THE MANIPULATION OF NEUTRAL PARTICLES

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by

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The written version of my lecture is a personal account of the development of laser cooling and trapping. Rather than give a balanced history of the field, I chose to present a personal glimpse of how my colleagues and I created our path of research.

I joined Bell Laboratories in the fall of 1978 after working with Eugene Commins as a graduate student and post-doc at Berkeley on a parity non-conservation experiment in atomic physics.[1] Bell Labs was a researcher's paradise. Our management supplied us with funding, shielded us from bureaucracy, and urged us to do the best science possible. The cramped labs and office cubicles forced us to rub shoulders with each other. Animated discussions frequently interrupted seminars and casual conversations in the cafeteria would sometimes mark the beginning of a new collaboration.

In my first years at Bell Labs, I wrote an internal memo on the prospects for x-ray microscopy and worked on an experiment investigating energy transfer in ruby with Hyatt Gibbs and Sam McCall as a means of studying Anderson Localization.[2, 3] This work led us to consider the possibility of Mott or Anderson transitions in other exciton systems such as GaP:N with picosecond laser techniques.[4] During this work, I accidentally discovered that picosecond pulses propagate with the group velocity, even when the velocity exceeds the speed of light or becomes negative.[5]

While I was learning about excitons and how to build picosecond lasers, I began to work with Allan Mills, the world's expert on positrons and positronium. We began to discuss the possibility of working together while I was still at Berkeley, but did not actually begin the experiment until 1979. After three long and sometimes frustrating years, a long time by Bell Labs standards, we finally succeeded in exciting and measuring the 1S–2S energy interval in positronium.[6]

MOVING TO HOLMDEL AND WARMING UP TO LASER COOLING

My entry into the field of laser cooling and trapping was stimulated by my move from Murray Hill, New Jersey, to head the Quantum Electronics Research Department at the Holmdel branch in the fall of 1983. During conversations with Art Ashkin, an office neighbor at Holmdel, I began to learn

about his dream to trap atoms with light. He found an increasingly attentive listener and began to feed me copies of his reprints. That fall I was also joined by my new post-doc, Leo Hollberg. When I hired him, I had planned to construct an electron energy-loss spectrometer based on threshold ionization of a beam of atoms with a picosecond laser. We hoped to improve the energy resolution of existing spectrometers by at least an order of magnitude and then use our spectrometer to study molecular adsorbates on surfaces with optical resolution and electron sensitivity. However, Leo was trained as an atomic physicist and was also developing an interest in the possibility of manipulating atoms with light.

Leo and I spontaneously decided to drive to Massachusetts to attend a workshop on the trapping of ions and atoms organized by David Pritchard at MIT. I was ignorant of the subject and lacked the primitive intuition that is essential to add something new to a field. As an example of my profound lack of understanding, I found myself wondering about the dispersive nature of the "dipole force". The force is attractive when the frequency of light is tuned below the resonance, repulsive when tuned above the resonance, and vanishes when tuned directly on the atomic resonance. Looking back on these early fumblings, I am embarrassed by how long it took me to recognize that the effect can be explained by freshman physics. On the other hand, I was not alone in my lack of intuition. When I asked a Bell Labs colleague about this effect, he answered, "Only Jim Gordon really understands the dipole force!"

By 1980, the forces that light could exert on matter were well understood.[7] Maxwell's calculation of the momentum flux density of light,[8] and the laboratory observation of light pressure on macroscopic objects by Lebedev[9] and by Nichols and Hull[10] provided the first quantitative understanding of how light could exert forces on material objects. Einstein[11] pointed out the quantum nature of this force: an atom that absorbs a photon of energy $h\nu$ will receive a momentum impulse $h\nu/c$ along the direction of the incoming photon $\mathbf{p}_{in}$. If the atom emits a photon with momentum $\mathbf{p}_{out}$, the atom will recoil in the opposite direction. Thus the atom experiences a net momentum change $\Delta\mathbf{p}_{atom} = \mathbf{p}_{in}-\mathbf{p}_{out}$ due to this incoherent scattering process. In 1930, Frisch[12] observed the deflection of an atomic beam with light from a sodium resonance lamp where the average change in momentum was due to the scattering of one photon.

Since the scattered photon has no preferred direction, the net effect is due to the absorbed photons, resulting in scattering force, $\mathbf{F}_{scatt} = N\mathbf{p}_{in}$, where N is the number of photons scattered per second. Typical scattering rates for atoms excited by a laser tuned to a strong resonance line are on the order of 10^7 to 10^8/sec. As an example, the velocity of a sodium atom changes by 3 cm/sec per absorbed photon. The scattering force can be 10^5 times the gravitational acceleration on Earth, feeble compared to electromagnetic forces on charged particles, but stronger than any other long-range force that affect neutral particles.

There is another type of force based on the lensing (i.e. coherent scatter-

ing) of photons. A lens alters the distribution of momentum of a light field, and by Newton's third law, the lens must experience a reaction force equal and opposite to the rate of momentum change of the light field. For example, a positive lens will be drawn towards regions of high light intensity as shown in Fig. 1.[13] In the case of an atom the amount of lensing is calculated by adding the amplitude of the incident light field with the dipole field generated by the atomic electrons driven by the incident field.

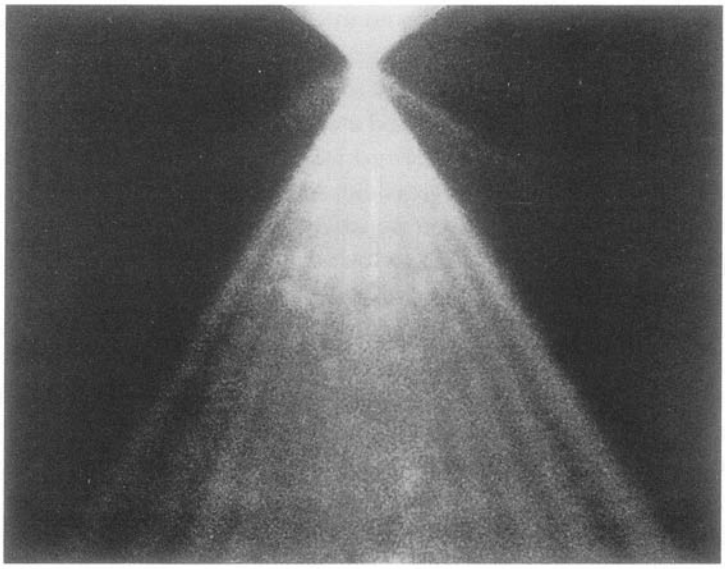

Figure 1. A photograph of a 10 μm glass sphere trapped in water with green light from an argon laser coming from above. The picture is a fluorescence image taken using a green blocking, red transmitting filter. The exiting (refracted) rays show a notable decrease in beam angles relative to the incident rays. The increased forward momentum of the light results in an upward force on the glass bead needed to balance the downward scattering force. The stria in the forward-scattered light is a common Mie-scattering ring pattern. (Courtesy A. Ashkin).

This reaction force is also called the "dipole force". The oscillating electric field **E** of the light induces a dipole moment **p** on the particle. If the induced dipole moment is in phase with **E**, the interaction energy $-\mathbf{p}\cdot\mathbf{E}$ is lower in high field regions. If the induced dipole moment is out of phase with the driving field, the particle's energy is increased in the electric field and the particle will feel a force ejecting it out of the field. If we model the atom or particle as a damped harmonic oscillator, the sign change of the dipole force is easy to understand. An oscillator driven below its natural resonant frequency responds in phase with the driving field, while an oscillator driven above its natural frequency oscillates out of phase with the driving force. Exactly on resonance, the oscillator is 90 degrees out of phase and $\mathbf{p}\cdot\mathbf{E} = 0$.

The dipole force was first discussed by Askar'yan[14] in connection with plasmas as well as neutral atoms. The possibility of trapping atoms with this force was considered by Letokhov,[15] who suggested that atoms might be confined along one dimension in the nodes or antinodes of a standing wave of light tuned far from an atomic transition. In 1970, Arthur Ashkin had succeeded

in trapping micron-sized particles with a pair of opposing, focused beams of laser light, as shown in Fig. 2. Confinement along the axial direction was due to the scattering force: a displacement towards either of the focal points of the light would result in an imbalance of scattered light that would push the particle back to the center of the trap. Along the radial direction, the outwardly directed scattering force could be overcome by the attractive dipole force. In the following years, other stable particle trapping geometries were demonstrated by Ashkin,[16] and in 1978, he proposed the first three-dimensional traps for atoms.[17] In the same year, with John Bjorkholm and Richard Freeman, he demonstrated the dipole force by focusing an atomic beam using a focused laser beam.[18]

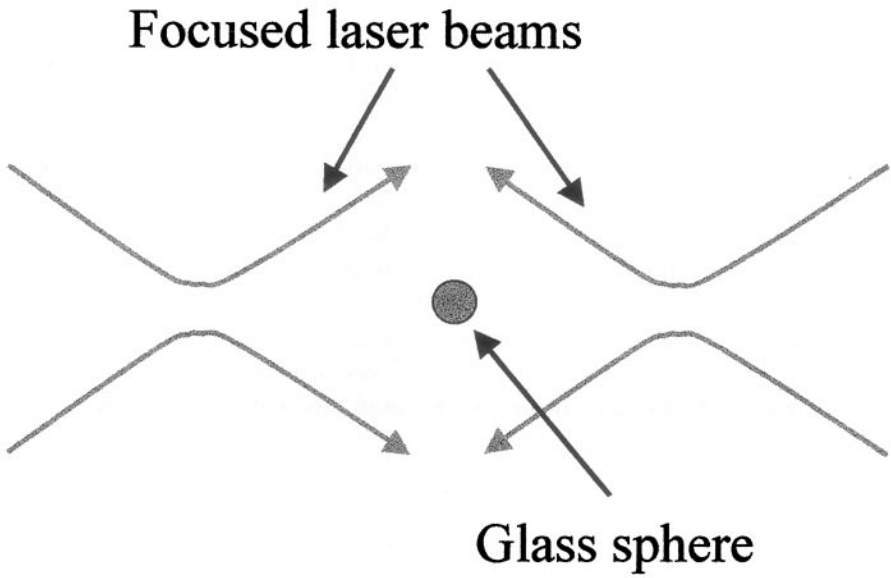

Figure 2. A schematic diagram of the first particle trap used by Ashkin. Confinement in the axial direction is due to an imbalance of the scattering forces between the left and right propagating beams. Confinement in the radial direction results from the induced dipole force which must overcome the outwardly directed scattering force.

Despite this progress, experimental work at Bell labs stopped a year later because of two major obstacles. First, the trapping forces generated by intense focused laser beams are feeble. Atoms at room temperature would have an average energy $\frac{3}{2}k_BT \sim \frac{1}{2}mv^2$, orders of magnitude greater than could be confined by the proposed traps. A cold source of atoms with sufficiently high flux did not exist and a trap with large volume was needed to maximize the number of atoms that could be trapped. Second, the relatively large-volume optical trap made from opposing light beams was found to have serious heating problems. An atom could absorb a photon from one beam and be stimulated back to the initial state by a photon from the opposing beam. In this process, it would receive two photon impulses in the same direction. However, the same atom could have been excited and stimulated by the two beams in the reverse order, resulting in a net impulse in the other direction. Since the

order of absorption and stimulated emission is random, this process would increase the random velocity of the atom and they would quickly heat and boil out of the trap. This heating effect was rigorously calculated by Jim Gordon with Ashkin for a two-level atom.[19]

TAKING THE PLUNGE INTO THE COLD

My first idea to solve the trap loading problem was modest at best, but it got me to think seriously about trapping atoms. I proposed to make a cold source of atoms by depositing sodium atoms into a rare-gas matrix of neon.[20] By heating the cryogenic surface supporting this matrix of atoms with a pulsed laser, I thought it should be possible to "puff" the neon and sodium atoms into a vapor with a temperature of a few tens of Kelvin. Once a vapor, a reasonable fraction of the sodium would become isolated atoms and the puffed source would contain the full Maxwell-Boltzmann distribution of atoms, including the very slowest atoms. In a conventional atomic beam, the slowest atoms are knocked out of the way by faster moving atoms overtaking them. In a puffed source, the surface could be quickly heated and cooled so that there would be no fast atoms coming from behind. An added advantage was that the source would turn off quickly and completely so that the detection of even a few trapped atoms would be possible.

Soon after my passage from interested bystander to participant, I realized that the route to trapping was through laser cooling with counter-propagating beams of light. If the laser beams were tuned below the atomic resonance, a moving atom would Doppler-shift the beam opposing its motion closer to resonance and shift the beam co-propagating with the motion away from resonance. Thus, after averaging over many impulses of momentum from both beams, the atom would experience a net force opposing its motion. In the limit where the atoms were moving slowly enough so that the difference in the absorption due to the Doppler effect was linearly proportional to the velocity, this force would result in viscous damping, $\mathbf{F} = -\alpha\mathbf{v}$. This elegant idea was proposed by Hänsch and Schawlow in 1975.[21] A related cooling scheme was proposed by Wineland and Itano in the same year.[22]

An estimate of the equilibrium temperature is obtained by equating the cooling rate in the absence of heating with the heating rate in the absence of cooling,

$$dW_{heating}/dt = dW_{cooling}/dt = -\mathbf{F}\cdot\mathbf{v}.$$

The heating rate is due to the random kicks an atom receives by randomly scattering photons from counter-propagating beams that surround the atoms.[23, 19] The momentum grows as a random walk in momentum space so the average random momentum p would increase as

$$\frac{dW_{heating}}{dt} = \frac{d}{dt}\left(\frac{p^2}{2M}\right) = \frac{N(p_r)^2}{2M}$$

where p_r is the momentum recoil due to each photon and N is the number of

photon kicks per second. By equating the heating rate to the cooling rate, one can calculate an equilibrium temperature as a function of the laser intensity, the linewidth of the transition, and the detuning of the laser from resonance. The minimum equilibrium temperature $k_B T_{min} = \hbar\Gamma/2$, where Γ is the linewidth of the transition, was predicted to occur at low intensities and a detuning $\Delta\nu = \Gamma/2$ where the Doppler shift asymmetry was a maximum. In the limit of low intensity, all of the laser beams would act independently and the heating complications that would result from stimulated transitions between opposing laser beams could be ignored.

Not only would the light cool the atoms, it would also confine them. The laser cooling scheme was analogous to the Brownian motion of a dust particle immersed in water. The particle experiences a viscous drag force and the confinement time in a region of space could be estimated based on another result in elementary physics: the mean square displacement $\langle x^2 \rangle$ after a time Δt described by a random walk, $\langle x^2 \rangle = 2Dt$, where the diffusion constant is given by the Einstein relation $D = k_B T/\alpha$. For atoms moving with velocities $\mathbf{v}$ such that $\mathbf{k}\cdot\mathbf{v}<\Gamma$, the force would act as a viscous damping force $\mathbf{F} = -\alpha\mathbf{v}$. By surrounding the atoms with six beams propagating along the $\pm$ x, y and z directions, we could construct a sea of photons that would act like an exceptionally viscous fluid: an "optical molasses".[24] If the light intensity was kept low, the atoms would quickly cool to temperatures approaching T_{min}. Once cooled, they would remain confined in a centimeter region of space for times as long as a fraction of a second.

At this point, Leo and I shelved our plans to build the electron spectrometer and devoted our energies to making the optical molasses work. We rapidly constructed the puffing source of sodium needed to load the optical molasses. To simplify matters, we began with a pellet of sodium heated at room temperature. Rather than deal with the complications of a rare gas matrix, Leo and I decided to increase the number of cold atoms by slowing atoms from the puff source before attempting the optical molasses experiment. There were several early experiments that slowed atomic beams with laser light,[25] but sodium atoms had to be slowed to velocities on the order of 200–300 cm/sec (essentially stopped!) before an atom trap could be loaded. Two groups achieved this milestone in late 1984: a group at the National Bureau of Standards in Gaithersburg, Maryland, led by Bill Phillips using a tapered magnetic field[26] and another NBS group in Boulder, Colorado, led by Jan Hall.[27] We decided to copy the technique of Ertmer, *et al.*,[27] and use an electro-optic generator to produce a frequency-shifted sideband. The frequency-shifted light is directed against the atoms coming off the sodium surface, and as the atoms slow down, the frequency is changed in order to keep the light in resonance with the Doppler shifting atoms.

Leo was better at electronics than I and assumed the responsibility of the radio-frequency part of the project while I set out to build a wideband, transmission line electro-optic modulator. One of the advantages of working at Bell Laboratories was that one could often find a needed expert consultant within the Labs. Much of the electro-optic modulator development was

pioneered at the Labs in Holmdel in the 1960s and we were still the leaders of the field in 1983. I learned about making electro-optic modulators by reading *the* book written by a colleague, Ivan Kaminow.[28] I enlisted Larry Buhl to cut and polish the $LiTaO_3$ crystal for the modulator. Rod Alferness taught me about microwave impedance matching and provided the SMA "launchers" needed to match Leo's electronics with my parallel-plate transmission line modulator. One month after we decided to precool the atoms with a frequency-swept laser beam, we had a functioning, wideband gigahertz electro-optic modulator and driver and could begin to precool the atoms from our puffing source.

In the early spring of 1984, Leo and I started with a completely bare optical table, no vacuum chamber, and no modulator. Later that spring, John Bjorkholm, who had previously demonstrated the dipole force by focusing an atomic beam, joined our experiment. In the early summer, I recruited Alex Cable, a fresh graduate from Rutgers. Officially he was hired as my "technician": unofficially, he became a super-graduate student. In less than one year, we submitted our optical molasses paper.[29, 30] The two papers reporting the stopping of atomic beams [26, 27] were published one month earlier.

The apparatus we built to demonstrate optical molasses is shown in Figs. 3a and 3b. We had an ultra-high-vacuum chamber, but did not want to be hampered by long bake-out times to achieve good vacuum. Instead, we built a cryo-shield painted with Aquadag, a graphite-based substance. When cooled

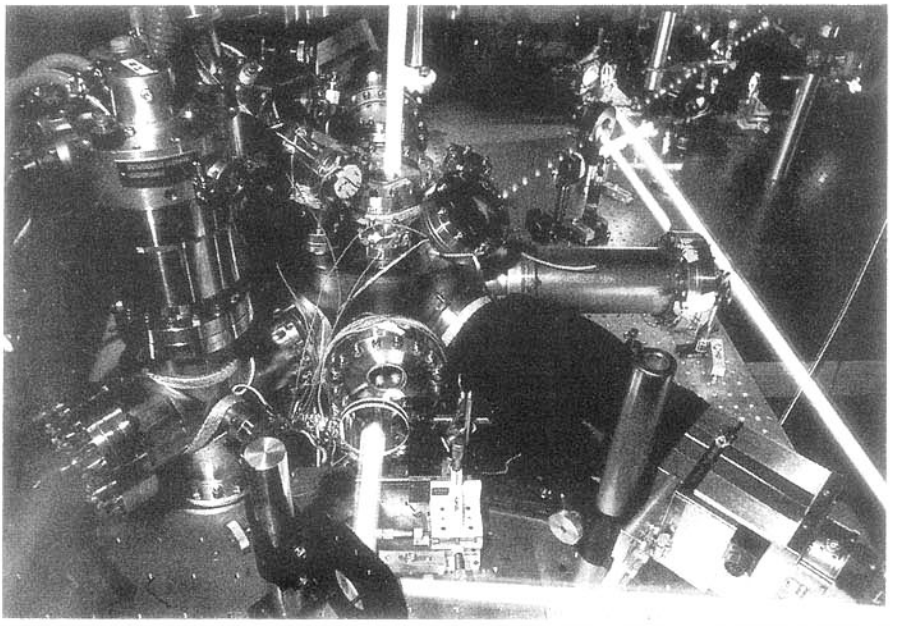

Figure 3 a. A photograph of the apparatus used to demonstrate optical molasses and the first optical trap for atoms. The photograph is a double exposure made by photographing the apparatus under normal lighting conditions and then photographing the laser beams by moving a white card along the beam path in a darkened room. The 10 Hz pulsed laser used to evaporate the sodium pellet (doubled YAG at 532nm) appears as dots of light.

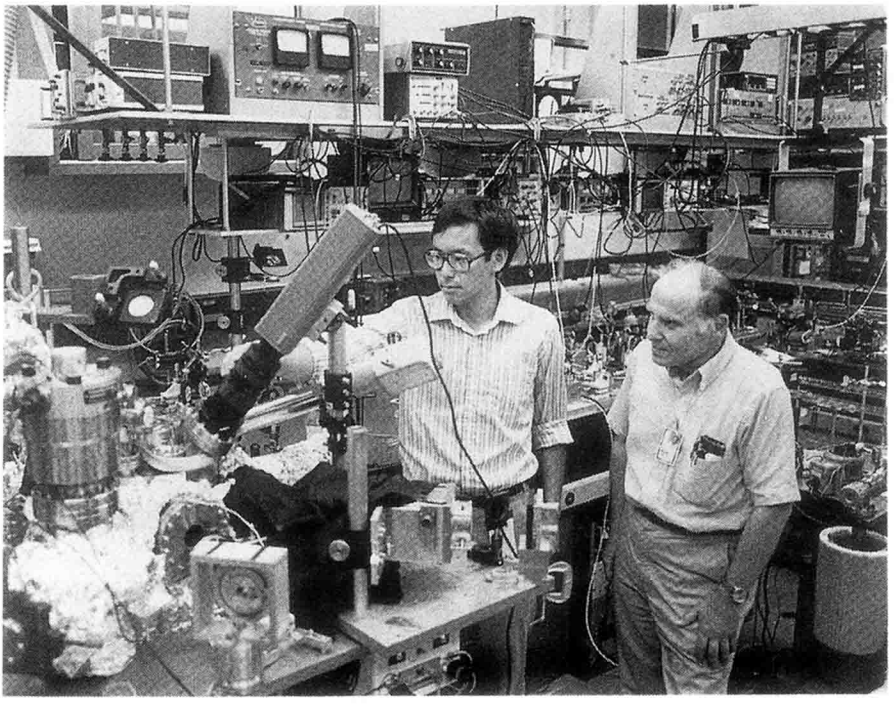

Figure 3 b. Art Ashkin and the author in front of the apparatus in 1986, shortly after the first optical trapping experiment was completed.

to liquid-nitrogen temperatures, the shield became a very effective sorption pump: we could open the vacuum chamber one day and be running by the next day. Fast turnaround time has always been important to me. Mistakes are unavoidable, so I wanted an apparatus that would allow mistakes to be corrected as rapidly as possible.

The first signals of atoms confined in optical molasses showed confinement times of a few tens of milliseconds, but shortly afterwards we improved the storage time by over an order of magnitude. Surprisingly, it took us a week after achieving molasses to look inside the vacuum can with our eyes instead of with a photomultiplier tube. When we finally did, we were rewarded with the sight shown in Fig. 4.

In this early work, the laser beams were aligned to be as closely counterpropagating as we could manage. A year later, we stumbled onto a misalignment configuration that produced another order of magnitude increase in the storage time. This so-called "super-molasses" alignment of our beams also created a compression of the atoms into a region of space on the order of 2 mm diameter from an initial spread of 1 cm. We were never able to understand this phenomena and after a number of attempts, published a brief summary of these results in conference proceedings.[31]

In our first molasses work, we realized that the traditional method of measuring the temperature by measuring the Doppler broadening of an atomic resonance line would not work for the low temperatures we hoped to achieve. Instead we introduced a time-of-flight technique to directly measure the vel-

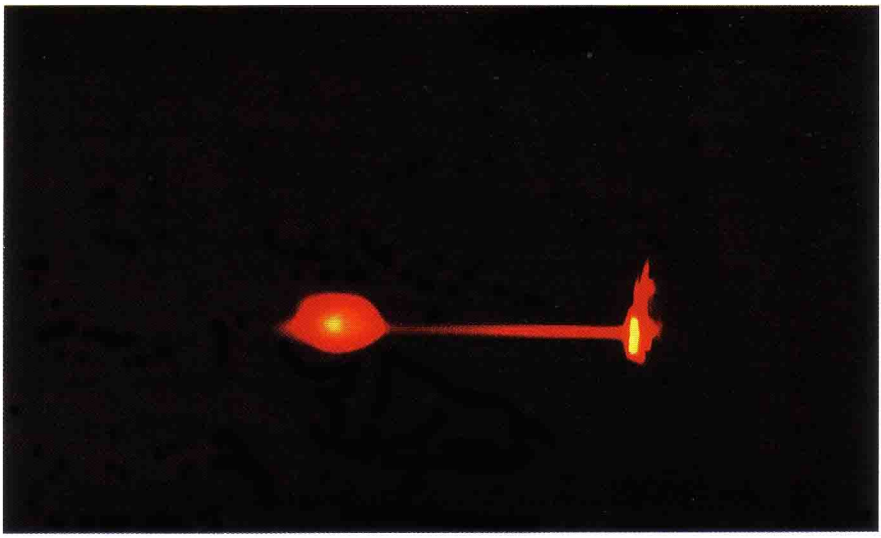

Figure 4. A photograph of sodium atoms confined in optical molasses experiment. The atoms were pre-cooled by a counterpropagating laser before entering the region of six crossed laser beams.

ocity distribution of the atoms. After allowing the atoms in the molasses to come to equilibrium, we turned off the light for a variable amount of time. The fast atoms escaped ballistically during this time while the slower atoms were recaptured by the molasses. Our first measurements showed a temperature of 185μK, slightly lower than the minimum temperature allowed by the theory of Doppler cooling. We then made the cardinal mistake of experimental physics: instead of listening to Nature, we were overly influenced by theoretical expectations. By including a fudge factor to account for the way atoms filled the molasses region, we were able to bring our measurement into accord with our expectations.

ON TO OPTICAL TRAPPING

Once we demonstrated optical molasses, we began to explore ways to achieve our original goal of optically trapping atoms. As a point of reference, Bill Phillips and his collaborators had reported the magnetic trapping of sodium atoms[32] two weeks before our optical molasses paper came out. Although the 1/e storage of the molasses confinement in our first experiment was a respectable $\tau \sim 0.36$ sec, optical molasses does not provide a restoring force that would push the atoms to the center of the trap.

Despite the fact that we were in possession of a great source of cold atoms, the path to trapping was not yet clear to us for a number of reasons: (*i*) Optical traps based strictly on the scattering force seemed to be ruled out because of a no-trapping theorem referred to as the "Optical Earnshaw Theorem". This theorem was published in response to earlier proposals to make atom traps based on the scattering force.[33, 34] (*ii*) We believed a trap

based on an opposing-beam geometry was not viable because of the severe stimulated heating effects. (*iii*) Finally, we ruled out a single focused laser beam because of the tiny trapping volume. We were wrong on all counts.

Immediately after the molasses experiment, we tried to implement a large-volume ac light trap suggested by Ashkin.[35] Our attempt failed, and after a few months, we began to cast around for other alternatives. One possibility was another type of ac trap we proposed at a conference talk in December of 1984,[36] but we wanted something simpler. Sometime in the winter of 1986, during one of our brainstorming sessions on what to do next, John Bjorkholm tried to resurrect the single focused beam trap first proposed in Ashkin's 1978 paper.[17] I promptly rejected the idea because of the small trapping volume. A ~1-watt laser focused to produce a ~5-mK-deep trap would have a trapping volume of $\sim 10^{-7}\text{cm}^3$. Since the density of atoms in our optical molasses was 10^6 atoms/cm^3, we would capture fewer than one atom in a trap surrounded by 10^6 atoms in molasses. A day or two after convincing the group that a trap based on a focused laser beam would not work, I realized that many more atoms would be captured by the trap than my original estimate. An atom close to the trap might not be immediately captured, but it would have repeated opportunities to fall into the trap during its random walk in optical molasses.

The trap worked. We could actually see the random walk loading with our own eyes. A tiny dot of light grew in brightness as more atoms fell into the trap. During the first days of trapping success, I ran up and down the halls, pulling people into our lab to share in the excitement. My director, Chuck Shank, showed polite enthusiasm, but I was not sure he actually picked out the signal from the reflections in the vacuum can windows and the surrounding fluorescence. Art Ashkin came down with the flu shortly after our initial success. He confessed to me later that he began to have doubts: as he lay in bed with a fever; he wasn't sure whether the fever caused him to imagine we had a working trap.

We tried to image the tiny speck of light onto an apertured photomultiplier tube, but the slightest misalignment would include too much light from the surrounding molasses. It was a frustrating experience not to be able to produce a repeatable signal on a photomultiplier tube if we could actually see the atoms with our eyes. Then it dawned on me: if we could see the signal with our eyes, we could record it with a sensitive video camera and then analyze the video tape! A local RCA representative, tickled by the experiment, loaned us a silicon-intensified video camera. Our trapping paper included a photo of our trapped atoms, the first color picture published in Physical Review Letters.[37]

As we began the atom trapping, Art decided to trap micron-sized particles of glass in a single focused beam as a "proof of principle" for the atom trap. Instead of an atom in optical molasses, he substituted a silica (glass) sphere embedded in water. A micron-sized sphere is far more polarizable than an atom and Ashkin felt that it could be trapped at room temperature if the intensity gradient in the axial direction that would draw the glass bead

into the focus of the light could overcome the scattering force pushing the particle out of the trap. This more macroscopic version of the optical tweezers trap was demonstrated quickly and gave us more confidence that the atom trap might work.[38] At that time, none of us realized how this simple "toy experiment" was going to flower.

Shortly after we demonstrated the optical trap, I hired Mara Prentiss as a new permanent staff member in my department. She began to work on the super-molasses riddle with us when I got a phone call from Dave Pritchard at MIT. He told me he and his student, Eric Raab, had been working on a scattering-force trap that would circumvent the Optical Earnshaw Theorem.[33] This theorem states that a scattering-force trap is impossible provided the scattering force $\mathbf{F}_{scatt}$ is proportional to the laser intensity **I**. The proof was straight forward: $\nabla \cdot \mathbf{F}_{scatt} = 0$ since any region in empty space must have the net intensity flux inward equal to the flux outward. Thus there cannot be a region in space where all force lines $\mathbf{F}_{scatt}$ point inward to a stable trapping point. Pritchard, Carl Wieman, and their colleagues had noted that the assumption $\mathbf{F}_{scatt} \propto \mathbf{I}$ need not be true.[39] They went on to suggest possible combinations of external magnetic or electric fields that could be used to create a stable optical trap.

Raab had had difficulties in getting a scattering-force trap to work at MIT and, as a last attempt before giving up, they asked if we were interested in collaborating with them on this work. The basic idea is illustrated in Fig. 5 for the case of an atom with F = 1 in the ground state and F = 2 in the excited state, where F is the total angular momentum quantum number. A weak spherical quadrupole trap magnetic field would split the Zeeman sublevels of a multilevel atom illuminated by counterpropagating circularly polarized laser beams. Due to the slight Zeeman-shift, an atom to the right of the trap center optically pump predominantly into the $m_F = -1$ state. Once in this state, the large difference in the scattering rates for σ^- light and σ^+ light causes the atom to experience a net scattering force towards the trap center. Atoms to the left of center would scatter more photons from the σ^+ beam. Since the laser beams remain tuned below all of the Zeeman split resonance lines, optical molasses cooling would still be occurring. The generalization to three dimensions is straightforward.

All we needed to do, was insert a pair of modest magnetic-field coils into our apparatus to test this idea. I wound some refrigeration tubing for the magnetic-field coils, but had to tear myself away to honor a previous commitment to help set up a muonium spectroscopy experiment with Allan Mills, Ken Nagamine and collaborators.[40] A few days later, the molasses was running again, and I received a call at the muon facility in Japan from Alex, his voice trembling with excitement. The trap worked spectacularly well and the atom cloud was blindingly bright compared to our dipole trap. Instead of the measly 1000 atoms we had in our first trap, they were getting 10^7 to 10^8 atoms.[41]

The basic idea for the trap was due to Jean Dalibard, a protegé of Claude Cohen-Tannoudji. His idea was stimulated by a talk given by Dave Pritchard on how the Earnshaw theorem could be circumvented. I called Jean in Paris

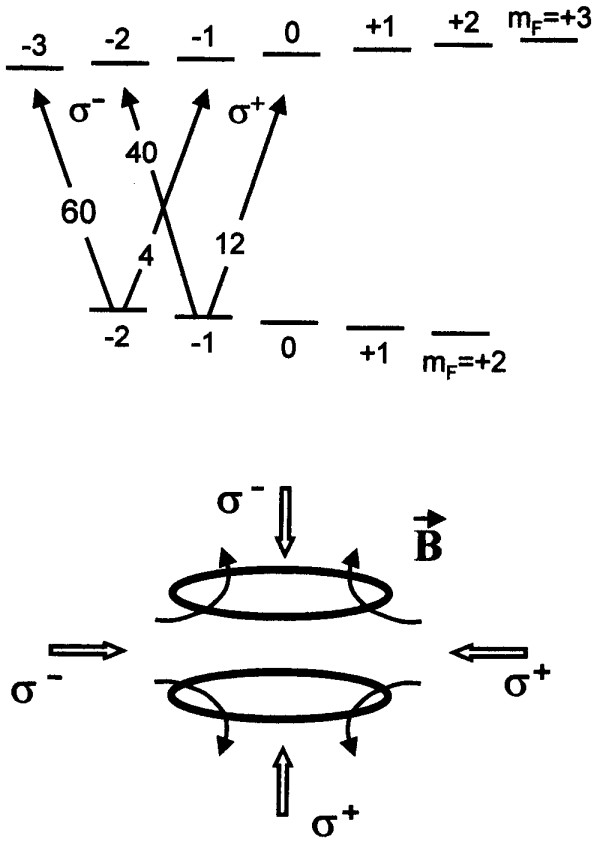

Figure 5. The magneto-optic trap for atoms with an F = 2 ground state and a F = 3 excited state. The slight energy level shifts of the Zeeman sub-levels cause symmetry to be broken and the atoms to optically pump predominantly into either the $m_F = +2$ or $m_F = -2$ state for $\mathbf{B}<0$ or $\mathbf{B}>0$. Once in the optically pumped states, the atoms are pushed towards the $\mathbf{B} = 0$ region due to the large difference in relative strengths of the transition rates. The relative transition rates for σ^+ and σ^- light for the $m_F = -2$ and -1 states are shown.

to convince him that his name should go on the paper we were writing. Jean is both brilliant and modest, and felt it would be inappropriate to be a co-author since he did not do any of the work.[42]

The magneto-optic trap (commonly referred to as the MOT) immediately seized the attention of the growing community of coolers and trappers. Carl Wieman's group showed that atoms could be directly loaded from a tenuous vapor without the intermediate step of slowing an atomic beam.[43] By increasing the size of the laser beams used in the trap, Kurt Gibble and I showed that as many as $\sim 4\times 10^{10}$ atoms could be trapped.[44] Wolfgang Ketterle, Pritchard, *et al.*[45] showed that the density of atoms in the MOT could be increased significantly by causing atoms to scatter less light in the central portion of the trap by blocking the repumping beam in that region of space. Stimulated by their shadowing idea, my collaborators and I at Stanford showed that by simply turning off the repumping light at the end stage of molasses dramatically increases the density of low-temperature atoms in the MOT.[46]

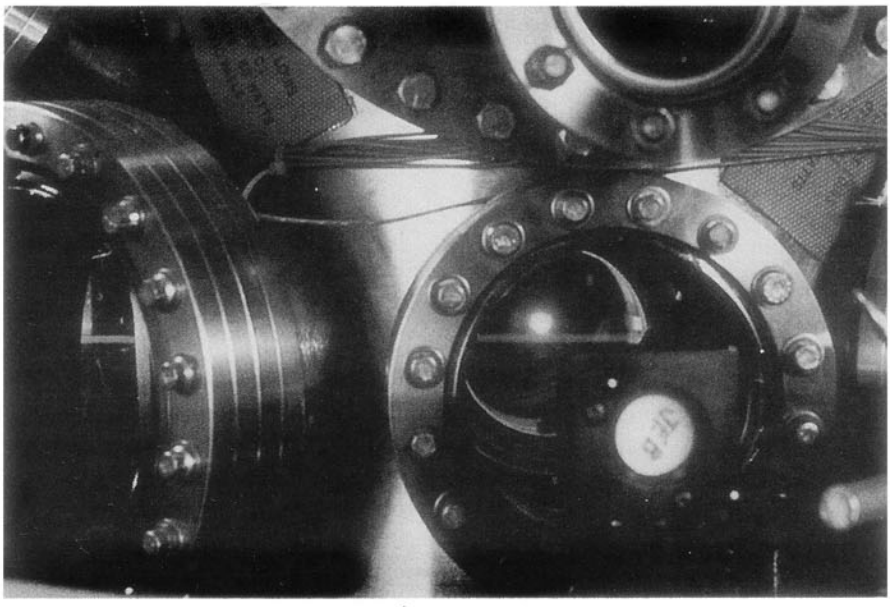

Figure 5 b. A photograph of atoms confined in a magneto-optic trap. The line of fluorescence below the ball of trapped atoms is due to the atomic beam used to load the trap.

The invention and development of the MOT exemplifies how the field of laser cooling and trapping grew out of the combined ideas and cooperation of an international set of scientists. For this reason, I find it especially fitting that the magneto-optic trap is the starting point of most experiments using laser-cooled atoms.

OPTICAL MOLASSES REVISITED

In the winter of 1987, I decided to leave the "ivory tower" of Bell Labs and accept an offer to become a professor at Stanford. When I left Bell Labs, we had just demonstrated the magneto-optic trap and it was clear the trap would provide an ideal starting point for a number of experiments. I arrived at Stanford in the fall of 1987, not knowing how long it would take to build a new research team.[47] Bill Phillips and Claude Cohen-Tannoudji were assembling powerful teams of scientists that could not be duplicated at Stanford. Dave Pritchard had been cultivating a powerful group at MIT. Other "home run hitters" in atomic physics such as Carl Wieman and Alain Aspect had just entered the field. Meanwhile, I had to start over again, writing proposals and meeting with prospective graduate students. If I had thought carefully about starting a new lab in the face of this competition, I might not have moved.

As with many aspects of my career, I may not have made the smart move, but I made a lucky move. From 1988 to 1993, I entered into the most productive time in my scientific career to date. My first three graduate students were Mark Kasevich, Dave Weiss, and Mike Fee. I also had two post-docs, Yaakov Shevy and Erling Riis who joined my group my first year at Stanford.

By January of 1988, Dave and Yaakov had a magneto-optic trap going in the original chamber we used to demonstrate optical molasses and the dipole trap. The plan was to improve the optical trapping techniques and then use the new laser cooling and trapping technology to explore new physics that could be accessed with cold atoms.

Another chamber was being assembled by Mark and Erling with the intent of studying the "quantum reflection" of atoms from cold surfaces. While I was at Bell Labs, Allan Mills and Phil Platzman began to get me interested in studying quantum reflection with ultracold atoms. The problem can be simply posed as follows: consider an atom with a long de Broglie wavelength λ incident on an idealized, short-range, *attractive* potential. In general there is a transmitted wave and reflected wave, but in the limit where λ is much greater than the length scale of the potential, one gets the counterintuitive result that the probability of reflection goes to unity. A real surface potential has a power-law attraction of the form $1/z^n$ and has no length scale. An atom near a surface will experience an attractive van der Waals force with a $1/z^3$ potential and, further away, the attractive potential would become $1/z^4$ due to "retarded potential" effects first discussed by Casimir. There are also subtleties to the problem when inelastic scattering channels are included. This problem had attracted the attention of a considerable number of theorists and experimentalists.

My plan of research was soon tossed out the window by a discovery that sent shock waves through the laser cooling community. By 1987, other groups began to produce optical molasses in their labs and measured atom temperatures near the expected limit,[48, 49] but in the spring of 1988, Bill Phillips and co-workers reported that sodium atoms in optical molasses could be cooled to temperatures far below the limit predicted by theory.[50] The NIST group reported the temperature of sodium atoms cooled in optical molasses to be 43±20 μK and that the temperature did not follow the frequency dependence predicted by theory. The result was so surprising, they performed three different time-of-flight methods to confirm their result. Within a few months, three separate groups led by Wieman, Cohen-Tannoudji, and myself verified that sodium and cesium atoms in optical molasses could be cooled well below the Doppler limit.

As with many big "surprises", there were earlier hints that something was amiss. My group had been discussing the "super-molasses" problem at conferences since 1986. At a laser spectroscopy conference in Åre, Sweden in 1987, the NIST group reported molasses lifetimes with a very different frequency dependence from the one predicted by the simple formula $\langle x^2 \rangle = 2D\tau/\alpha^2$ that we published in our first molasses paper.[51] This group also found that the trap was more stable to beam imbalance than had been expected. In our collective euphoria over cooling and trapping atoms, the research community had not performed the basic tests to measure the properties of optical molasses, and I was the most guilty.

At the end of June, 1988, Claude and I attended a conference on spin-polarized quantum systems in Torino, Italy and gave a summary of the new sur-

prises in laser cooling known at that time.[52] After our talks, Claude and I had lunch and compared the findings in our labs. The theory that predicted the minimum temperature for two-level atoms was beyond reproach. We felt the lower temperatures must be due to the fact that the atoms we were playing with were *real* atoms with Zeeman sub-levels and hyperfine splittings. Our hunch was that the cooling mechanism probably had something to do with the Zeeman sub-level structure and not the hyperfine structure, since cesium ($\Delta\nu_{hfs}$ = 9.19 GHz) and sodium ($\Delta\nu_{hfs}$ = 1.77 GHz) were both cooled to temperatures corresponding to an rms velocity on the order 4 to 5 times the recoil velocity, $v_{recoil} = \hbar k/M$ and $k = 2\pi/\lambda$. By then we also knew that the magnetic field had to be reduced to below 0.05 Gauss to achieve the best cooling.

After the conference, Claude returned to Paris while I was scheduled to give several more talks in Europe. My next stop was Munich, where I told Ted Hänsch that I thought it had to be an optical pumping effect. My knowledge of optical pumping was rudimentary, so I spent half a day in the local physics library reading about the subject. I was getting increasingly discouraged when I came across an article that referred to "Cohen-Tannoudji states". It was beginning to dawn on me that Claude and Jean were better positioned to figure out this puzzle.

After Munich, I went to Pisa where I gave a talk about our positronium and muonium spectroscopy work.[53, 54, 55] There, I finally realized how molasses was cooling the atoms. The idea was stimulated by a intuitive remark made by one of the speakers during his talk, "...the atomic polarization responds in the direction of the driving light field..." The comment reminded me of a ball-and-stick model of an atom as an electron (cloud) tethered by a weakly damped harmonic force to a heavy nucleus. I realized the cooling was due to a combination of optical pumping, light shifts, and the fact that the polarization in optical molasses changed at different points in space. A linearly polarized laser field drives the atomic cloud up and down, while a circularly polarized field drives the cloud in a circle. In optical molasses, the x, y, and z-directed beams all have mutually perpendicular linear polarizations and the polarization of the light field varies from place to place. As a simple example, consider a one-dimensional case where two opposing light beams have mutually perpendicular linear polarizations as shown in Fig. 6. The electron cloud wants to rotate with an elliptical helicity that is dependent on the atom's position in space.

Another effect to consider is the ac Stark (light) shift. In the presence of light, the energy levels of an atom are shifted, and the amount of the shift is proportional to the coupling strength of the light. Suppose an atom with angular momentum F = 2 is in σ^+ light tuned below resonance. It will optically pump into the $m_F = +2$ state and its internal energy in the field will be lowered as shown in Fig. 6 c. If it then moves into a region in space where the light is σ^-, the transition probability is very weak and consequently the ac Stark shift is small. For sodium the $m_F = +2$ energy is lowered 15 times more in σ^+ light than in σ^- light. Hence, the atom gains internal energy by moving into the σ^- region. This increase in internal energy must come at the expen-

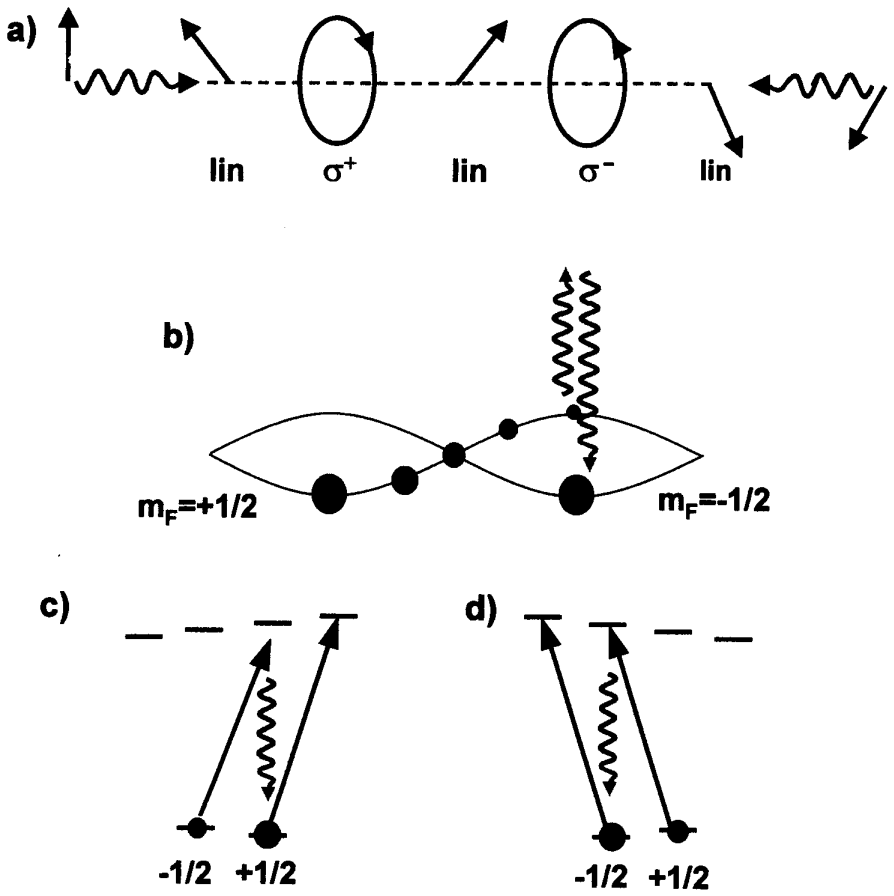

Figure 6. Polarization gradient cooling for an atom with an F = 1/2 ground state and an F = 3/2 excited state. a) The interference of two linearly polarized beams of light with orthogonal polarizations creates a field of varying elliptical polarization as shown. Under weak excitation, the atom spends most of its time in the ground states. b) The energy of the $m_F = \pm 1/2$ ground states as a function of position in the laser field is shown. c) An atom in a σ^+-field will optically pump mostly into the $m_F = +1/2$ ground state, the lower internal energy state. d) If the atom moves into a region of space where the light is σ^-, its internal energy increases due to the decreased light shift (AC Stark shift) of the $m_F = +1/2$ state in that field. The atom slows down as it goes up a potential hill created by the energy level shift. As the atom nears the top of the hill, it begins to optically pump to the $m_F = -1/2$ state, putting the atom into the lowest energy state again. Laser cooling by repeated climbing of potential hills has been dubbed "Sisyphus cooling" after the character in the Greek myth condemned forever to roll a boulder up a hill.

se of its kinetic energy. The final point is that the atom in the new region in space will optically pump into the $m_F = -2$ state (Fig. 6 d). Thus the atom will find itself again in a low-energy state due to the optical pumping process. The ensemble of atoms loses energy, since the spontaneously emitted photons are slightly blue-shifted with respect to the incident photons.

Cooling in polarization gradients is related to a cooling mechanism that occurs for two-level atoms in the presence of two counter-propagating laser beams. In the low-intensity limit, the force is described by our intuitive notion of scattering from two independent beams of light, as first discussed by

Hänsch and Schawlow. [21] However, at high intensities, the force reverses sign so that one obtains a cooling force for positive detuning. This cooling force has been treated by Gordon and Ashkin for all levels of intensity in the low velocity limit,[19] and by Minogin and Serimaa in the high-intensity limit for all velocities.[56] A physical interpretation of the cooling force in the high-intensity limit based on the dressed-atom description was given by Dalibard and Cohen-Tannoudji.[57] In their treatment, the atom gains internal energy at the expense of kinetic energy as it moves in the standing-wave light field. The gain in internal energy is dissipated by spontaneous emission, which is more likely to occur when the atom is at the maximum internal energy. When the atom makes a transition, it will find itself most often at the bottom of the dressed-state potential hills. Following Albert Camus, Jean and Claude again revived *Le Mythe de Sisyphe* by naming this form of cooling after the character in Greek mythology, Sisyphus, who was condemned eternally roll a boulder up a hill.

The name "optical molasses" takes on a more profound meaning with this new form of cooling. Originally, I conceived of the name thinking of a viscous fluid associated with cold temperatures: "slow as molasses in January". With this new understanding, we now know that cooling in optical molasses has two parts: at high speeds, the atom feels a viscous drag force, but at lower speeds where the Doppler shift becomes negligible, the optical pumping effect takes over. An atom sees itself walking in a swamp of molasses, with each planted foot sinking down into a lower energy state. The next step requires energy to lift the other foot up and out of the swamp, and with each sinking step, energy is drained from the atom.

The Pisa conference ended on Friday, and on Sunday, I went to Paris to attend the International Conference on Atomic Physics. That Sunday afternoon, Jean and I met and compared notes. It was immediately obvious that the cooling models that Jean and Claude and I concocted were the same. Jean, already scheduled to give a talk at the conference, gave a summary of their model.[58] I was generously given a "post-post-deadline" slot in order to give my account of the new cooling mechanism.[59]

Detailed accounts of laser cooling in light fields with polarization gradients followed a year later in a special issue of JOSA B dedicated to cooling and trapping. Dalibard and Cohen-Tannoudji provided an elegant quantum mechanical treatment of simple model systems.[60] They discussed two different types of cooling, depending on whether the counter-propagating light beams were comprised of mutually perpendicular linear polarizations or opposing σ^+ -σ^- beams. Their approach allowed them to derive the cooling force and diffusion of momentum (heating) as a function of experimental parameters such as detuning, atomic linewidth, optical pumping time, etc., that could be experimentally tested.

My graduate students and I presented our version of the Sisyphus cooling mechanism in the same issue.[61] In order to obtain quantitative calculations that we could compare to our experimental results, we chose to calculate the cooling forces using the optical Bloch equations generalized for the sodium F

= 2 ground state → F = 3 excited state transition. We derived the steady-state cooling forces as a function of atomic velocity for the same two simple polarization configurations, but for sodium atoms instead of a model system. However, we also showed considered by Dalibard and Cohen-Tannoudji that steady-state forces *cannot* be used to estimate the velocity distribution and that the transient response of the atom in molasses with polarization gradients was significant.[62] A weak point of our paper was that we made *ad hoc* assumptions in our treatment of the diffusion of momentum, and the predicted Monte Carlo calculations of the velocity distributions were sensitive to the details of these assumptions. Since that time, more rigorous quantum Monte Carlo methods have been developed.

In a companion experimental paper,[63] we measured non-thermal velocity distributions of atoms cooled in the laser fields treated in our theory paper. We also measured the velocity distributions of atoms cooled in σ^+–σ^+ light.[64] Under these conditions, sodium atoms will optically pump into an effective two-level system consisting of the $3S_{1/2}$, F = 2, $m_F = +2$ and $3P_{3/2}$, F = 3, $m_F = +3$ states. This arrangement allowed us finally to verify the predicted frequency dependence of the temperature for a two-level atom, three years after the first demonstration of Doppler cooling. In the course of those experiments, Dave Weiss discovered a magnetic-field-induced cooling[63] that could be explained in terms of Sisyphus-like effects and optical pumping.[61] This cooling mechanism was explored in further detail by Hal Metcalf and collaborators.[65]

The NIST discovery of sub-Doppler temperatures showed that the limiting temperature based on the Doppler effect was not actually a limit. What is the fundamental limit to laser cooling? One might think that the limit would be the recoil limit $k_B T \sim (p_r)^2/2M$, since the last photon spontaneously emitted from an atom results in a random velocity of this magnitude. However, even this barrier can be circumvented. For example, an ion tightly held in a trap can use the mass of the trap to absorb the recoil momentum. The so-called sideband cooling scheme proposed by Dehmelt and Wineland[66] and demonstrated by Wineland and collaborators[67] can in principle cool an ion so that the fractional occupancy of two states separated by an energy ΔE can have an effective temperature T_{eff} less than the recoil temperature, where T_{eff} is defined by $e^{-\Delta E/k}\, T_{eff}$, i.e. the fraction of time the ion spends in the ground state.

For free atoms, it is still possible to cool an ensemble of atoms so that their velocity spread is less than photon recoil velocity by using velocity-selection techniques. The Ecolé Normale group devised a clever velocity-selection scheme based on a process they named "velocity selective coherent population trapping".[68] In their first work, metastable helium atoms were cooled along one dimension of an atomic beam to a transverse (one-dimensional) temperature of 2 μK, a factor of 2 below the single photon recoil temperature. The effective temperature of the velocity-selected atoms decreases roughly as the square root of the time that the velocity-selection light is on, so much colder temperatures may be achieved for longer cooling times. In subsequent experiments, they used atoms precooled in optical molasses and achieved much colder temperatures in two and three dimensions.[69] An im-

portant point to emphasize is that this method has no strict cooling limit: the longer the cooling time, the smaller the spread in velocity. However, there is a trade-off between the final temperature and the number of atoms cooled to this temperature since the atom finds it harder to randomly walk into a progressively smaller section of velocity space. Eventually, the velocity-selective cooling becomes velocity "selection" in the sense that the number of atoms in the velocity-selected state begins to decrease.

APPLICATIONS OF LASER COOLING AND TRAPPING

During the time we were studying polarization gradient cooling, my group of 3 students and one post-doc at Stanford began to apply the newly developed cooling and trapping techniques, but even those plans were soon abandoned.

After the completion of the studies of polarization gradient optical molasses cooling, Erling Riis, Dave Weiss and Kam Moler constructed a two-dimensional version of the magneto-optic trap where sodium atoms from a slowed atomic beam were collected, cooled in all three dimensions and compressed radially before being allowed to exit the trap in the axial direction.[70] This "optical funnel" increased the phase space density of an atomic beam by five orders of magnitude. Another five orders of magnitude are possible with a cesium beam and proper launching of the atoms in a field with moving polarization gradients. Ertmer and colleagues developed a two-dimensional compression and cooling scheme with the magneto-optic trap.[71] These two experiments demonstrated the ease with which laser cooling can be used to "focus" an atomic beam without the limitations imposed by the "brightness theorem" in optics.

In our other vacuum chamber, Mark Kasevich and Erling Riis were given the task of producing an atomic fountain as a first step in the quantum reflection experiment. That was to be Mark's thesis. The idea was to launch the atoms upwards in an atomic fountain with a slight horizontal velocity. When the atoms reached their zenith, they would strike a vertically oriented surface. As they were setting up this experiment, I asked them to do the first of a number of "quickie experiments". "Quickies" were fast diversions I promised would only take a few weeks, and the first detour was to use the atomic fountain to do some precision spectroscopy.

In the early 1950s, Zacharias attempted to make an "atomic fountain" by directing a beam of atoms upwards. Although most of the atoms would crash into the top of the vacuum chamber, the very slowest atoms in the Maxwell distribution were expected to follow a ballistic trajectory and return to the launching position due to gravity. The goal of Zacharias' experiment was to excite the atoms in the fountain with Ramsey's separated oscillatory field technique, the method used in the cesium atomic clock.[72] Atoms initially in state $|1\rangle$ would enter a microwave cavity on the way up and become excited into a superposition of two quantum states $|1\rangle$ and $|2\rangle$. While in that superposition state, the relative phases of the two states would precess with a frequency $\hbar\omega = E_1 - E_2$. When the atoms passed through the microwave cavity on

the way down, they would again be irradiated by the microwave field. If the microwave generator were tuned exactly to the atomic frequency ω, the second pulse would excite the atoms completely into the state $|2\rangle$. If the microwave source were π radians (half a cycle) out of phase with the atoms, they would be returned to state $|1\rangle$ by the second pulse. For a time Δt separating the two excitation pulses, the oscillation "linewidth" $\Delta\omega_{rf}$ of this transition satisfies $\Delta\omega_{rf}\,\Delta t = \pi$.

This behavior is a manifestation of the Heisenberg uncertainty principle: the uncertainty ΔE in the measurement of an energy interval times the quantum measurement time Δt must be greater than Planck's constant $\Delta E \Delta t \geq \hbar$. An atomic fountain would increase the measurement time by more than two orders of magnitude as compared to conventional atomic clocks with horizontally moving thermal beams. Zacharias hoped to measure the gravitational redshift predicted by Einstein: identical clocks placed at different heights in a gravitational field will be frequency shifted with respect to each other. The atom fountain clock, during its trajectory, would record less time than the stationary microwave source driving the microwave cavity.

Unfortunately, Zacharias' experiment failed. The slowest atoms in the Maxwell-Boltzmann distribution were scattered by faster atoms overtaking them from behind and never returned to the microwave cavity. The failure was notable in several respects. The graduate student and post-doc working on the project still got good jobs, and the idea remained in the consciousness of the physics community.[73] With our source of laser cooled atoms, it was a simple matter for us to construct an atomic fountain.[74] Atoms were first collected in a magneto-optic trap and then launched upwards by pushing from below with another laser beam. At the top of the ballistic trajectory, we irradiated the atoms with two microwave pulses separated by 0.25 seconds, yielding a linewidth of 2 Hz. Ralph DeVoe at the IBM Almaden Research center joined our experiment and provided needed assistance in microwave technology. With our demonstration atomic fountain, we measured the sodium ground-state hyperfine splitting to an accuracy of one part in 10^9.

After the theory of polarization-gradient cooling was developed, we realized that there was a much better way to launch the atoms. By pushing with a single laser beam from below, we would heat up the atoms due to the random recoil kicks from the scattered photons. However, by changing the frequency of the molasses beams so that the polarization gradients would be in a frame of reference moving relative to the laboratory frame, the atoms would cool to polarization-gradient temperatures in the moving frame. The atoms could be launched with precise velocities and with no increase in temperature.[75]

André Clairon and collaborators constructed the first cesium atomic fountain.[76] Kurt Gibble and I analyzed the potential accuracy of an atomic fountain frequency standard and suggested that the phase shifts due to collisions might be a limiting factor to the ultimate accuracy of such a clock.[77] We then constructed an atomic fountain frequency source that surpassed the short term stability of the primary Cs references maintained by standards laboratories.[78] In that work, we also measured the frequency shift due to ultracold col-

lisions in the fountain, a systematic effect which may be the limiting factor of a cesium clock. The group led by Clairon has recently improved upon our short-term stability. More important, they achieved an accuracy estimated to be $\Delta\nu/\nu \leq 2\times10^{-15}$, limited by the stability of their hydrogen maser reference.[79] Such a clock started at the birth of the universe would be off by less than four minutes today, ~15 billion years later.

The next "quickie" to follow the atomic fountain was the demonstration of normal incidence reflection of atoms from an evanescent wave. Balykin, *et al.*[80] deflected an atomic beam by a small angle with an evanescent sheet of light extending out from a glass prism. If the light is tuned above the atomic resonance, the induced dipole **p** will be out of phase with the driving field. The atom with energy $-\mathbf{p}\cdot\mathbf{E}$ is then repelled from the light by the dipole force. The demonstration of normal incidence reflection with laser-cooled atoms was a necessary first step towards the search for quantum reflection. With our slow atoms, we wanted to demonstrate an "atomic trampoline" trap by bouncing atoms from a curved surface of light created by internally reflecting a laser beam from a plano-concave lens. Unfortunately, the lens we used produced a considerable amount of scattered light, and the haze of light "levitated" the atoms and prevented us from seeing bouncing atoms. Mark ordered a good quality lens and we settled for bouncing atoms from the dove-prism surface[81] with the intent of completing the work when the lens arrived. We never used the lens he ordered because of another exciting detour in our research. A few years later, a trampoline trap was demonstrated by Cohen-Tannoudji's group.[82] The evolution of gravito-optic atom traps is summarized in Fig. 7.

While waiting for the delivery of our lens, we began to think about the next stage of the quantum reflection experiment. The velocity spread of the atoms in the horizontal direction would be determined by a collimating slit, but I was unhappy with this plan. The quantum reflection experiment would require exquisitely cold atoms with a velocity spread corresponding to an effective temperature of a small fraction of a micro-kelvin. Given the finite size of our atoms confined in the MOT, very narrow collimating slits would reduce the flux of atoms to distressingly low levels. Ultimately, collimating slits would cause the atoms to diffract.

While flying home from a talk, the solution to the velocity-selection problem came to me. Instead of using collimating slits, we could perform the velocity selection with the Doppler effect. Usually, the Doppler sensitivity is limited by the linewidth of the optical transition. However, if we induced a two-photon transition between two ground states with lasers beams at frequencies ν_1 and ν_2, there is no linewidth associated with an excited state. If the frequency of ν_2 is generated by an electro-optic modulator so that $\nu_2 = \nu_1 + \nu_{rf}$, the frequency jitter of the excitation laser would not enter since the transition would depend on the frequency difference $\nu_2-\nu_1 = \nu_{rf}$. The linewidth $\Delta\nu$ would be limited by the transition time Δt it took to induce the two-photon transition, and our atomic fountain would give us lots of time. Despite the fact that the resonance would depend on the frequency *difference*, the

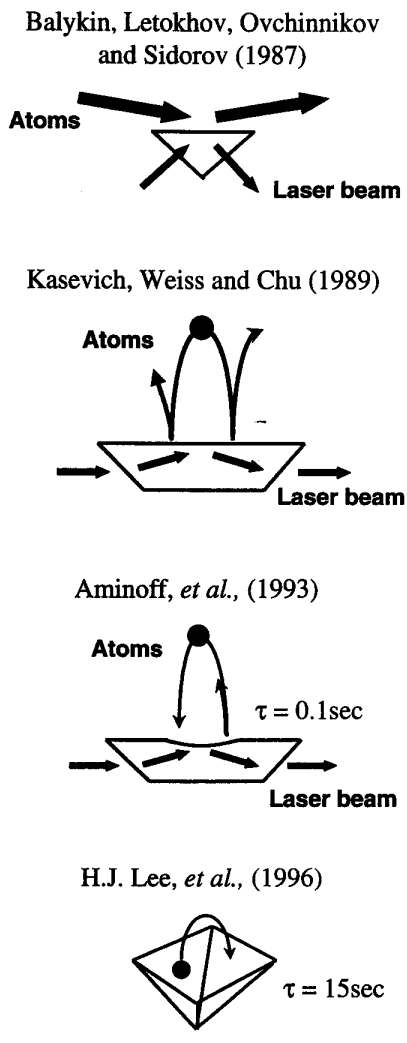

Figure 7. Some of the highlights in the development of the reflection of atoms from optical sheets of light tuned to the blue side of the atomic resonance. Since the atoms spend a considerable amount of time in free fall, blue de-tuned optical traps allow fairly efficient cooling with stimulated Raman pulses. Over 3×10^6 sodium atoms have been Raman cooled to the recoil temperature at densities of 2×10^{11} atoms/cm^3 in an inverted pyramid trap.

Doppler sensitivity would depend on the frequency *sum* if the two laser beams were counter-propagating. This idea would allow us to achieve Doppler sensitivity equivalent to an ultraviolet transition, but with the frequency control of the microwave domain, and it would be easy. In a proof of principle experiment, we created an ensemble of atoms with a velocity spread of 270 μm/sec corresponding to an effective 1-dimensional "temperature" of 24 picokelvin and a de Broglie wavelength of 51 μm.[83] We also used the Doppler sensitivity to measure velocity distributions with sub-nanokelvin resolution.

By 1990, we were aware of several groups trying to construct atom interferometers based on the diffraction of atoms by mechanical slits or diffraction gratings, and their efforts stimulated us to think about different approaches to atom interferometry. We knew there is a one-to-one correspondence between the Doppler sensitivity and the recoil an atom experiences when it makes an optical transition. With a two-photon Raman transition with counter-propagating beams of light, the recoil is $\Delta p = \hbar k_{eff}$, where $k_{eff} = (k_1+k_2)$, and it is this recoil effect that allowed us to design a new type of atom interferometer.

If an atom with momentum p and in state $|1\rangle$, described by the combined quantum state $|1,p\rangle$, is excited by a so-called "$\pi/2$" pulse of coherent light, the atom is driven into an equal superposition of two states $|1,p\rangle$ and $|2,p+\hbar k_{eff}\rangle$. After a time Δt, the two wave packets will have separated by a distance $(\hbar k_{eff}/M)\Delta t$. Excitation by a π pulse induces the part of the atom in state $|1,p\rangle$ to make the transition $|1,p\rangle \rightarrow |2,p+\hbar k_{eff}\rangle$ and the part of the atom in $|2,p+\hbar k_{eff}\rangle$ to make the transition $|2,p+\hbar k_{eff}\rangle \rightarrow |1,p\rangle$. After another interval Δt, the two parts of the atom come back together and a second $\pi/2$ pulse with the appropriate phase shift with respect to the atomic phase can put the atom into either of the states $|1,p\rangle$ or $|2,p+\hbar k_{eff}\rangle$. This type of atom interferometer is the atomic analog of an optical Mach-Zender interferometer and is closely related to an atom interferometer first discussed by Bordé.[84] In collaboration with the PTB group led by Helmcke, Bordé used this atom interferometer to detect rotations.[85]

By January of 1991, shortly after we began seeing interference fringes, we heard that the Konstanz group led by Jürgen Mlynek[86] had demonstrated a Young's double slit version atom interferometer and that the MIT group, led by Dave Pritchard[87] had succeeded in making a grating interferometer. Instead of using atoms in a thermal beam, we based our interferometer on an atomic fountain of laser-cooled atoms. We knew we had a potentially exquisite measuring device because of the long measurement time and wanted to use our atom interferometer to measure something before we submitted a paper.

As we began to think of what we could easily measure with our interferometer, Mark made a fortuitous discovery: the atom interferometer showed a phase shift that scaled as Δt^2, the delay time between the $\pi/2$ and π pulses, and correctly identified that this phase shift was due to the acceleration of the atoms due to gravity. An atom accelerating will experience a Doppler shift with respect to the lasers in a laboratory frame of reference propagating in the direction of **g**. Even though the laser beams were propagating in the nominally horizontal direction, the few milliradian "misalignment" created enough of phase shift to be easily observable.

Our analysis of this phase shift based on Feynman's path-integral approach to quantum mechanics was outlined in the first demonstration of our atom interferometer[88] and expanded in our subsequent publications.[89, 90, 91, 92] Storey and Cohen-Tannoudji have published an excellent tutorial paper on this approach as well.[93] Consider a laser beam propagating parallel to the di-

rection of gravity, as shown in Fig 8. The phase shift of the atom has two parts: (*i*) a free-evolution term $e^{iS_{Cl}/\hbar}$, where

$$S_{Cl} = \int_r L dt$$

is the action evaluated along the classical trajectory *r*, and (*ii*), a phase term due to the atom interacting with the light. The evaluation of the integrals for both paths shows that the free-evolution part contributes no net phase shift between the two arms of the interferometer. The part of the phase shift due to the light/atom interaction is calculated by using the fact that an atom that makes a transition $|1,p\rangle \rightarrow |2,p+\hbar k\rangle$ acquires a phase factor $e^{-i(k_L z-\omega t)}$, where z is the vertical position of the atom and $k_L = k_1 + k_2$ is the effective *k* vector of the light. A transition $|2,p+\hbar k\rangle \rightarrow |1,p\rangle$ adds a phase factor $e^{+i(k_L z-\omega t)}$. If the atom does not make a transition, the phase factor due to the light is unity. If k_L is parallel to g, the part of the atom in the upper path will have a total phase $\phi_{upper} = k_L \cdot (z_A - z_B)$ read into the atom by the light. The part of the atom in the lower path will have a given phase angle $\phi_{lower} = k_L \cdot (z_{B'} - z_C)$. In the absence of gravity, $z_A - z_B = z_{B'} - z_C$, and there is no net phase shift between the two paths. However, with gravity, $z_B - z_A = g\Delta t^2/2$, while $z_{B'} - z_C = 3g\Delta t^2/2$. Thus the net phase shift is $\Delta\phi = k_L g \Delta t^2$. Notice that the acceleration is measured in the

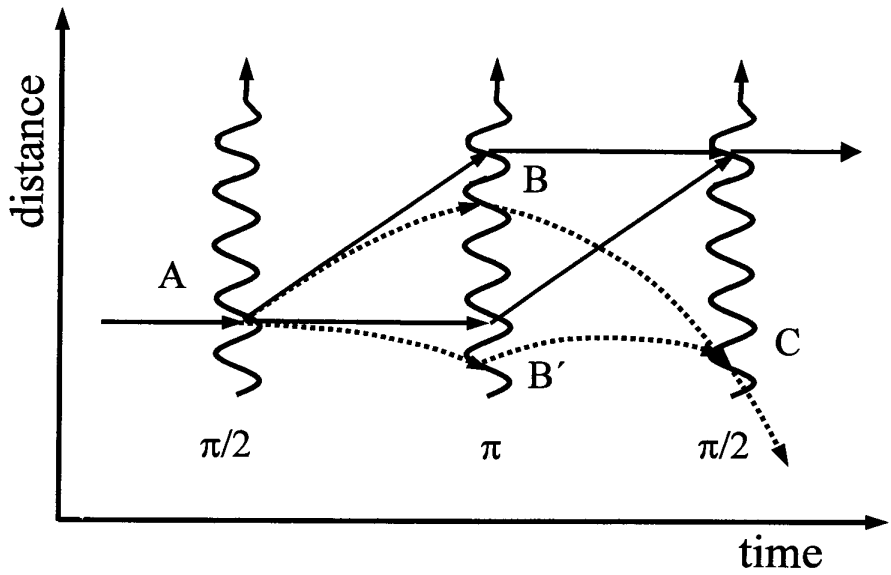

Figure 8. An atom interferometer based on optical pulses of light. The phase of the optical field is read into the atom during a transition from one state to another. In the absence of gravity (solid lines), the part of the atom moving along the upper path from the first $\pi/2$ pulse to the π pulse will experience 3 cycles of phase less than the part of the atom that moves along the lower path. The lower path experiences an identical loss of phase during the time between the π pulse and the second $\pi/2$ pulse. If the excitation frequency is exactly on resonance, the atom will be returned back to the initial state. With gravity (dotted lines), the phase loss of the upper path is more than the phase loss of the lower path since $z_C - z_{B'}$ is greater than $z_B - z_A$. Thus, by measuring displacements during a time Δt in terms of a phase difference, we can measure velocity changes due to g or photon recoil effects (Fig. 9) in the time domain.

time domain: we record the change in phase $\Delta\phi = k_L \Delta z$ that occurs after a time Δt.

The phase shift of the interferometer is measured by considering the relative phase between the atomic phase of the two parts of the atom and the phase of the light at position C. If the light is in phase with the atom, the second $\pi/2$ pulse will cause the atom to return to state $|1,p\rangle$. If it is π out of phase, the atom will be put into state $|2,p+\hbar k\rangle$. Thus the phase shift is measured in terms of the relative populations of these two states.

For the long interferometer times Δt that are obtainable in an atomic fountain, the phase shift can be enormous. For $\Delta t = 0.2$ seconds, over 4×10^6 cycles of phase difference accumulate between the two paths of the interferometer. In our first atom interferometer paper, we demonstrated a resolution in g of $\Delta g/g = 10^{-6}$, and with improved vibration isolation, achieved a resolution of $\Delta g/g < 3\times10^{-8}$.[89] With a number of refinements, including the use of an actively stabilized vibration isolation system,[94] we have been able maintain the full **fringe contrast for times up to $\Delta t = 0.2$ seconds and have improved the fractional resolution to $\Delta g/g \sim 10^{-10}$.**[92]

Soon after the completion of our first atom interferometer measurements, Mark Kasevich thought of a way to cool atoms with stimulated Raman transitions.[95] Since the linewidth of a Raman transition is governed by the time to make the transition, we had a method of addressing a very narrow velocity slice of atoms within an ensemble already cooled by polarization-gradient cooling. Atoms are initially optically pumped into a particular hyperfine state $|1\rangle$. A Raman transition $|1\rangle \rightarrow |2\rangle$ is used to push a small subset of them towards v = 0. By changing the frequency difference ν_1–ν_2 for each successive pulse, different groups of atoms in the velocity distribution can be pushed towards $v = 0$, analogous to the "frequency chirp" cooling methods used to slow atomic beams. A critical difference is that Raman pulses permit much higher-resolution Doppler selectivity. After each Raman pulse, a pulse is used to optically pump the atom back into $|1\rangle$. During this process, the atom will spontaneously emit one or more photons and can remain near $v = 0$. The tuning of the optical pulses are adjusted so that an atom that scatters into a velocity state near $v = 0$ will have a low probability of further excitation. This method of cooling is analogous to coherent population trapping except that the walk in velocity space is directed towards $v = 0$. In our first demonstration of this cooling process, sodium atoms were cooled to less than $0.1T_{recoil}$ in one dimension, with an 8-fold increase in the number of atoms near $v = 0$. In later work, we extended this cooling technique to two and three dimensions.[96]

This cooling technique has also been shown to work in an optical dipole trap. We were stimulated to return to dipole traps by Phillips' group[97] and by Dan Heinzen's group,[98] who demonstrated dipole traps tuned very far from resonance. In this type of trap, the heating due to the scattering of trapping light is greatly reduced. A nondissipative dipole trap turns out to be useful in a number of applications. In traps formed by sheets of blue detuned light (a successor to the trampoline traps), we showed that atomic coherences can be

preserved for 4 seconds despite hundreds of bounces.[99] We also demonstrated evaporative cooling in a red detuned dipole trap made from two crossed beams of light.[100, 101] Atoms can be Raman cooled in both red and blue detuned dipole traps.[102, 46] In our most recent work, over 10^6 atoms have been Raman cooled in a blue-detuned dipole trap to less than T_{recoil}. This is a factor of ~300 below what is needed for Bose condensation, but a factor of 400 improvement over the "dark-spot" magneto-optic trap phase space densities. Unfortunately, a heating process prevented us from evaporatively cooling to achieve Bose condensation with an optical trap. Recently, Wolfgang Ketterle and collaborators have loaded an optical dipole trap with a Bose condensate created in a magnetic trap.[103] With this trap they have been able to find the Feshbach resonances[104] calculated for sodium[105] in which the s-wave scattering length changes sign. Since this resonance is only one gauss wide, a nonmagnetic trap makes its detection much easier. Optical traps could also be used to hold Bose condensates in magnetic-field-insensitive states for precision atom interferometry.

Our ability to measure small velocity changes with stimulated Raman transitions suggested another application of atom interferometry. If an atom absorbs a photon of momentum $p_\gamma = h\nu/c$, it will receive an impulse $\Delta p = M\Delta v$. Thus $h/M = c\Delta v/\nu$, and since Δv can be measured as a frequency shift, the possibility of making a precision measurement of h/M dropped into our lap. After realizing this opportunity, I called Barry Taylor at NIST and asked if this measurement with an independent measurement of Planck's constant could put the world on an atomic mass standard. He replied that the first application of a precise h/M measurement would be a better determination of the fine-structure constant α, since α can be expressed as

$$\alpha^2 = (2R_\infty/c)(m_p/m_e)(M_{atom}/m_p)(h/M_{atom}).$$

All of the quantities[106] in the above relation can be measured precisely in terms of frequencies or frequency shifts.

Dave Weiss' thesis project was changed to measure h/M with our newly acquired Doppler sensitivity. The interferometer geometry he chose was previously demonstrated as an extension of the Ramsey technique into the optical domain.[84] If two sets of $\pi/2$ pulses are used, two interferometers are created with displaced endpoints as shown in Fig. 9. The displacement is measured in terms of a phase difference in the relative populations of the two interferometers, analogous to the way we measured the acceleration of gravity. This displacement was increased by sandwiching a number of π pulses in between the two pairs of $\pi/2$ pulses. With Brent Young, Dave Weiss obtained a resolution of roughly a part in 10^7 in h/M_{Cs}.[107, 108] In that work, systematic effects were observed at the 10^6 level, but rather than spending significant time to understand those effects, we decided to develop a new atom interferometer method with a vertical geometry to measure h/M.

Instead of using impulses of momentum arising from off-resonant Raman pulses, I wanted to use an adiabatic transfer method demonstrated by Klaus Bergmann and collaborators.[109] The beauty of an adiabatic transfer method

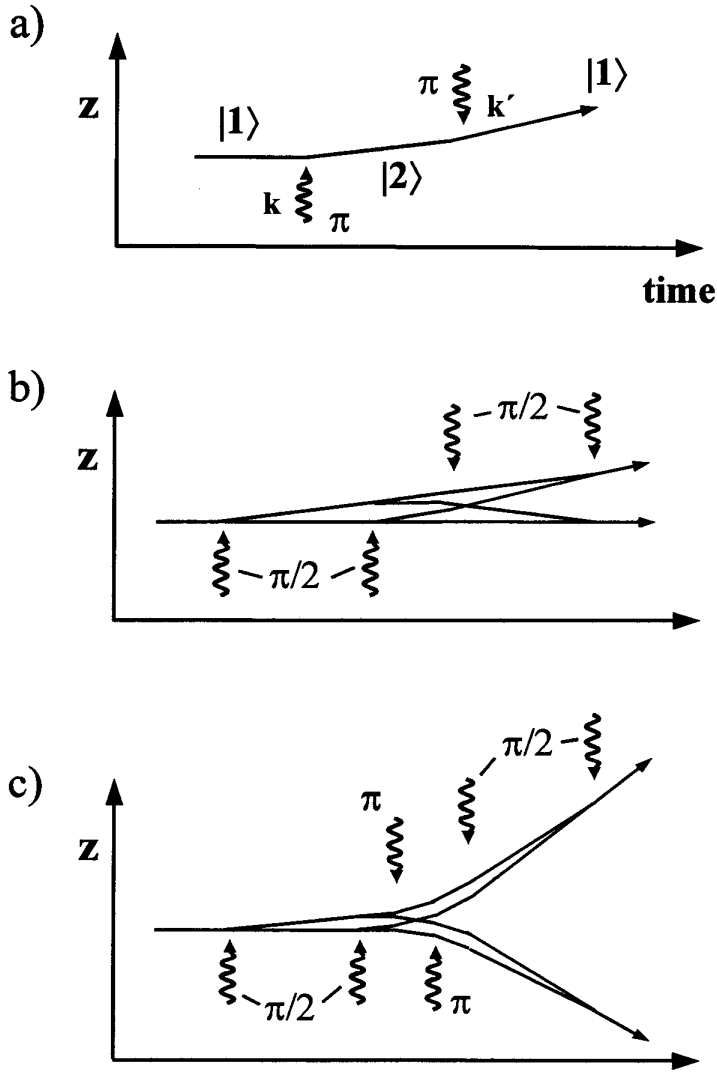

Figure 9 a. The basic method for measuring the recoil velocity requires two counterpropagating pulses of light. Because of energy and momentum conservation, the excitation light must satisfy $\hbar\omega - \hbar\omega_{12} = \mathbf{k}\cdot\mathbf{v} \pm (\hbar k)^2/2m$, where v is the velocity of the atom relative to the k-vector of the light and the sign depends on whether the initial state is higher or lower in energy than the final state. An atom at rest in ground state $|1\rangle$ is excited by a π pulse at frequency $\omega = \omega_{12} + \hbar k^2/2m$. The atom, recoiling with velocity $v = \hbar k/m$ in state $|2\rangle$ is returned back to $|1\rangle$ with a counterpropagating photon $\omega' = \omega_{12} - \hbar k k'/m + \hbar k^2/2m$. The two resonances are shifted relative to each other by $\Delta\omega = \omega' - \omega = \hbar(k+k')^2/2m$.

Figure 9 b. In order to increase the resolution without sacrificing counting rate, two sets of counterpropagating $\pi/2$ pulses are used instead of two π pulses. Thus, we are naturally led to use two atom interferometers whose end points are separated in space due to the photon recoil effect. Since the measurement is based on the relative separation of two similar atom interferometers, there are a number of "common mode" subtractions that add to the inherent accuracy of the experiment.

Figure 9 c. To further increase the resolution of the measurement, we sandwich many π pulses, each pulse coming from alternate directions. Only 2 π pulses are shown in the figure, but up to 60 π pulses are used in the actual experiment, where each π pulse separates the two interferometers by a velocity of $4\hbar k/m$.

is that it is insensitive to the small changes in experimental parameters such as intensity and frequency that adversely affect off-resonant π pulses. In addition, we showed that the ac Stark shift, a potentially troublesome systematic effect when using off-resonant Raman transitions, is absent when using adiabatic transfer in a strictly three level system.[110]

Consider an atom with two ground states and one excited state as shown in Fig 10 a. Bergmann *et al.* showed that the rediagonalized atom/light system will always have a "dark" eigenstate, not connected to the excited state. Suppose, for simplicity, that the amplitudes $A_1 = \langle e|H_{EM}|g_1\rangle$ and $A_2 = \langle e|H_{EM}|g_2\rangle$ are equal, where H_{EM} is the Hamiltonian describing the light/atom interaction. An atom initially in state $|g_1\rangle$ is in the dark state provided only ω_2 light is on. If we then slowly increase the intensity of ω_1 light until the beams have equal intensities, the dark state will adiabatically evolve into $\frac{1}{\sqrt{2}}[|g_1\rangle - |g_2\rangle]$. If we then turn down the intensity of ω_2 while leaving ω_1 on, the atom will evolve into state $|g_2\rangle$. Thus we can move the atom from state $|g_1\rangle$ to state $|g_2\rangle$ without ever going through the excited state.

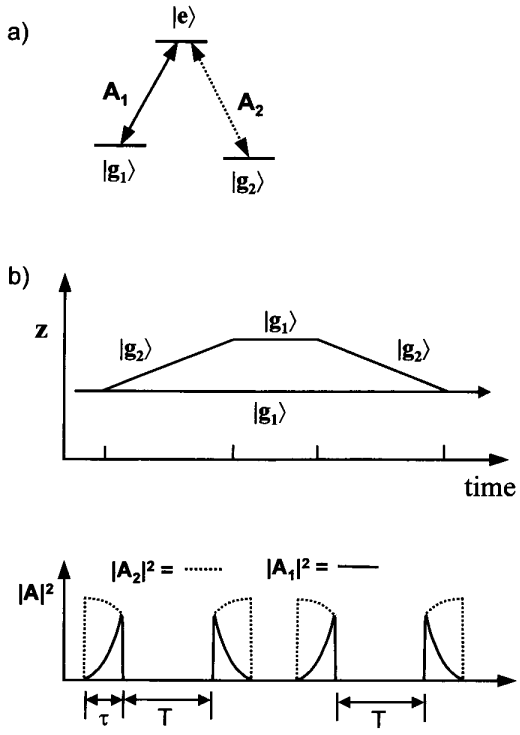

Figure. 10 a. An atomic system consisting of ground states $|g_1\rangle$ and $|g_2\rangle$ and an excited state $|e\rangle$ connected by amplitudes A_1 and A_2.

Fig. 10 b. In this space-time diagram of our adiabatic interferometer, the first interaction transfers the atom from $|g_1\rangle$ to the superposition state $(1/\sqrt{2})(|g_1\rangle + |g_2\rangle)$. In the second region, both frequencies are turned on simultaneously, projecting the atomic state $|\Psi(T+\tau)\rangle$ onto the dark superposition state $|\Psi(T+\tau)\rangle_D$ evaluated at the start of the pulse. This state is then adiabatically evolved into $|g_1\rangle$ by the light profiles shown in the second interaction region. To complete the interferometer, the sequence is repeated for adiabatic transfers with k_{eff} in the opposite direction as in Fig 9. Atom paths that do not contribute to the interference signal are not shown.

The work of Bergmann prompted Marte, Zoller and Hall[111] to suggest that this transfer process could also be used to induce a momentum change on an atom. Groups led by Mara Prentiss[112] and Bill Phillips[113] soon demonstrated the mechanical effect of this transition. In these experiments, the time-delayed light pulses were generated by having the atoms intersect spatially displaced laser beams. With atoms moving slowly in an atomic fountain, we could independently vary the intensity of each beam with acousto-optic modulators. This freedom allowed us to construct an atom interferometer using the adiabatic transfer method.[114] At different interaction points, differently shaped pulses are required, as shown in Fig. 10. For example, the first "adiabatic" beamsplitters require that ω_2 turn on first, but both ω_1 and ω_2 turn off in unison, while the second interaction point has both ω_1 and ω_2 turn on together and then ω_1 turn off first. With an adiabatic transfer interferometer, we are able to separate the two atom interferometers by up to ~250$\hbar$k units of momentum without significant degradation of signal.

Currently, our atom interferometric method of measuring h/M_{Cs} has fractional resolution of ~2 10^{-9} (1 ppb in α), corresponding to a velocity resolution less than 1/30 of an atom diameter/second. In terms of Doppler spectroscopy, this precision corresponds to a resolution in a Doppler shift of less than 100 μHz out of ~10^{15} Hz. We have been looking for systematic effects for the past five months and there are a few remaining tests to perform before publishing a value for h/M. The other measurements needed to determine α, such as the mass ratios m_e/m_p and m_p/M_{Cs}, and the frequency of the Cs D_1 **line will be measured with a fractional resolution better than ~10^{-9} in the near future. Curiously, some of the most accurate methods of determining α are** direct applications of three Nobel Prizes: the Josephson effect (56 ppb), the quantized Hall effect (24 ppb) and the equating of the ion-trap measurement of the electron magnetic moment with the QED calculation (4.2 ppb).[115]

OTHER APPLICATIONS IN ATOMIC PHYSICS

The topics I have discussed above are a small, personally skewed sampling of the many applications of the new technology of laser cooling and atom trapping. These techniques have already been used in nonlinear optics and quantum optics experiments. Laser-cooled atoms have spawned a cottage industry in the study of ultracold collisions. Atom traps offer the hope that radioactive species can be used for more precise studies of parity nonconservation effects due to the weak interactions and more sensitive searches for a breakdown of time-reversal invariance.

A particularly spectacular use of cold-atom technology has been the demonstration of Bose condensation in a dilute gas by Eric Cornell, Carl Weiman and collaborators,[116] and later by teams led by Wolfgang Ketterle[117] and Randy Hulet.[118] The production of this new state of matter opens exciting opportunities to study collective effects in a quantum gas with powerful diagnostic methods in laser spectroscopy. The increase in phase-space density of Bose condensed atoms will also generate new applications, just as the

phase-space density increase due to laser cooling and trapping started a number of new areas of research.

APPLICATIONS IN BIOLOGY AND POLYMER SCIENCE

In 1986, the world was excited about atom trapping. During this time, Art Ashkin began to use optical tweezers to trap micron-sized particles. While experimenting with colloidal tobacco mosaic viruses,[119] he noticed tiny, translucent objects in his sample. Rushing into my lab, he excitedly proclaimed that he had "discovered *Life*". I went into his lab, half thinking that the excitement of the last few years had finally gotten the better of him. In his lab was a microscope objective focusing an argon laser beam into a petri dish of water. Off to the side was an old Edmund Scientific microscope. Squinting into the microscope, I saw my eye lashes. Squinting harder, I occasionally saw some translucent objects. Many of these objects were "floaters", debris in my vitreous humor that could be moved by blinking my eyes. Art assured me that there were *other* objects there that would not move when I blinked my eyes. Sure enough, there were objects in the water that could be trapped and would swim away if the light were turned off. Art had discovered bugs in his apparatus, but these were *real* bugs, bacteria that had eventually grown in his sample beads and water.

His discovery was quickly followed by the demonstration that infrared light focused to megawatts/cm^2 could be used to trap live e-coli bacteria and yeast for hours without damage.[120] Other work included the internal cell manipulation of plant cells, protozoa, and stretching of viscoelastic cytoplasm.[121] Steve Block and Howard Berg soon adapted the optical tweezers technique to study the mechanical properties of the flagella motor,[122] and Michael Burns and collaborators used the tweezers to manipulate live sperm.[123] Objects on the molecular scale could also be manipulated with optical tweezers. Block *et al.* sprinkled a low-density coverage of kinesin motor molecules onto a sphere and placed the sphere on a microtubule. When the kinesin was activated with ATP, the force and displacement generated by a single kinesin molecule could be measured.[124] Related experiments on the molecular motor actin/myosin associated with skeletal muscles have also been performed by Jeff Finer, Bob Simmons and Jim Spudich[125] using an active feedback optical tweezers developed in my lab.[126] Steve Kron and I developed a method to hold and simultaneously view a single molecule of DNA by attaching polystyrene handles to the ends of the molecule.[127, 128] These early experiments introduced an important tool for biologists, at both the cellular and the molecular level. The applications of this tool in biology have exploded and may eventually overtake the activity in atomic physics.[129]

My original goal in developing methods to manipulate DNA was to study, in real time, the motion of enzymes moving on the molecule. However, once we began to play with the molecules, we noticed that a stretched molecule of DNA would spring back like a rubber band when the extensional force was turned off, as shown in Fig 11. The "springiness" of the molecule is due to

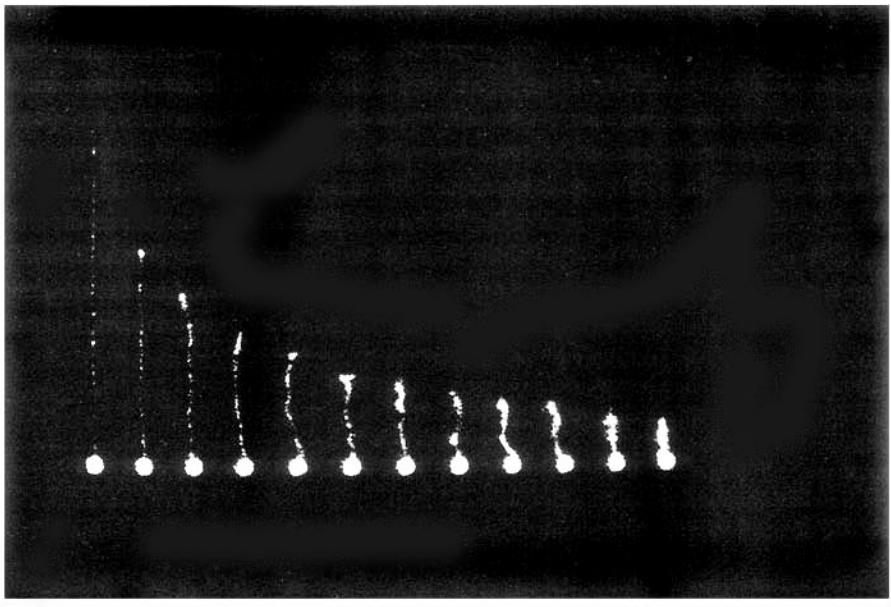

Fig. 11a: A series of video images showing the relaxation of a single molecule "rubber band" of DNA initially stretched by flowing fluid past the molecule. The DNA is stained with approximately one dye molecule for every 5 base-pairs and visualized in an optical microscope.[132]

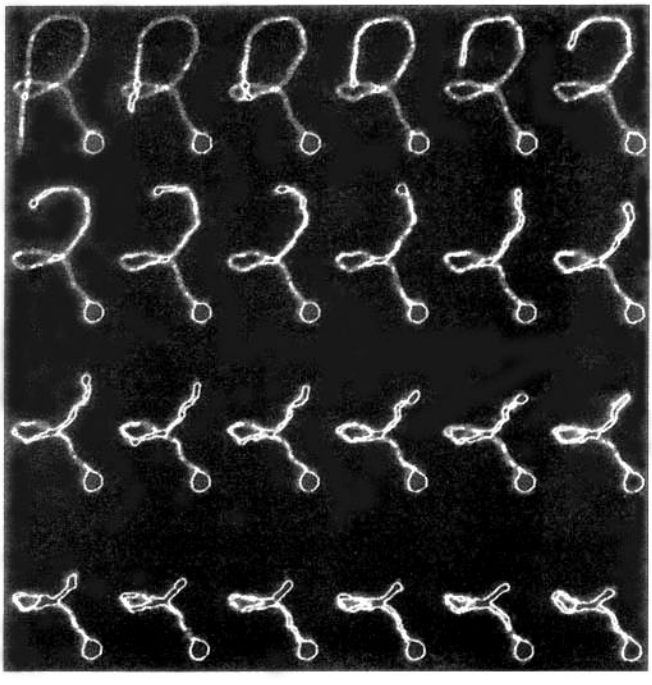

Fig. 11b: The relaxation of a stained DNA molecule in an entangled solution of unstained DNA. The molecule, initially pulled through the polymer solution with an optical tweezers, is seen to relax along a path defined by its contour. This work graphically shows that polymers in an entangled solution exhibit "tube-like" motion. [131] This result and a separate measurement of the diffusion of the DNA in a similar polymer solution[134] verifies de Gennes' reptation theory used to explain a general scaling feature of viscoelastic materials.

entropy considerations: the configurations of a flexible polymer are enumerated by counting the possible ways of taking a random walk of a large, but finite number of steps. A stretched molecule is in an unlikely configuration, and the system will move towards the much more likely equilibrium configuration of a random coil. Our accidental observation of a single-molecule rubber band created yet another detour: DNA from a lambda-phage virus is large enough to visualize and manipulate, and yet small enough so that the basic equations of motion describing a polymer are still valid. We stumbled onto a new way of addressing long-standing questions in polymer dynamics and began a program in polymer physics that is continuing today.[130, 131, 132, 133, 134, 135, 136, 137]

CLOSING REMARKS

The techniques I have discussed, to borrow an advertising slogan of AT&T, have enabled us to "reach out and touch" atoms and other neutral particles in powerful new ways. Laser beams can now reach into a vacuum chamber, capture and cool atoms to micro-kelvin temperatures, and toss them upwards in an atomic fountain. With this technique, a new generation of atomic clocks is being developed. Atoms quantum mechanically split apart and brought back together in an interferometer have given us inertial sensors of exquisite precision and will allow us to measure fundamental constants with unprecedented accuracy. Atom trapping and cooling methods allow us to Bose-condense a gas of atoms. With this condensate, we have begun to examine many-body effects in a totally new regime. The condensates are beginning to provide a still brighter source of atoms which we can exploit. Laser traps allow us to hold onto living cells and organelles within cells without puncturing the cell membrane. Single molecules of DNA are being used to study fundamental questions in polymer dynamics. The force and displacement generated by a dynesin molecule as it burns *one* ATP molecule can now be measured. This proliferation of applications into physics, chemistry, biology and medicine has occurred in less than a decade and is continuing, and we will no doubt see further applications of this new-found control over matter.

In 1985, when my colleagues and I first demonstrated optical molasses, I never foresaw the wealth of applications that would follow in just a few years. Instead of working with a clear vision of the future, I followed my nose, head close to the ground where the scent is strongest.

All of my contributions cited in this lecture were the result of working with the numerous gifted collaborators mentioned in this lecture. Without them, I would have done far less.

On a larger scale, the field of cooling and trapping was built out of the interwoven contributions of many researchers. Just as my associates and I were inspired by the work of others, our worldwide colleagues have already added immensely to our contributions. I consider this Nobel Prize to be the recognition of our collective endeavors. As scientists, we hope that others take

note of what we have done and use our work to go in directions we never imagined. In this way, we continue to add to the collective scientific legacy.

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