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MANIPULATING ATOMS WITH LIGHT

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ABSTRACT

Techniques have been developed for manipulating atoms with laser light. An atomic beam can be slowed, even brought to rest, and a gas of atoms can be refrigerated to the submilliKelvin regime with a laser cooling method. The atoms are generally highly polarized due to efficient optical pumping. The cooled atoms can be confined in free space with a trap. Although the densities so far achieved are low, the methods have potential applications for polarized sources and targets.

1. Introduction

The pressure of light prevents stars from collapsing, steers comets' tails and smashes deuterons in inertial confinement experiments. It can also be used to retard the motion of atoms so precisely that their temperature must be reckoned in units of microKelvins. Laser-cooling of atoms has been made possible by the development of dye lasers that are accurate in frequency and flexible in control, and by new methods from atomic physics. The motivation for this work is to study atoms in a new dynamical regime, to advance the precision of spectroscopy, and to develop new types of atomic clocks. Among the possible applications are polarized sources or targets, though for the present the densities are far too low to be useful. This paper constitutes a brief progress report on these developments.

2. Slowing Atomic Beams

When an atom absorbs a photon from light with frequency ν it experiences a momentum recoil of $\Delta p = h\nu/c$. The resulting velocity change, $\Delta v = h\nu/Mc$, is small: for sodium excited on its principal transition, $\Delta v \approx 3$ cm/sec. Experiments on the deflection of atomic beams by resonance radiation by Otto Frisch in the 1930's demonstrated the effect of momentum recoil, but until the past few years the recoil effect was merely a curiosity. However, with lasers recoil can be so large that it becomes a powerful tool for manipulating atomic motion.

If resonant laser light counterpropagates along an atomic beam, as shown in Figure 1, the atoms will successively absorb and emit photons. Absorption and stimulated emission result in zero net momentum transfer, since they occur in the same direction with opposite signs. Spontaneous emission, however, is isotropic, carrying away no momentum on the average. Thus, absorption followed by spontaneous emission results in a net slowing of the atomic motion.

The important parameter is not the speed change Δv but the acceleration $a = \gamma\Delta v$, where γ is the maximum photon absorption rate. γ is limited by the lifetime for the transition. If the transition is driven extremely hard, $\gamma \approx 1/2\tau$, where τ is the natural lifetime. (In a strong resonant field the atom spends approximately one-half of the time in the excited state and spontaneously radiates photons with a mean period of 2τ.) For sodium, $\gamma \approx 3\times10^7$/sec, and $a \approx 10^8$cm/sec^2. This acceleration, 10^5 times the acceleration of gravity, is large enough to stop atoms from a hot atomic beam oven in about a half meter.

The power to saturate the principal sodium transition, roughly 10 milliwatts/cm^2 within the natural line width, is readily available from a tunable dye laser. Nevertheless, there is a formidable technical challenge: the spread of speeds in a thermal atomic beam is huge- comparable to the mean speed- so that light which retards one particular velocity group will be out of resonance with the other groups. Furthermore, as any given velocity group slows down, the changing Doppler effect destroy the

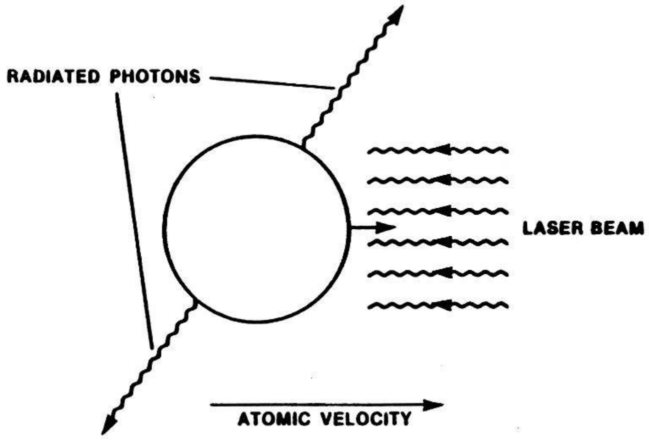

Figure 1. Laser cooling: momentum absorbed form the laser slows the atom. The momentum due to spontaneous emission averages to zero. (Courtesy of W. Phillips.)

resonance condition. To add to the problems, the hyperfine splitting in sodium is comparable to the thermal Doppler linewidth. Only one hyperfine level is excited optically. Unless precautions are taken, the excited atoms will radiate into the other hyperfine level and be effectively lost from the experiment.

Bill Phillips and his colleagues at the National Bureau of Standards, Gaithersburg, were the first to overcome these difficulties [1-3]. The Zeeman shift from a space-varying magnetic field was used to compensate the changing Dopper shift as the atoms slowed. The laser light, colinear to the atomic beam, was circularly polarized so that the entire population was rapidly pumped into the "stretched" state. Excitation took place as the atoms passed through a tapered solenoid which was shaped so that the field (and the transition frequency) monotonically decreased. The initial Zeeman shift was larger than the Doppler shift for all but the fastest atoms: the laser was tuned slightly below resonance for fast atoms at the input to the solenoid. As the atoms progressed through the solenoid, each velocity class entered into resonance at some particular value of the field. Thereafter, as the atoms slowed their changing Doppler shift was compensated by the changing Zeeman shift. As a result, at each point on the axis, all the atoms has the same velocity and a type of velocity focusing was achieved. Essentially the entire beam was brought to rest at a given point in the solenoid. "Rest" is used here in the sense that the longitudinal speed was reduced to zero: the transverse motion was unaffected. (The geometry is shown below, in Figure 4.)

An alternative method for achieving the same goal was devised by John Hall and his colleagues at the Joint Institute for Laboratory Astrophysics, Boulder [4]. The laser frequency was rapidly swept downward through a range large compared to the Doppler width of the atomic beam. The atoms' motions were retarded so that they stayed in resonance with the laser. By stopping the process at the right moment, the population was left at rest in free space.

Both of these experiments succeeded in stopping atoms, at least in one dimension, but for most purposes this is not enough. It is necessary to trap the atoms that are to be observed for long times. Neutral atom traps are difficult to devise because the forces due to electric or magnetic fields are feeble compared to those exerted on charged particles. However, if the atoms are moving slowly, then feeble forces are adequate.

3. Laser Cooling

Stopping an atomic beam with laser light does not really cool the atoms, for the transverse motion is unaffected. Some years ago Hansch and Schalow [5] proposed a method for literally refrigerating a confined gas using laser light. The method, which has now been realized, works as follows: Laser light, tuned slightly above resonance, is directed into a gas of atoms or trapped particles such as ions. Atoms moving toward the light are shifted into resonance by the Doppler effect. These atoms absorb photons and are retarded. Atoms moving away from the light, however, are unaffected. The result is a net slowing of the motion. If the process is repeated over and over, and if the particles make enough collisions to retain thermal equilibrium, then the gas is progressively cooled. Alternatively, laser beams can be directed along three perpendicular axes, separately cooling each component of motion.

In the absence of heating mechanisms, laser cooling continues until the atoms are moving so slowly that their Doppler shift becomes comparable to their natural linewidth. The limiting temperature is given by $kT \approx h\gamma/2$. In many cases this is less than one milliKelvin.

Laser cooling of atoms has been achieved by Steven Chu at AT&T Bell Laboratories [6]. The setup is shown in Figure 3. Three perpendicular standing wave laser beams were used to cool the low end tail of the velocity distribution of sodium atoms that were "puffed" from a solid sample by a separate laser pulse. The laser beams create a viscous force that is so strong that the gas is almost instantaneously cooled. (The effect has come to be called "optical molasses"). The temperature can be determined by turning off the laser light for a short period, and then turning it on to reveal how large the cloud has grown by diffusion. The cloud is easily visible under the laser light, allowing direct measurement of the diffusion constant. A temperature of 240 microKelvin has been observed [6].

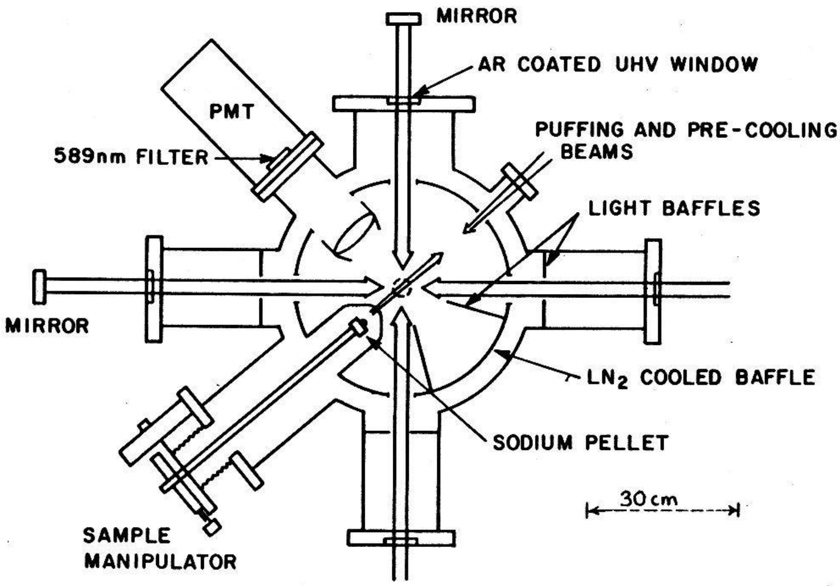

Figure 2. Laser-cooling: the creation of "optical molasses". (From ref. 6.)

4. Atom Traps

Paramagnetic atoms can be confined magnetically through the magnetic interaction $W = -\mu\cdot B$. Trapping requires an extremum of the energy in free space. Earnshaw's theorem prohibits a maximum in the field, but it does not prohibit a minimum. Figure 3 shows the geometry of a trap that has been used to trap laser-cooled sodium [7]. The quadrupole field has a zero at its center: it is evident that the magnitude of the field increases in every direction. The direction of the field changes azimuthly, and the atom spin must be able to follow the changing direction as the atom moves. Atoms passing through the center cannot meet this condition, and they are rapidly lost. Other atoms remain trapped as long as they do not make collisions which could drive them through the center. Thus the trap is only suitable for low densities. However, this impediment is not fundamental: Harald Hess describes elsewhere in these proceedings a trap designed to confine spin-polarized hydrogen at high densities that does not suffer from this problem.

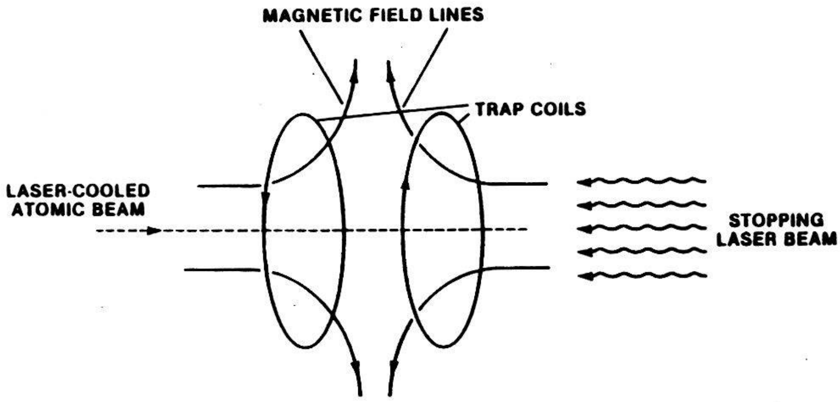

Figure 3. Neutral particle trap. A laser-cooled atomic beam, incident from the left, is stopped by a pulse of laser light from the right. The stopped atoms are confined near the magnetic field minimum formed at the center of the two opposed trap coils. (Courtesy of W. Phillips.)

The need to cool atoms before attempting to trap them is evident from energy considerations: equating the trap energy to the thermal energy yields a characteristic trap temperature $T \approx \mu B/k$ where μ is the Bohr magneton and k is Boltzmann's constant. For a 1 tesla trap, which is hefty but feasible, T = 0.65K. Thus, the atoms need substantial precooling. In the first demonstration of trapping by Phillips and his colleagues [7], an atomic beam was brought close to rest by the method described above, and the retarding laser was momentarily switched off (see figure 4). The atoms drifted out of the solenoid into the trap, where they were brought close to rest by an additional retarding pulse. The trapped atoms were lost with a characteristic time of about one second, but this was essentially limited by the poor vacuum, not by any trap instability.

5. Prospects

Cooling of atoms by laser light, and confining cooled atoms in a pure magnetic trap, have both been demonstrated. The densities achieved so far are modest, typically in the range of 10^6atoms/cm^3, but one can look forward to much higher densities. Furthermore, many other cooling techniques and trapping methods are being explored [8]. It is too early to start considering whether these methods will have eventual applications to the construction of polarized sources or targets, but the new found ability to confine highly polarized atoms in essentially free space is certainly suggestive.

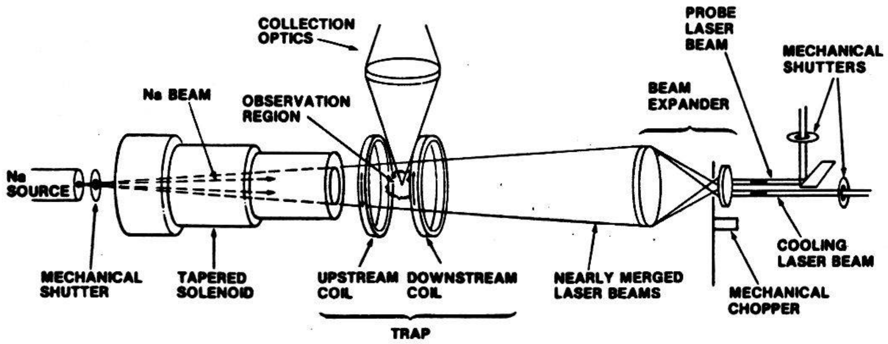

Figure 4. Trapping of laser-cooled atoms using the trap shown in Fig. 3. (From ref. 7.)

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