e} = 30$ minutes) of trapped Na atoms so that we had sufficient signal and time to perform rf resonance measurements as a diagnostic of the effects of doppler cooling on the atoms' energy distribution.

An rf resonance curve for the $| F=2,M=2>$ to $| F=2,M=1>$ hyperfine transition was obtained by measuring the relative peak heights of the fluorescence spectrum for the two states as a function of the frequency of the applied rf. Figure 15 contrasts the rf resonance curve for "hot" atoms after initial loading of the trap with the curve of "cool" atoms after application of longitudinal
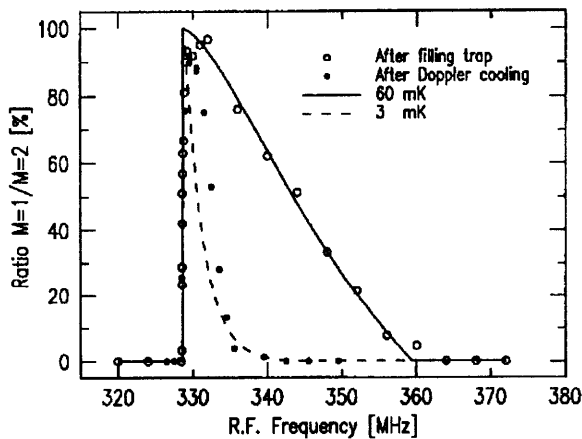

Figure 15. rf resonance curve for atoms after initial loading of the trap (open circles) and after application of doppler cooling (closed circles). The dashed and solid lines are theoretical fits using truncated Boltzmann distribution of 3 and 60 mK respectively.

doppler cooling. Doppler cooling of the sample required a very weak standing wave laser beam to avoid excess heating of the transverse degrees of freedom.

In addition to rf spectroscopy, we have obtained an optical spectrum of doppler cooled atoms in both absorption and fluorescence showing linewidths of $\sim \Gamma_N$ where Γ_N is the natural decay rate of the Na D-line.

The shape of the rf spectrum is directly related to the energy distribution of the trapped atoms because the transition frequency between the two levels increases monotonically with magnetic field. Cold atoms are confined to magnetic field regions close to the minimum value of the magnetic field and will never resonate with rf above the transition frequency in the maximum field to which their thermal energy can carry them. The height of the resonance curve at each frequency is therefore determined by the fraction of atoms energetic enough to reach the corresponding magnetic field, and the lineshape of the high-frequency tail becomes a direct measure of the energy distribution of the atoms in the trap. Thus, it is possible to extract the energy distribution of the trapped atoms from the derivative of the resonance curves of figure 15.

Figure 16 is a plot of the logarithm of the energy distribution as a function of energy for the data of figure 15. The linear fits in figure 16 suggest that the "hot" atom distribution is a truncated Boltzmann distribution with a temperature of 60^{+48}_{-38} mK while the "cold" atom distribution is approximately Boltzmann at higher energies with a temperature of ~ 2mK.

Both radio frequency and optical manipulation of trapped atoms are necessary to realize proposed schemes for super-cooling trapped atoms to micro-Kelvin temperatures.[15] Such ultra-cold atoms show great promise in high resolution spectroscopy

[14] A.G. Martin, K. Helmerson, V.S. Bagnato, G.P. Lafyatis, D.E. Pritchard, "rf Spectroscopy of Trapped Neutral Atoms," *Phys. Rev. Lett.* 61:2431 (1988).

[15] D.E. Pritchard, "Cooling Neutral Atoms in a Magnetic Trap for Precision Spectroscopy," *Phys. Rev. Lett.* 54:1336 (1983).
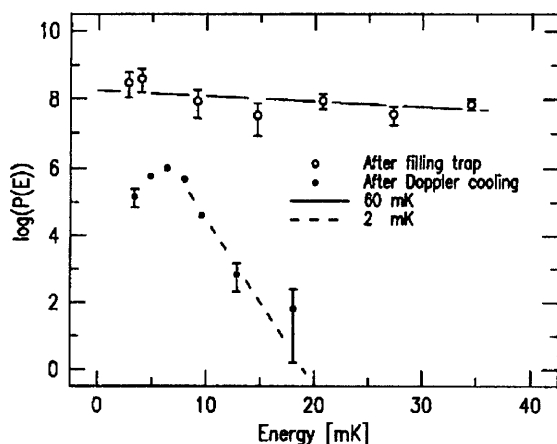
Figure 16. Logarithm of the energy distribution P(E), of the trapped particles vs. energy. The solid and dashed lines represent Boltzmann distributions of 60 and 2 mK respectively.

and atomic frequency standards and are essential for the observation of novel collective effects such as Bose condensation.

Another novel research area involving trapped neutral atoms is collisions of cold atoms. This year we reported measurements of a large cross section for a collisional mechanism between cold atoms which knocked the atoms out of the trap.[16] In collaboration with Alan Gallagher at the Joint Institute for Laboratory Astrophysics at the University of Colorado in Boulder, we have made semi-classical calculations of several exoergic collision processes for excited state atoms which we think may be responsible for the observed trap loss.[17]

2.7 Forces on Atoms from Light

Sponsors

National Science Foundation
(Grant PHY 86-05893)

Project Staff

Bruce G. Oldaker, Peter J. Martin, Dr. Min Xiao, and Professor David E. Pritchard

We have been investigating the radiative forces experienced by a two-level atom interacting with light. These forces provide a new way to study the fundamental interaction between atoms and radiation, and have important applications in the slowing, cooling, trapping, and manipulation of neutral atoms using light.

Emphasis in previous years has been on experiments where the laser is detuned far enough from resonance so that spontaneous emission was negligible and the processes we studied could be described by a simple Hamiltonian and Schrodinger equation. This past year we have explored two new areas where spontaneous emission is important — statistics of travelling wave deflection and uni-directional, multi-photon momentum resonances in standing waves.

When a two-level atom interacts with a traveling wave, the atom will undergo a series of absorptions followed by spontaneous or stimulated emissions. It is important to understand these processes because of their effects in the laser cooling of atomic beams and trapped particles and ions. Experimental work on the statistical properties of these processes has been dominated by techniques based on observing the photons given off from the spontaneous emissions. These experiments were plagued by low detector efficiencies, as the photons are given off in random directions. Our experiment determines the momentum transfer to the atoms after their interaction with the travelling laser beam, by physically measuring the momentum transferred to the atoms. We can easily resolve the momentum transfer equivalent to the absorption of one photon, so we effectively detect all of the photons.

The average momentum transfer in a travelling wave is due to the recoil following the

---

[16] M. Prentiss, A. Cable, J.E. Bjorkholm, S. Chu, E.L. Raab, and D.E. Pritchard, "Atomic-Density-Dependent Losses in an Optical Trap," *Opt. Lett.* 13:452 (1988).

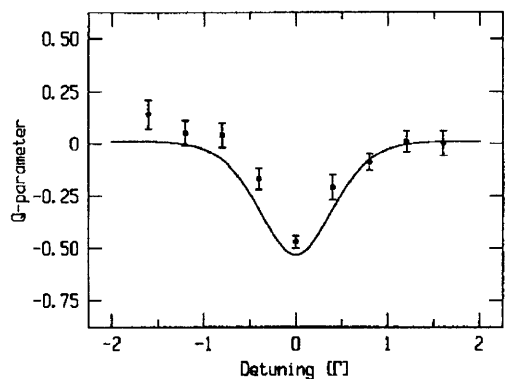[17] A. Gallagher and D.E. Pritchard, to be published.

Figure 17. Dependence of Mandel's Q-parameter as a function of laser detuning.

represents the first study of Q as a function of detuning of the laser from the atomic transition and we observed Q = -0.47 ± 0.03.[20] Figure 17 displays our data. The reasonable agreement between theory and experiment confirms the theoretical predictions of the dependence of Q on the detuning of the laser. The effects of this anomalous diffusion are predicted to play an important role in the laser cooling of atomic beams.[21]

In the second area of uni-directional, multi-photon momentum transfer in a standing wave we have completed a theoretical study of "Doppleron" resonances.[22] These resonances are predicted to exist in an intense radiation field, but previous multi-photon theories incorrectly predict their locations because these resonances are not small perturbations. This regime requires sophisticated approaches involving density matrix techniques that include the recoil effects on the atoms during their interactions with the laser. In the past year, we have succeeded in modeling the problem using three different approaches all of which give consistent predictions for the necessary experimental parameters to observe these resonances. These models indicate that as much as 90 percent of the initial momentum state's population can be coherently transferred to a single momentum state through the exchange of an odd number of photons with the field. Next year, we hope to observe Dopplerons experimentally.

absorption of a photon and the subsequent recoil from spontaneous emission. The diffusion of momentum about this average is caused by two effects — the random direction of the spontaneous emission and the fluctuations in the number of photon absorptions. This latter effect is an inherently quantum effect and the theory predicts correlations between subsequent events that were heretofore thought to be completely random and uncorrelated. Interpretations of these correlations are not completely clear although their properties have been studied not only by atomic theorists but by quantum optics theorists. This is called "anomalous diffusion" because the diffusion does not obey Poissonian statistics when the laser is tuned very close to the atomic transition frequency.

The deviation from Poissonian statistics is measured by a parameter Q, defined to be Q $\equiv [< (\Delta n)^2 > - < n >]/<n>$.[18] A negative Q would mean a distribution with a width narrower than a Poissonian distribution, which would have Q = 0. Photon-counting experiments observed negative Q's with order of magnitude 10^{-3} as early as 1977.[19] Our experiment utilizing momentum transfer

Publications

Gallagher, A., and D.E. Pritchard, "Exoergic Collisions of Cold Na*-Na," submitted to *Phys. Rev. Lett.*

Gould, P.L., P.J. Martin, G.A. Ruff, R.E. Stoner, J-L. Picque, and D.E. Pritchard, "Momentum Transfer to Atoms by a

---

[18] L. Mandel, *Opt. Lett.* 4:205 (1979).

[19] R. Short and L. Mandel, *Phys. Rev. Lett.* 51:384 (1983).

[20] B.G. Oldaker, P.J. Martin, M. Xiao, and D.E. Pritchard, to be submitted to *Phys. Rev. A.*

[21] H. Wallis and W. Ertmer, *J. Phys. B* 21:2999 (1988).

[22] E. Kyrola and S. Stenholm, *Opt. Comm.* 22:123 (1977).

Standing Light Wave; Transition From Diffraction to Diffusion," submitted to *Phys. Rev. Lett.*

Keith, D.W., M.L. Schattenburg, H.I. Smith, and D.E. Pritchard, "Diffraction of Atoms by a Transmission Grating," *Phys. Rev. Lett.* 61:1580 (1988).

Magill, P.D., B. Stewart, N. Smith, and D.E. Pritchard, "Dynamics of Quasi-Resonant Vibration↔Rotation Transfer in Atom-Diatom Scattering," *Phys. Rev. Lett.* 60:1943 (1988).

Magill, P.D., T.P. Scott, N. Smith, and D.E. Pritchard, "Level-to-Level Vibrationally Inelastic Rate Constants for Li$_2^*$ -X (X = He, Ne, Ar, Xe) Collisions," submitted to *J. Chem. Phys.*

Martin, A.G., K. Helmerson, V.S. Bagnato, G.P. Lafyatis, and D.E. Pritchard, "RF Spectroscopy of Trapped Neutral Atoms," *Phys. Rev. Lett.* 61:2431 (1988).

Martin, P.J., B.G. Oldaker, A.H. Miklich, and D.E. Pritchard, "Bragg Scattering of Atoms from a Standing Light Wave," *Phys. Rev. Lett.* 60:515 (1988).

Prentiss, M., A. Cable, J.E. Bjorkholm, Steven Chu, E.L. Raab and D.E. Pritchard, "Atomic-Density-Dependent Losses in an Optical Trap," *Optics Lett.* 13:452 (1988). Pritchard, D.E., K. Helmerson and A.G. Martin, "Atom Traps," Proceedings of the 11th International Conference on Atomic Physics, Paris, 1988, to be published.

Stewart, B., P.D. Magill, T.P. Scott, J. Derouard, and D.E. Pritchard, "Quasi-resonant V↔R Transfer in Atom-Diatom Collisions," *Phys. Rev. Lett.* 25:282 (1988).

Weisskoff, R.M., G.P. Lafyatis, K.R. Boyce, E.A. Cornell, R.W. Flanagan, and D.E. Pritchard, "R.F. SQUID Detector for Single Ion Trapping Experiments," *J. Appl. Phys.* 63:4599 (1988).

MIT Theses

Bagnato, V.S., *Magnetic Trap for Laser Cooled Neutral Atoms.* Ph.D. diss., Dept. of Physics, MIT, 1987.

Landry, J., *Modeling a Zeeman Tuned Slower of Neutral Atoms.* S.B. thesis, Dept. of Physics, MIT, 1988.

Magill, P.D., *Classical Resonance in Vibrationally Inelastic Collisions of Diatomic Molecules: Experiments and Modeling.* Ph.D. diss., Dept. of Physics, MIT, 1988.

Martin, P.J., *Momentum Transfer to Atoms Moving Through a Standing Wave of Light.* Ph.D. diss., Dept. of Physics, MIT, 1988.

Miklich, A.H., *Momentum Transfer to Atoms by Light.* S.B. thesis, Dept. of Physics, MIT, 1988.

Raab, E.L., *Trapping Sodium with Light.* Ph.D. diss., Dept. of Physics, MIT, 1988.

Stewart, B.A.,*Vibrational-Rotational Resonance in Inelastic* Li$_2^*$− ≠ *Collisions.* Ph.D. diss., Dept. of Chemistry, MIT, 1987.

Weisskoff, R.M., *Detecting Single, Trapped Ions.* Ph.D. diss., Dept. of Physics, MIT, 1988.