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Cooling and Trapping Neutral Atoms with Radiative Forces

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Abstract Techniques to slowand trap neutral atoms at high densities with radiative forces are discussed in this review article. It isshown that the radiative force on an atomic system has two components, one coming from the momentum transferred from the photon to the atom and the other resulting from the interaction of the transition dipole moment with the radiation field gradient. Among several methods of laser cooling, we emphasize Zeeman tuning of the electronic levels and frequency-sweeping techniques. Trapping of neutral atoms is another interesting subject discussed in this review. We present recent results obtained in light and magnetic traps. Finally, techniques to further cool atoms inside traps are presented and the future of laser cooling of neutral atoms by means of radiation pressure is discussed.

1. INTRODUCTION

The development of techniques to trap and cool ions has revolutionized atomic physics during the last decade[1-4]. The ability to isolate a single ion and recuce its thermal motion to only a few milli-Kelvin of temperature allows the suppression of the first and second order Doppler shifts, yielding spectroscopic measurements and time standards of unprecedented accuracy.

The advent of several successful experiments demonstrating cooling of trapped ions suggested the possibility of doing the same for neutral atoms. The neutral character of trapped species opens a new door in the study of effects where high densities, not achievable with ions, are useful or necessary, such as in ultracold atomic collisions and collective quantum effects. Moreover, cooling and trapping of neutral atoms will make spectroscopic measurements easier. Substantial improvements in the accuracy of atomic clocks and measurements of fundamental constants are ultimately feasible. The possibility of studying collisions with slow atoms will provide the investigator with a better understanding of atomic forces and chemical bonds between atoms. At

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high densities, wave packets representing the atoms start to overlap in such a way that quantum effects should manifest thernselves. For a system of bosons, the phase transition known as Bose-Einstein condensation should be observed, demonstrating a very importantpredictionof Quantum Statistics.

In the last five years a number of experiments on the cooling of atomic beams have been performed with different approaches. Pulsed stomic beam deceleration due to laser radiation was first reported in 1980 in an experiment where the laser frequency was scanned to compensate for the reduction of the atomic velocity[5]. Further improvement of this method has allowed better deceleration of atomic beams[6,7].

The development of a scherne to produce a continuous flow of cold atoms occured in 1982, when a group from the National Bureau of Standards (NBS) in Gaithersburg was able to change the atomic resonance frequency in synchronism with the reduction of the velocity[8]. In this technique, the atomic frequency is changed by means of an inhomogeneous magnetic field and the laser frequency is kept constant.

One of the most interesting applications for slow atoms is trapping. The first observation of trapped atoms occurred in 1985 when a pulse of cold atoms was used to load a magnetic trap[9]. In that experiment, about 10^3 atoms were trapped in a volume of 30 cm^3 for about 0.8 s, but the temperature of the atoms was not measured. Recently, a group from MIT was able to increase the trapping time to 6 minutes, accumulating up to 10^9 atoms inside a trap whose volume was about 60 cm^3 and the temperature of the trapped atoms was estimated to be 10 mK [10]. In experiments using optical traps [11], densities as high as 10^{11} atoms per cubic centimeter and temperatures as low as 240 μK have been achieved.

This paper aims to critically review the current efforts to achieve very cold atoms at high densities. We start bypresentingbasic equations describing the interaction between atom and radiation. This is done in section 2. Section 3 reports on the techniques used up to now to slow neutral atoms and the experimental problems related to the cooling process. Magnetic and light traps for these cold atoms are discussed in section 4. Techniques to further cool the atoms inside traps

and the future of laser cooling are discussed respectively in sections 5 and 6.

2. RADIATIVE FORCES

The forces exerted on an atomic system due to interaction with radiation can be classified into two groups: spontaneous and induced forces. The spontaneous forces originate from the momentum transferred during the photon absorption. Each photon absorbed or emitted during a trançition transfers a momentum $\hbar\vec{k}$ to the atom in a time that depends on the laser intensity, laser detuning and excited state lifetime. The maximum spontaneous force occurs when the atom is pumped above saturation and it is proportional to $\hbar\vec{k}/2\tau$, where τ is the excited state lifetime. The induced force comes from the interaction of the induced electric dipole during the electronic transition with gradients in the radiation intensity. The usual approach used to calculate radiative forces consists in treating the atom as a two-level quantum system and the radiation as a classical electromagnetic field. Let us assume that an electromagnetic field of polarization $\vec{e}$ and amplitude

$$E(\vec{R},t) = \frac{1}{2}\, E(\vec{R})\ \exp i\left[\Theta(R) + \omega_L t\right] + \text{c.c.} \qquad (1)$$

interacts with a two-level atom located at position $\vec{R}$ and with velocity $\dot{\vec{R}}$. Using the Heisenberg representation and Ehrenfest's theorem one can show that the force on the atom due to the interaction with radiation is given by

$$\vec{F} = \langle \vec{\mu}.\vec{e} \rangle\, \nabla E(\vec{R},t) \qquad (2)$$

where $\vec{\mu}$ is the electric dipole operator. After some mathematical manipulation[13-15] we get

$$\vec{F} = -\frac{\left[\hbar A\Omega^2\nabla\Theta + \hbar(\Delta+\dot{\Theta})\nabla\Omega^2\right]}{\left[4(\nabla+\dot{\Theta})^2 + A^2 + 2\Omega^2\right]} \qquad (3)$$

where

$$\Omega = \mu E(\vec{R},t)/\hbar$$

is the Rabi frequency,

$$\Delta = \omega_L - \omega_0$$

is the detuning between the laser frequency and the atomic resonance frequency

$$\omega_0 = (E_2 - E_1)/\hbar \quad ,$$

A is Einstein's A coefficient (for a two-level atom it also represents the linewidth) and Θ is the phase of the wave defined in eq. (1). We can single out two contributions from the above expression: the gradient of the phase stands for the spontaneous force and the gradient of the intensity ($\Omega^2 \propto$ Intensity) represents the induced force.

Eq. (3) holds for any excitation field. For the sake of simplicity, we will consider only the case of a plane wave. With this assumption we may write

$$\vec{E}(\vec{R},t) = E_0 \vec{e} \cos(\vec{k}.\vec{R} - \omega_L t) \quad ,$$

the Rabi frequency

$$\Omega = \mu E_0/\hbar$$

is a constant and the phase is

$$0 = -\vec{k}.\vec{R} \quad .$$

Under these conditions eq. (3) becomes

$$\vec{F} = \frac{A\,\Omega^2}{[4(\Delta - \vec{k}.\dot{\vec{R}})^2 + A^2 + 2\Omega^2]}\,\hbar\vec{k} \qquad (4)$$

which has a saturation value at $A\hbar k/2$. This saturation in the spontaneous force was expected since the atom cannot cycle faster than $A/2$, which corresponds to having it half of the time in the excited state and half of the time in the ground state. The knowledge of the saturation valu'e is very important since it determines the minimum distance for an effective deceleration to take place.

The first term in the denominator is velocity dependent and, as the atom slows down, it represents a changing Doppler shift which

sets the atom out of resonance. In order to keep the atom resonant with the laser beam, the Doppler shift has to be compensated either by changing the laser or the atom frequency. The way of doing this is described in the next section.

3. METHODS OF SLOWING ATOMS

The use of radiation pressure to modify the velocity of atoms has a long history[16]. The first authors to propose the useof radiation pressure for the cooling of a gaseous sample were Hansch and Schawlow[17]. The absorption of a photon from a quasi-resonant laser beam produces a velocity change, in an atom with mass M, given by $\Delta\vec{v} = \hbar\vec{k}/M$ (= 3 cm/s for the D_2 1ine of sodium) which has the same direction as the incident beam. The spontaneously re-radiated photon will change the velocity of the atoms by the same amount, but in a random direction. Ifweconsider severa1 cycles of absorption and emission, there is nonetcontribution to the velocity coming from spontaneous emission, but there is one from absorption. The process is represented in fig.1.

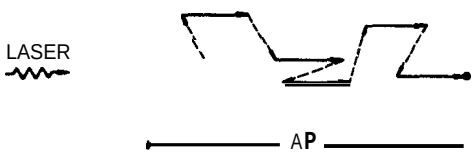

Fig.1 - Absorption-emission cycles in momentum space for a resonant atom in a laser beam. The full line represents the momentum change after the absorption while the dashed line stands for the change after spontaneous emission. ΔP is the net momentum transferred to the atom.

Absorption followed by stimulated emission has no effect on the atomic velocity since absorption and emission in this case occur in the same direction. However, the existence of a gradient in the amplitude of the wave generates a force during the stimulated process (called induced, dipole or gradient force).

The spontaneous force associated to the momentum change represented in fig. 1 can be used to decelerate atoms. Shining a laser against the propagation of an atomic beam one is able to reduce the

velocity of the atoms during the absorption, despite the net heating due to the statistical nature of the emission. Let us consider a typical thermal (T - 1000K) sodium beam. The maximum of the velocity distribution is at about 100 m/s. Since each photon will reduce the velocity by Δv = 3 cm/s, the number of required scattering events to bring an atom to rest is $v_0/\Delta v \simeq 33.000$. At this point we find the first experimental problem. Since the laser frequency is fixed, there will be a changing Doppler shift as the atom starts to slow down and it will scatter only a few photons before going out of resonance. The Doppler shift in the case where the atomic velocity and the photon momentum are antiparallel is given by

$$\omega_L' = \omega_L \left(\frac{1 + v/c}{1 - v/c} \right)^{1/2} \simeq \omega_L \left(1 + \frac{v}{c} \right) \tag{5}$$

where ω_L is the laser frequency, ω_L' the laser frequency in the atom rest frame and c the speed of light. Therefore, the atom sees the laser light blue shifted. To a first approximation, this shift is given by

$$\Delta\omega = \frac{\omega_L}{c} v \tag{6}$$

We expect successive absorptions to occur (at a fast rate) until the change in frequency due to the Doppler shift ir of the order of the natural linewidth. For sodium, the natural linewidth is $A = 6.8 \times 10^7$ rad/s, meaning a variation of velocity of 589 cm/s before the atom goes out of resonance. This implies that after the absorption of about 200 photons, the changing Doppler shift has swept through the natural linewidth and the atom falls out of resonance. If we would wait for a long time the atom could absorb more photons, but this creates an experimental problem because it involves too long an interaction region. In conclusion, the number of photons scattered will be a small fraction of the total number needed for an appreciable deceleration.

In order to keep the atom in resonance with the radiation during the whole process, it is required that the laser frequency in the rest frame of the atom be always close to W. To keep the condition

$$\omega_0 = \omega_L (1 + v/c)$$

valid as v changes, it is necessary to change either ω_0 or the laser frequency ω_L. The choice between these two possibilities originates the two available methods of slowing an atomic beam whicharedescribed below.

a) Spatial Zeeman tuned technique[8]

This technique uses a spatially varying magnetic field to change the resonance frequency ω_0 in such a way that the Zeeman shift compensates any change in the velocity. In the presence of a magnetic field B, the resonance frequency of the atom is given by

$$\omega(z) = \omega_0 + \gamma B(z) \tag{7}$$

where γ is a constant and the linearity of the Zeeman shift can be arranged by selecting a specific atomic level. For Na we have to cycle the atom between the levels $3S_{1/2}$ $(F = 2,\ M_F = 2)$ and $3P_{3/2}$ $(F = 3,\ M_F = 3)$, using circularly polarized light. Comparing $\omega(z)$ with the Doppler shifted laser frequency, we have the matching condition between velocity and B-field at each point z

$$\omega_L\left(1 + \frac{v}{c}\right) = \omega_0 + \gamma B(z) \tag{8}$$

The atomic velocity as a function of z is given by

$$v(z) = (v_0^2 - 2az)^{1/2} \tag{9}$$

where v_0 is the initial velocity and a is the deceleration of the atom. Substituting eq. (8) into eq. (9), the magnetic field which compensates the Doppler shift at any point is

$$B(z) = B_b + B_0\sqrt{1 - \beta z} \tag{10}$$

where

$$B_b = \frac{\Delta}{\gamma}\ ,\ B_0 = k\frac{v_0}{\gamma} \text{ and } \beta = \frac{2a}{v^2}\ .$$

The deceleration a cannot take any value; it has a maximum allowed value which corresponds to the maximum transition rate, i.e., $a_{max} = (1/2)\hbar k A/M$. If a system is designed to operate with $a > a_{max}$, the atom will not be able to follow the magnetic field profile, since it cannot cycle between the ground and the excited states faster than $A/2$. B_0 corresponds to the field which produces a Zeeman shift equal to the Doppler shift for atoms travelling at v_0. The distance necessary to stop an atom with v_0 is $1/\beta$. Atoms moving faster than v_0 arenot affected at all, while slower atoms start to be affected when the field has the correct strength to compensate their Doppler shift. In conclusion, all atoms will have the same velocity at each point along the trajectory after they reach the resonance condition. Due to this feature, all atoms are brought to rest at the same place. The first group to report successful use of the Spatial Zeeman tuned technique was thegroup from NBS-Gaithersburg [8]. Their experimental set-up is shown in fig.2.

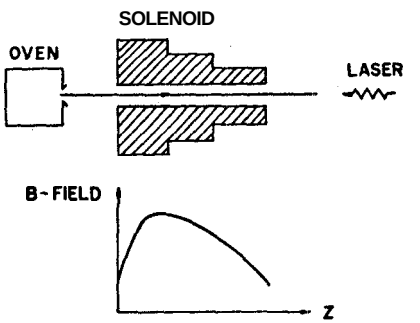

Fig.2 - Schematic view of the laser cooling experiment of Philips et al[8].

In thiç' technique, the magnetic field is provided by asolenoid wound with more turns in the region closeto the atomicsource, yielding a magnetic field with the profile given by eq. (10). A typical result[18] of the Zeeman cooling scheme is depicted in fig. 3. The dashed curve shows the origina1 velocity distribution when the laser is off. After turning the laser on, faster atoms are decelerated into a narrow velocity group as seen in the full line curve.

The net atomic velocity change is established by the rnagnetic field profile. Foragiven field distribution the initial andfinal velocities can be chosen by varying the cooling laoer detuning. Fig. 4

shows a number of cornpressed velocity distributions obtained with several detunings[19].

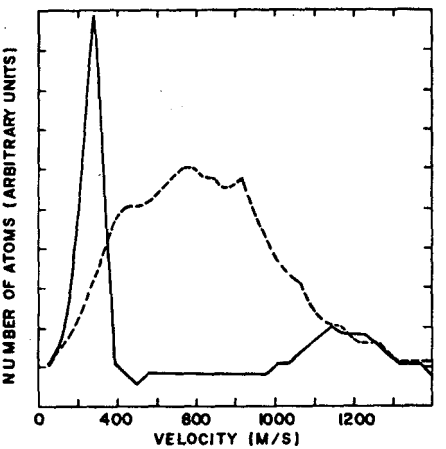

Fig.3 - Velocity bunching observed in the original velocity distribution with the spatial Zeeman technique.

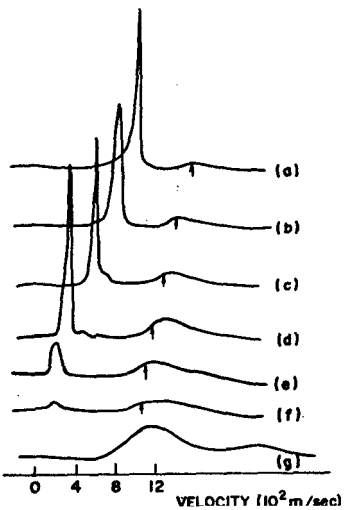

Fig.4 - Laser-cooled velocity distributions for different laser tunnings. Thehighest velocity resonant with the laser in each case is indicated by the arrows. Trace (g) is the uncooled velocity distribution.

b) Frequency-sweeping technique

The first proposal forscanning the laser frequency in order to compensate the changing Doppler shift when the atomic beam slows down was made by Letokhov and Minogin[20]. Because the laser must sweep quickly and over a large range (~ 2 GHz for Na), this technique is known as *frequency chirping*[6].

The velocity of a slowing atom, expressed as a function ofits changing transition frequency, can be obtained from eq. (5)

$$v(t) = c\left[1 - \frac{\omega_L(t)}{\omega_0}\right] \qquad (11)$$

where the resonance frequency ω_0 is now kept constant, and both velocity and laser frequency are time dependent. The change in velocity is given by the derivative of eq. (11) with respect to time. On the other hand, the change in velocity of a two-level system due to the momentum transferred during the absorption is given by

$$\dot{v}(t) = - \frac{\hbar \omega_L A}{2Mc} \tag{12}$$

provided that the laser intensity is high enough to saturate the transition. In order to determine the time dependence at $\omega_L(t)$ and $v(t)$, we solve the resulting differential equation

$$- c \frac{\dot{\omega}_L(t)}{\omega_0} = - \hbar \omega_L \frac{A}{2Mc} \quad \text{or} \quad \dot{\omega}_L - \alpha \omega_L = 0 \tag{13}$$

with

$$\alpha = \hbar\omega_0 A/2Mc^2 \quad .$$

The solution of eq. (13) is

$$\omega_L(t) = \omega_s e^{\alpha t} \quad ,$$

where ω_s denotes an initially given starting frequency. If we consider Na, with $3S_{1/2} \rightarrow 3P_{3/2}$ being the cooling transition, we get $a = 3\times10^{3}/s$. The stopping time is 1 ms for atoms with an initial velocity of 1000 m/s. Comparing this time with α, we see that the exponential behaviour of the frequency can be almost entirely replaced by a linear approximation. So, the laser frequency varies as

$$\omega_L = \omega_s(1 + \alpha t) \tag{14}$$

Due to the frequency scan and the corresponding deceleration, all velocities less than the starting velocity ($v_s = c(1 - \omega_s/\omega_0)$) will ultimately come into resonance and will join the group of already slowed atoms. The basic idea is represented in fig. 5.

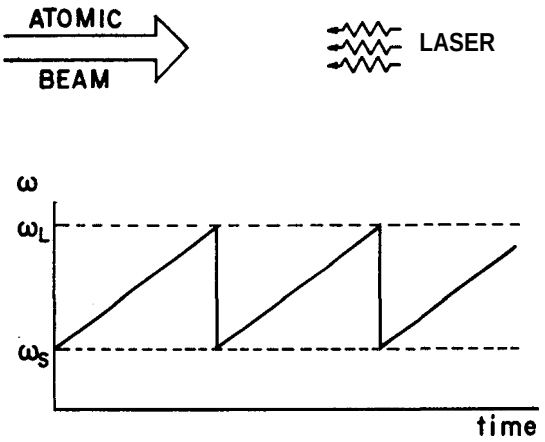

Fig.5 - Diagramof the laser cooling technique using frequency-sweeping.

Severa1 groups have already used the *frequency* ***chirping*** technique successfully. Work with sodium has been performed by two independent groups at NBS-Boulder[6] and at USSR-Moscow[21]. Experimental results achieved by the former group are presented in fig.6. This technique has also been used by Watts and Wieman with a diode laser and a beam of cesium atoms[22]. Recently, the deceleration of a Rb beam with this technique has been reported[23].

The disadvantage of the *frequency chirping* technique lies in its pulsed nature which results in a small number of slow atoms produced per unit time.

c) Other techniques

Although the deceleration of an atomic beam using frequency chirping or Zeeman tuning have both been used successfully to overcorne the changing Doppler shift, other methods are also possible. One can use a *white* light source rather than a single frequency laser. The optical spectrum of such a source must cover the entire Dopplerwidth of the atomic beam. In this way, regardless of the atom velocity, there is always some light resonant with it to produce deceleration. Such a source can be a multi-mode laser[24]. The required power has to be higher

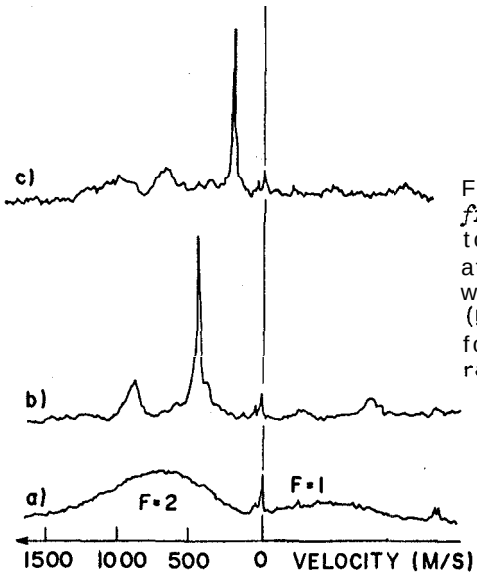

Fig.6 - Experimental results of the *frequency chirping* techníque applied to sodium. Trace (a) represents the atomic beam velocity distribution when the cooling laser if off. Traces (b) and (c) show slow atoms produced for two different frequency sweeping ranges.

than for the other techniques, since the laser must provide saturation intensity in each of the modes separated by about one natural 1inewidth and extending over the Doppler width. For Na atoms this is about 200 modes. The *white* light technique provides no spatial compression ofthe atoms; all velocity groups decelerate at the same rate for all points in space.

Another possibility for overcoming the changing Doppler shift is a variation on the Zeeman tuning technique. The magnetic field can be uniform in space but modulated in time[19,25]. This requires a rapid change in magnetic field, which is an experimental problem, but it has the advantage of being able to decelerate different kinds of atoms by modulating at different rates.

d) The optical pumping problem

During the cooling process, the changing Doppler shift is not the only difficulty that we face. Since the atom is nota real two-level system, optical pumping is another important problem to be considered. In order to analyse this situation, let us consider a Na atom, whose relevant energy levels are shown in fig.7.

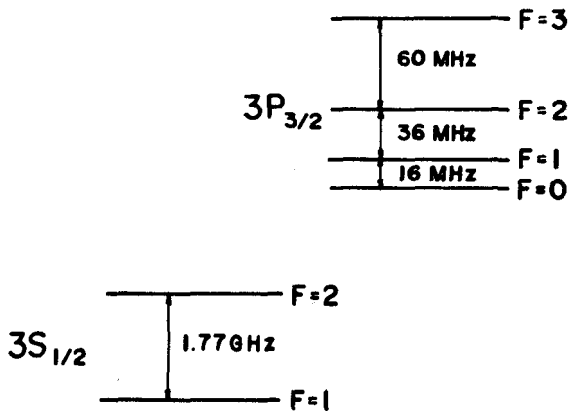

Fig.7 - Hyperfine structure of the relevant electronic levels of Na.

If we choose the cooling process to take place shift is $S_{1/2}(F=2) \rightarrow P_{3/2}(F=2)$ transition, after the first excitation the system can also decay to the $S_{1/2}(F=1)$ state and the laser cannot reexcite the atom because it is too far out of resonance (about 170 linewidths). This makes it impossible for the atoms to scatter the necessary number *of photons to decelerate significantly.*

If the initial excitation is $3S_{1/2}(F=2) \rightarrow 3P_{3/2}(F=3)$, the electric dipole selection rule for $F(\Delta F = \pm 1, 0)$ will drive the atom back to F=2 and the system can be easily reexcited. The $3P_{3/2}(F=2)$ state is only 60 MHz away from the F=3 state, which can lead to off-resonant excitation out of the $3S_{1/2}(F=2)$ level. For every few hundred excitations to the F=3 level, one excitation to F=2 is expected and after that, the atom may decay to the $3S_{1/2}(F=1)$ state, ending the absorption process. In this way, optical pumping limits the cooling process as much as the changing Doppler shift does.

The first obvious solution to this problem is the use of an auxiliary laser tuned to the $3S_{1/2}(F=1) \rightarrow 3P_{3/2}(F=2)$ transition as a *recovering* beam, as has been done for laser cooling of ions[26].

A second alternative to solve the problem is to use the transition selection rule for the magnetic quantum number m_F[9,10]. Assuming the quantization axis to be along the propagation of the laser beam and

using right (or left) circularly polarized light, conservation of angular moment requires that $\Delta m = +1$ (or -1). Atoms originally in the $3S_{1/2}$ $(F=2, m_F=2)$ state will be excited only to $3P_{3/2}$ $(F=3, m_F=3)$ and can only decay back to the original state. The behaviour is like that of a two-level system. If the atom starts in any of the m_F states of the $3S_{1/2}$ $(F=2)$ manifold, the cyclic interaction will transfer the system to the $m_F=2$ state[27]. The use of this solution requires the presence of a magnetic field to set the quantization direction and m_F as a good quantum number. Therefore, it is very suitable for the Zeeman tuning technique, since the magnetic field is already there.

Bad aligment between the laser beam and the magnetic field will produce *wrong* transitions and the two-level picture fails. The presence of a *bias* field helps to separate the different m_F levels, decreasing the probability of excitations to wrong levels by taking them further off resonance.

For the case of the frequency sweeping technique, the optical pumping problem must be solved using an auxiliary laser to recover atoms that suffer wrong transitions. The presence of side band in the slowing laser can also be used for this purpose. There are other approaches to the problem, like using RF to recover the $S_{1/2}$ $(F=1)$ atoms, but we will not describe them here. One should keep in mind that a good deceleration scheme has to take into account both optical pumping and the changing Doppler shift.

4. TRAPPING NEUTRAL ATOMS

At the present time there are two different ways for trapping neutral atoms. One of them uses the magnetic force acting in the system when it is in a region of inhomogeneous field[9,10,28,29]. The second alternative uses the interaction of radiation with the atom to confine it[30,31]. Both ways have already been successfully used and will be described briefly here.

a) Magnetic traps

Magnetic traps are based on the fact that the electronic ground states of certain atoms with unpaired electron spin have

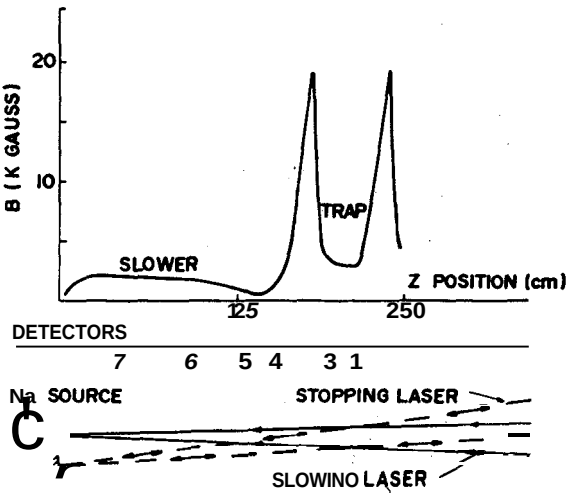

Fig.10 - Arrangement of the longitudinal magnetic fields, laser beams and fluorescence detectors used in the experiment for continuous stopping and trapping of neutral atoms.

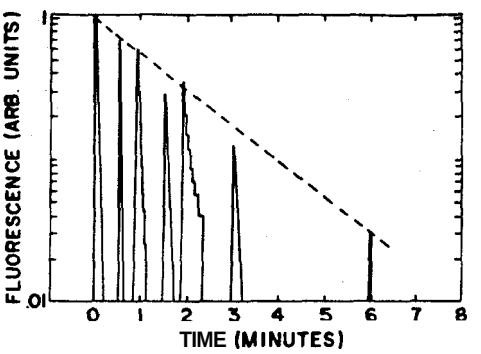

Fig.11 - Fluorescence of trapped atoms produced by unblocking the stopping laser after various trapping times.

Ashkin[30] and consists of two counter-propagating laser beams with their focuses as shown in fig.12. In this configuration there is an axial restoring force (spontaneous force) and a transverse restoring force due to the radial field gradient.

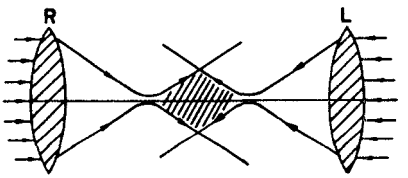

Fig.12 - Light trap proposed by Ashkin[30].

A second possibility for optical trap consists in using only the induced dipole force as the restoring force. Consider a single focused gaussian laser beam detuned severa1 hundred 1inewidths below resonance. An atom close to the focus will feel a restoring force towards it, since the intensity decreases from the focus in all directions. The first observation of optically trapped atoms was made by S.Chu et *al* [35] with the help of the *optical molasses* which is a three dimensional viscous confinement of atoms by resonant radiation pressure.

A pure spontaneous light force optical trap has been recently demonstrated by E.Raab et *al*[11]. In this trap, six laser beams coming from the $\pm x$, $\pm y$ and $\pm z$ directions are superposed to a weak magnetic field produced by a *spheroidal quadrupole*, in such a way that atoms interact more strongly with the beam opposing their velocities, producing a restoring force towards the center of the trap.

The configuration discussed above was originally introduced by Pritchard et *al*[31] as a way of overcoming the so called *optical Earnshaw* theorem formulated by Ashkin and Gordon[36]. The idea behing this theorem is as follows: in the absence of radiation sources the divergence of the Poynting vector of a stationary laser beam must be zero. Therefore, if the force is proportional to the laser intensity, it must also be divergenceless, thus ruling out the possibility of having an inward force everywhere on a closed surface. Ashkin and Gordon proved this theorem for the scattering force on particles with a *scalar polarizability* whose dipoles depend linearly on the field. This condition assumes the scat-

an energy that grows with magnetic field, producing a force on theatom toward the minimum of the field. In fig.8 we show the ground state hyperfine levels of atomic hydrogen. As we can see, the levels $S_{1/2}$ (F=1, m_F=1) and $S_{1/2}$ (F=1, m_F=0) have a positive slope with increasing magnetic field, and the atoms in these states are *pushed* towards the minimum in the field. For this reason they are called *weak field seekers*. In the same way, atoms with negative slope are forced towards higher magnetic fields, and therefore they are called *strong field seekers*. We could trap particles in any of these states, needing only to produce a minimum or maximum of magnetic field. Unfortunately, this is not possible because, in free space, the total magnetic field can only have a minimum and therefore only *weak* field seekers can be trapped in a static field. Dynamic traps have been proposed to trap both species[32]. The ability to trap only particles which are drawn to weak field is not necessarily a serious limitation since the spontaneous decay rate for the spin up-spin down transition is about 10^{-10}/s. However, various spin changing collisions may limit the maximum attainable density.

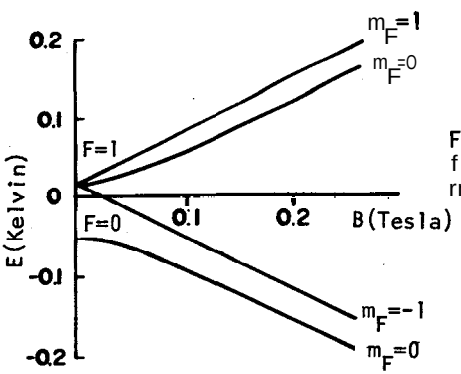

Fig.8 - Energies of hydrogen hyperfine states as a function of the rnagnetic field.

The first static magnetic field trap for neutral atomswas recently demonstrated at NBS and it consists of a pair of Helmholtz coils connected backwards so that a zero field is produced at the center. This trap, shown in fig.9, has the disadvantage of having a B=0 point at the minimum. As the atom travels through this point, a non-adiabatic transition can take place, leaving the atoms in a untrapped state and

therefore acting as a leak mechanism for the trap. At the B=0 point, the hyperfine sublevels (represented as the F=1 manifold in fig.8) will collapse to the same energy. Therefore, an atom in a $m_F=1$ state, which is a trapped state since the energy increases with the magnetic field, may leave the region is an untrapped $m_F=-1$ state. This problem can be solved using a *magnetic bottle* configuration with no point of zero field[10,29,33]. Several different magnetic trap configurations for neutral atoms have already been proposed[34].

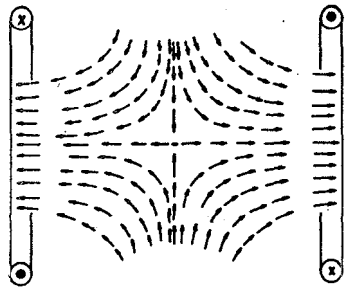

Fig.9 - Magnetic trap used by Migdall et al[9].

The arrangement of the longitudinal magnetic fields, laser beams and fluorescence detectors used in the experiment of ref. 10 is shown in fig.10. As a first step, the atoms are slowed from 1000 to 200 m/s in the slowing field. These slow atoms go inside the trap region where they are stopped by means of a second laser. When the correct laser frequency is used, the trap starts filling up and the fluorescence measured by detectors 1, 2 and 3 increases dramatically. In order to find out for how long atoms can be trapped, the following sequence of measurements is made: a) lasers on to fill the trap, b) lasers off for a variable period of time and c) stopping laser backon to probe the remaining trapped atoms. Fig. 11 shows the fluorescence observed for several trapping times.

b) Light traps

The method of optically trapping atoms is based on radiation pressure forces, namely the spontaneous and induced forces discussed in sect. 2 of this review. The first optical trap geometry was proposed by

tering force to be proportional to the Poynting vector.

For atoms, however, the interna1 degrees of freedom can change this proportionality between force and Poynting vector in a position-dependent way and thus allow static spontaneous force traps. Such a change can occur, for example, due to external fields which shift the resonant frequency.

Several other possibilities for spontaneous light traps have been proposed in a recent paper by D. Pritchard et al[31]. Light traps are very useful to study photon assisted collisions or to achieve very high densities since they are very sharp and deep. However, for precision spectroscopy and for the study of collective quantum effects, they are not good because the strong electromagnetic field perturbs the atomic system.

5. COOLING NEUTRAL ATOMS

The cooling process is very important in the trapping of atoms. As we pointed out before, in the deceleration process there is a heating mechanism due to random emission To make trapping worthwhile for most applications, it is necessary to have a three dimensional cooling of the sample. There are many proposals for cooling atoms and ions, and some of them have already been successfylly used.

a) Doppler cooling

Doppler cooling was independently suggested for a gas of neutral atoms[17] and for ions bound in an electromagnetic trap[18]. Let us consider an unbound gas of atoms as being a set of two-level systems with resonance frequency ω_0 and radiative linewidth A. Let usalso consider these atoms submitted to a monochromatic low intensity radiation directed along a given direction, but detuned slightly below the resonance frequency. Atoms of a particular velocity class moving against the radiation are Doppler shifted to the blue so they will resonate with the laser beam. On the other hand, atoms moving along the laser direction will be Doppler shifted farther out of resonance. The result is that the counter-propagating atoms scatter photons at a faster rate, and

therefore the net momentum transferred in the absorption process retards the motion of the atoms (the reemited photons cause no net momentum transfer). The momentum transfer per scattering event will be $\Delta\vec{v} = \hbar\vec{k}/M$ and this leads to a net cooling, provided that $|\vec{v} + \Delta\vec{v}| < |\vec{v}|$. Due to the randomness of the reemitted photons, we expect that the minimum possible energy to be reached in the cooling process results from a balance between the recoil heating of each absorption or emission and the Doppler cooling. Detailed calculations for this process were carried out by Bagnato[37] and the minimum kinetic energy found is

$$K_{min} = \frac{1}{4}\frac{\hbar(\Delta^2 + A^2/4)}{\Delta}(s + 1) \qquad (15)$$

where

$$s = \frac{\Omega^2/2}{\Delta^2 + A^2/4}$$

is the saturation parameter. This expression can still be minimized with respect to A, giving the optimum values $\Delta \simeq A/2$ for small s and

$$\Delta = \sqrt{\Omega^2/2 + A^2/4}$$

for large s. For small saturation parameter we have

$$(K)_{min} = \frac{1}{4}\hbar A(s+1) \qquad (16)$$

As a numerical example, we have $(K)_{min} \simeq 2 \times 10^{-4}$ K for S=I and A = 60 MHz, which represents Na under saturation light.

b) Other cooling techniques

Several other proposed cooling schemes in the literature will be described briefly here.

Cyclic cooling[33] is based on the fact that the potential energy of neutral particles in the trap changes when the atom changes internal quantum states as shown in fig.13. Each state has a distinct dependence on the external field. Let us imagine a trapped atom in the ground state (2) with energy E. This atom oscillates between two

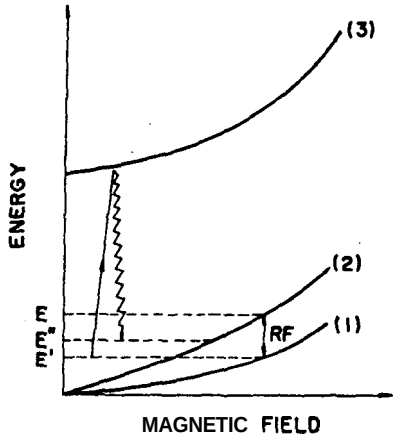

Fig.13 - Cyclic cooling scheme.

points limited by this energy. If RF transitions are induced preferentially when the oscillating atoms are near their maxima in potential energy (minimum in kinetic energy), the atom is taken to internal state (1), the RF photon takes E–E' of kinetic energy and the atom can be restored to state (2) using laser optical pumping. When theatom goes back to state (2), the energy is $E'' < E$ and therefore there is a cooling effect after this cycle. A large fraction of the trapped particle thermal energy will be lost for each cycle.

The *stimulated Raman cooling*[38] method uses a 2-photon stimulated process to transfer more than $\hbar\vec{k}$ of momentum to the atom. Imagine the 3-level system shown in fig.14, where (3) can bea real or a virtual level. The coherent transition (2) → (1) is a two-photon process which transfer a momentum $\Delta P = \hbar(\vec{k}_1 - \vec{k}_2)$ to the atom. For a given atomic velocity v, we can choose the propagation vectors $\vec{k}_1$ and $\vec{k}_2$ of two laser beams in such a way that ΔP is contrary to the motion of the atom. Taking the Doppler effect into account, the lasers will be resonant with the atomic transitions with frequencies ν_1 and ν_2 when the laser frequencies are given by $\nu_1^L = \nu_1 - \vec{k}_1.\vec{v}$ and $\nu_2^L = \nu_2 - \vec{k}_2.\vec{v}$. By changing the laser frequencies we are able to select the velocities of the atoms to be woled. In the case of very small velocities, the resonance condition is ailways achieved, since the lasers and electronic tran-

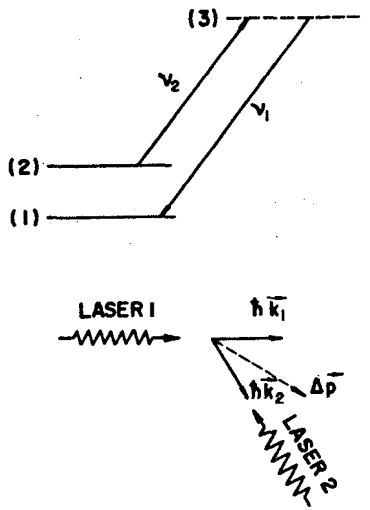

Fig.14 - Stimulated Raman cooling scheme.

sitions have finite linewidths. One advantage of this process is that, since it is stimulated, there is no heating comming from spontaneous emission.

Evaporative cooling has recently been demonstrated for magnetically trapped spin-polarized hydrogen[29,39]. It consists in isolating the trapped gas and allowing the hotter atoms to escape, taking with them energy that they acquired from collisions with others. As this evaporation process proceeds, the gas temperature falls. In order to have successful cooling, there must be many collisions among the less energetic atoms for every hight energy evaporating atom that leaves the trap, in such a way that the population of energetic atoms in the Boltzmann tail is recovered.

Still another process, *Stimulated emission cooling (blue molasses)*, has been recently demonstrated[40]. This new cooling scheme is mainly based on a stimulated redistribution of photons between two counterpropagating waves by a moving atom. In constrast with usual radiation pressure cooling, this stimulated process works for blue detuning and does not saturate at high intensities.

6. THE FUTURE OF LASER COOLING

A large part of today's fundamental research in atomic physics consists in performing precise and well controlled spectroscopic measurements on atoms. In these experiments, the presence of a thermal motion in the sample under study is undersirable because every result comes from the convolution of the intrinsic atomic effect with the velocity distribution.

The performance of atomic clocks, which are the most precise time keepers as well as accurate frequency standards, is fundamentally limited by motional effects. The production of very cold samples of atoms (in beams or in traps) will allow unprecedented accuracy in atomic clocks. This high precision will help the accomphishment of refined experiments on general relativity. The gravitational red shift could be measured more accurately by comparing clock rates in different gravitational potentials. Atomic clocks also have practical applications in navigation on earth and in space.

Experiments on collision of atoms aiming at understanding atomic interaction and chemical processes are often disturbed by poor control of the velocities of the colliding atoms, resulting in difficulties to test collision theory with high precision. The productionof cold atornic beams may solve this problem since good control of the beam is possible once we have a very stable laser frequency. In cold trapped atoms, the col'l ision effects are very conveniently observed, as has recently been done by Raab et al[11].

The slow motion of atoms increases considerably the resolution of atomic beam spectroscopy due to the almost complete absence of transit time broadening and of the second order Doppler effect (the first order effect can be avoided by using perpendicular beams is Doppler free spectroscopy).

Another class of experiments centers on the physics of trapping process. Atoms trapped at very low temperature and high. density may manifest important collective effects like Bose-Einstein condensation. In this phase transition, a macroscopic fraction of the sample should coherently occupy the ground state of the trap potential.

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Resumo

Técnicas óticas para reduzir a velocidade de átomos neutros e armazená-los de forma a se obter densidades elevadas são discutidas neste artigo, de revisão. Mostra-se que a força de radiação existente quando um feixe de laser incide sobre um sistema atômico possui uma componente oriunda da transferência do momentum do fóton para o átomo e outra advinda da interação do dipolo induzido durante a transição-com o gradiente do campo de radiação. Dentre os métodos de se resfriar átomos, damos ênfase às técnicas de sintonização Zeeman dos níveis eletrônicos e varredura da frequência do laser. O aprisionamento de átomos é outro assunto de interesse que discutimos no artigo. São apresentados os resultados mais recentes obtidos em armadilhas de luz e do tipo magnético. Finalmente, técnicas para produzir um resfriamento adicional dos átomos aprisionados são abordadas e o futuro de resfriamento de átomos neutros por meio da pressão de radiação é discutido.