Trapping and Cooling in Optical Lattices

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Abstract

Atom trapping and cooling using optical lattices is reviewed. A general theory and an example of a one-dimensional lattice is discussed. Some experimental achievements in the field are reviewed.

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I. INTRODUCTION

A set of intersecting laser beams establishes a stable periodic potential through its interference pattern. Neutral atoms can be trapped in the wells of this potential via the ac Stark effect("light shift"), creating a lattice structure, that is commonly referred to as optical lattice (OL). The localized atoms in the OL can be as many as a few micrometers apart. At this distance, strong interactions between neighboring atoms are negligible, which enables one to study an atom's sole interaction with the environment. The optical lattice potential can be modeled exactly and can be produced relatively easily in the laboratory. Using a careful choice of the lasers' parameters (polarization, intensity, frequency, and geometry of the set of lasers), one can easily choose and control the lattice (lattice symmetry, potential well depth and size). We begin the discussion of OLs in Section II, with a one-dimensional model developed by Dalibard and Cohen-Tannoudji [1]. In this system, the OL is constructed by two cross-polarized plane waves propagating in opposite directions. The trapped atom has angular momenta $J_g = 1/2$ in the ground state and $J_e = 3/2$ in the excited state. In this model, the atom is trapped only in one dimension. The field's polarization and/or intensity are varying only in one dimension; therefore it is the only dimension in which the atom is trapped. In the other two dimensions, the atom is free to move and is not cooled. The process called "*Sisyphus Cooling*", in which an atom looses its kinetic energy (i.e., gets cooled), is described in this section. In section III, we discuss the basic theory of laser cooling in OLs. In section IV, the use of spectroscopy to probe cooling in OLs is discussed. In section V, we review two spectacular experiments in OL recently conducted, and in chapter VI, we discuss possible new developments and directions that the research might take.

II. SISYPHUS COOLING IN 1D OPTICAL LATTICES

We consider a 1D model made of two counter-propagating plane waves propagating in the $+\hat{z}$ and the $-\hat{z}$ direction, and linearly polarized in the $\hat{x}$ and $\hat{y}$ direction, respectively. The electric field of of the laser $E_L(\vec{z})$ is:

$$\begin{aligned} E_L(\vec{z}) &= -E_0(\hat{x}exp[ikz] + i\hat{y}exp[-ikz]) \\ &= \sqrt{2}E_0(\hat{e_+}\cos kz - i\hat{e_-}\sin kz) \end{aligned} \tag{1}$$

From Eq. (1), we see that the field can be expressed as a superposition of two standing waves with polarizations σ_+ and σ_-, respectively; it is offset by $\lambda/4$ so that the amplitude maxima of one wave coincide with the amplitude minima of the other one. The intensity, I, of the field is constant and independent of the spatial coordinate z ($I\alpha\left|E\right|^2$), while the polarization changes from circular to linear and back to circular as z changes by $\lambda/4$.

Consider an atom with angular momenta $J_g = 1/2$ in the ground state and $J_e = 3/2$ in the excited state, represented in Fig. 1. Taking into consideration the field at hand that has only σ_+ and σ_- components, the atom-laser system divides itself into two subsystems: $(\left|e,-1/2\right\rangle, \left|g,1/2\right\rangle, \left|e,3/2\right\rangle)$ and $(\left|e,-3/2\right\rangle, \left|g,-1/2\right\rangle, \left|e,1/2\right\rangle)$. These two systems are coupled through $\delta m = 0$ spontaneous transition between $\left|e,\pm 1/2\right\rangle$ states. The potentials for the $\left|g,\pm 1/2\right\rangle$ states have simple form in a low saturation regime,

$$U_{1/2}(z) = \frac{2}{3}U_0\cos(kz)^2 + \frac{1}{3}U_0 \tag{2}$$

$$U_{-1/2}(z) = \frac{2}{3}U_0\sin(kz)^2 + \frac{1}{3}U_0 \tag{3}$$

where the maximum value of the light shift is $U_0 = \frac{1}{2}\hbar\Delta s_0$. The saturation parameter for $\left|g,+1/2\right\rangle \longleftrightarrow \left|g,-1/2\right\rangle$ transition at a point where the polarization of the laser field is purely σ_+ is $s_0 = 2\Omega^2/(4\Delta^2 + \Gamma^2)$, with associated Rabi frequency Ω and detuning of the lattice from atomic resonance $\Delta = \omega_L - \omega_A$. For negative detuning, $\Delta < 0$, cooling of the atom occurs due to optical pumping between the ground states $\left|g,+1/2\right\rangle \longleftrightarrow \left|g,-1/2\right\rangle$.

Considering the center-of-mass and the momentum of the atom classically, the illustration of the process of cooling is simplified. Suppose an atom moving in the **z** direction, originally

in the ground state $|g, +1/2\rangle$. At some time this atom is at the minimum of the potential $U_{1/2}$. As the atom continues to move, it decreases its kinetic energy climbing out of the potential well of $U_{1/2}$. At first, the probability that optical pumping will occur is minimal since the local polarization is mostly σ_+. As it continues to propagate, the atom encounters the region where the local polarization is more σ_-, thus the probability of pumping increases. It reaches maximum at the top of the hill of $U_{1/2}$, which corresponds to the bottom of the well of $U_{-1/2}$ potential, and the atom undergoes transition to $|g, -1/2\rangle$ state. Upon transition, it finds itself on the bottom of the well of $U_{-1/2}$ potential. As the atom continues to move along $\mathbf{z}$ direction, it decreases its kinetic energy, again due to the increase of the potential energy along the hill of $U_{-1/2}$ potential. At the top of the hill of $U_{-1/2}$ potential, the atom undergoes another optical pumping that takes it to the bottom of the well of $U_{1/2}$ potential. The process continues until the atom loses enough of its energy and becomes localized in one of the potential wells. This process in which the atom constantly climbs potential hills and loses its kinetic energy, was named *Sisyphus Cooling* [1].

The above model describes the position of the atom up to the atomic wavelength scale. Once the atom is trapped, the dynamics of the atom near the bottom of the potential well can be approximated by a thermally excited simple harmonic oscillator (SHO). We expand the optical potential about the minimum of the potential well, which gives the oscillation frequency of the SHO,

$$\omega_{OSC} = \frac{2}{3}\sqrt{6}\sqrt{U_0 E_R}, \tag{4}$$

$$E_R = \frac{1}{2}\frac{\hbar^2 K_L^2}{M}, \tag{5}$$

where E_R is the single photon recoil energy (i.e., kinetic energy an atom with mass M receives if it absorbes a photon with $\hbar K_L$ momentum). The oscillatory motion approximation only makes sense if the time that the atom spends in the potential well is comparable to the inverse of the oscillation frequency. In this case, one must treat the problem quantum mechanically since the variation of the atomic center-of-mass can be on the order of the atomic wavelength.

III. THEORY OF LASER COOLING IN OPTICAL LATTICES

Consider a system of a monochromatic laser field tuned near resonance of an atomic transition between ground and excited energy levels corresponding to two values of angular momentum, J_g and J_e, respectively. The atomic system consists of a total of $2(J_g + J_e + 1)$ states that evolve coherently through the interaction with the laser field. The dissipation in the atomic system is due to the interaction with vacuum. In the case of a low intensity laser field or large detuning, we reach the low saturation limit. In this limit, the population of the excited state is small compared to the population of the ground state. Therefore, the time scale of spontaneous emission is large compared to the time scale of optical pumping. Effectively, populations and coherences relating the excited states become constant compared to changes in populations and coherences of the ground state. Thus, the simplified Hamiltonian has the following form,

$$H = \frac{1}{2}\frac{\vec{P}^2}{M} U_0 (\vec{\epsilon_L}(\vec{x})\hat{d})^\dagger (\vec{\epsilon_L}(\vec{x})\hat{d}) \tag{6}$$

where the dipole operator $\hat{d} \equiv \sum C_{m_g}^{m_g+q} |e; J_e, m_g + q\rangle \langle g; J_g, m_g| e_q^*$. The atomic center-of-mass variables are $\vec{P}$ and $\vec{x}$, and $C_{m_g}^{m_g+q}$ is a shorthand notation for Clebsch-Gordan coefficients for the states $|J_e, m_e\rangle$ and $|J_g, m_e\rangle$ and e_q are spherical basis vectors (q = 1, 0, -1). The above given Hamiltonian in Eq.(6) describes only the coherent evolution of the atomic state. To study laser cooling dissipative processes, the optical pumping between ground states, must be considered as well. The master equation for density operator ρ does this. As shown in [2] the master equation for the density operator, after adiabatic variables were eliminated, has the following form

$$\frac{d\rho}{dt} = \frac{[H, \rho]}{i\hbar} - \gamma_s \{\Lambda, \rho\} + \gamma_s \sum \int d^2 k_s N_h(k_s) (W_h(k_s) \rho W_h^\dagger(k_s)) \tag{7}$$

where the operator Λ is given by $\Lambda = (\vec{\epsilon}_L \hat{d})^\dagger (\vec{\epsilon}_L \hat{d})$, $\{\cdot, \cdot\}$ is the anticommutator, and the operator $W_h(k_s) = (exp(ik_s x)\vec{e}_h \hat{d})^\dagger (\vec{\epsilon}_L \hat{d})$ represents absorption of a lattice photon, followed by emission of a fluorescence photon of wavevector k_s and helicity h along the quantization

axis. The first term in the master equation, Eq. (7), is the term from the Heisenberg equation of motion due to the Schrödinger Hamiltonian. It describes a coherent evolution of the density matrix operator. This term determines the time scale of coherent processes such as the oscillation of an atom when extremely localized close to the bottom of the potential well. The next two terms describe the dissipative processes in the system and determine the time scale associated with those processes. The second term characterizes the depletion of population of a ground state to another ground state due to optical pumping. The third term characterizes the replenishing of a population of a ground state due to optical pumping to that ground state from some other ground states. Eq. (7) provides a description of laser-atom interaction in a low saturation limit. However, solving it is a non-trivial task. For a discussion of different approaches of solving Eq. (7) see [3].

IV. SPECTROSCOPY AND OPTICAL LATTICES

Spectroscopy has been used as the most successful method for probing the cooling in atomic lattices. We briefly discuss two spectroscopic techniques: *Resonance Fluorescence* and *Probe Transition Spectroscopy*. The former we discuss in more detail than the latter.

The group of Phillips [4] has developed a technique of optical heterodyne spectroscopy of resonance fluorescence, which is shown schematically in Fig. 2(a). An atom, cooled and trapped emits fluorescence that is collected, mixed with a local oscillator beam, and detected by a photodiode. The signal from the photodiode is input to a radio frequency analyzer which outputs the power spectrum of the atomic fluorescence. Figure 2(c) shows the fluorescence spectra obtained in the experiment conducted by Jessen [5], where alkali atoms were cooled in a 1D lattice discussed in section II. With a classical treatment of center-of-mass motion for low saturation, the power spectrum of the scattered electric field is a delta function centered at laser frequency ω_L broadened by the atomic motion. The presence of only one pair of strongly suppressed sidebands is strong evidence that the radiating atoms are well localized in potential wells of the OL [3]. Such a successful localization of atoms,

also known as Lamb-Dicke limit, is on the order of localization achieved in experiments with ion trapping [6]. On average, an atom undergoes one full oscillation before it is optically pumped or photon scattering randomizes the phase of oscillation. Quantum mechanical consideration of the atom's center-of-mass motion provides a description of the sidebands in the spectra (Fig. 2(c)) in terms of transitions between quantized vibrational states in a harmonic potential. These transitions are spontaneous Stokes and anti-Stokes Raman transitions depicted in Fig. 2(b), which change the atomic vibrational quantum number by $\Delta n = \pm 1$. That is why these bands are referred to as "Raman sidebands". Finally, the temperature of the cooled atomic sample can be extracted from the asymmetry in the Raman sideband and the oscillation frequency ω_{OSC} [3].

Another successful technique, developed by Salomon, Grynberg, and Kimble [7], measures the attenuation of a weak probe beam as its frequency is varied in the neighbourhood of the lattice laser frequency. In this case, Raman transitions between oscillatory eigenstates are stimulated (Fig. 3(a)). Figure 3(c) shows the spectra obtained in the experiment using the probe technique, applied to a sample of alkali atoms [8].

V. EXPERIMENTS

We choose to discuss two experiments in which atoms are trapped and cooled in OLs.

A. Resolved-Sideband Raman Cooling

This subsection is based on an experiment discussed in [9]. Neutral Cs atoms were trapped in a 2D OL and cooled by resolved-sideband Raman cooling. The method relies on Raman coupling intrinsic to the lattice potential and uses a magnetic field to tune the coupling to the "red sideband". The cooling results in a ground state population greater than 95%.

Figure 4(a) illustrates the experimental setup. Three coplanar laser beams [10] with equal amplitudes E_1 and linear polarizations are in the lattice plane. The lattice consists of nearly

isotropic potential wells located at positions where the local polarization is either σ_+ or σ_-. The lasers are detuned far (typically 20 GHz) below the $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}(F' = 5)$ transition at 852 nm. A weak magnetic field B_z along $\hat{z}$ is added to Zeeman shift states $|n, m = 4\rangle$ and $|n-1, m = 3\rangle$ into degeneracy. Here $|n\rangle$ is a two-dimensional harmonic oscillator state in a harmonic potential for the magnetic sub-level $|m\rangle$. The transition $|n, m = 4\rangle \leftrightarrow |n-1, m = 3\rangle$ is then stimulated by the lattice. Optical pumping provides relaxation from $|n-1, m = 3\rangle$ to $|n-1, m = 4\rangle$ via a pair of σ_+-polarized beams.

The experiment is conducted as follows. A sample of $\sim 10^6$ Cs atoms was confined to a volume $\sim 400\mu m$ and cooled to the temperature of about 3 K, using a vapor cell magneto-optic trap and 3D optical molasses. The atoms are further cooled in a near-resonance 2D OL with the same beam configuration. A far-off-resonance lattice (FORL) is then adiabatically imposed while the near-resonance lattice was diminished. When the adiabatic transfer is completed and the atoms are localized deep in the Lamb-Dicke regime, resolved-sideband Raman cooling is initiated first, by adding a field B_z tuned so that the lattice Raman coupling occurs in the red sideband and secondly, by turning on the pumper-repumper beams. Figure 4(c) shows that after 11 ms of cooling, at least 90% of the atoms have been transfered to $|m = 4\rangle$ ground state. From the experimental data, an average kinetic temperature $T = 997 \pm 50nK$ is obtained. This corresponds to a population $\Pi_0 = 0.984 \pm 31$ for atoms in $|m = 4\rangle$ state in two-dimensional vibrational ground state.

B. High Density Cooled Atoms in OLs

In the experiment discussed in [11], atoms are cooled and trapped in a 3D far-off-resonance OL with high degree of occupancy (44% of the lattice sites have a single atom near the vibrational ground state). The atoms are first cooled in a 3D FORL constructed from three orthogonal standing waves. The amplitudes of two horizontal lattice beams are decreased to zero adiabatically, so that only a 1D FORL trap remains. Distributed in a "pancake-shape" manner, the atoms are confined to 50 nm in the vertical and 0.4 nm in

the horizontal direction. The 1D wells are about 200 μK deep. The atoms have less then 1 μK of kinetic energy, forcing them to be near the top of their trajectories in the transverse, Gaussian shaped potential. After a quarter of a cycle, all the trapped atoms collapse at about the same time toward the center of the trap. At this instance, when the concentration of atoms is the greatest, the horizontal beams are turned back on adiabatically, trapping 85% of the atoms at the lattice potential wells. To cool the atoms to a lower temperature, laser cooling is applied again in the 3D FORL. The best results of this experiment show that with a high initial density, $44\% \pm 1\%$ of the lattice cites are populated with atoms after multiply occupied cites decay, leaving the atom sample at average temperature of 350 nK. The reported phase space density is 0.037, which is 6 times higher than the results in any experiment that does not require evaporative cooling.

VI. OUTLOOK

OLs are of considerable importance in numerous areas and have recently been used in experiments studying wave packet dynamics, laser cooling, and atom optics. Since OLs are relatively easy to implement in the laboratory with a high degree of control, OLs find their place in the experiments that are traditionally condensed matter in nature, such as Bragg scattering and Bloch oscillations. Potential applications are numerous as well. For example, OLs can be used for preparing cold atomic samples for atomic fountain clocks, developing new lithographic techniques based on light-controlled deposition of atoms onto a substrate [3]. If OLs were occupied more densely, as in the example discussed in section V B, then experiments that depend on atomic interactions could be performed as well. In this case, it may be possible to achieve Bose-Einstein condensation without any use of evaporative cooling [11]. Finally, it may be possible to obtain quantum logic gates and open the way for costructing of quantum computers [11].

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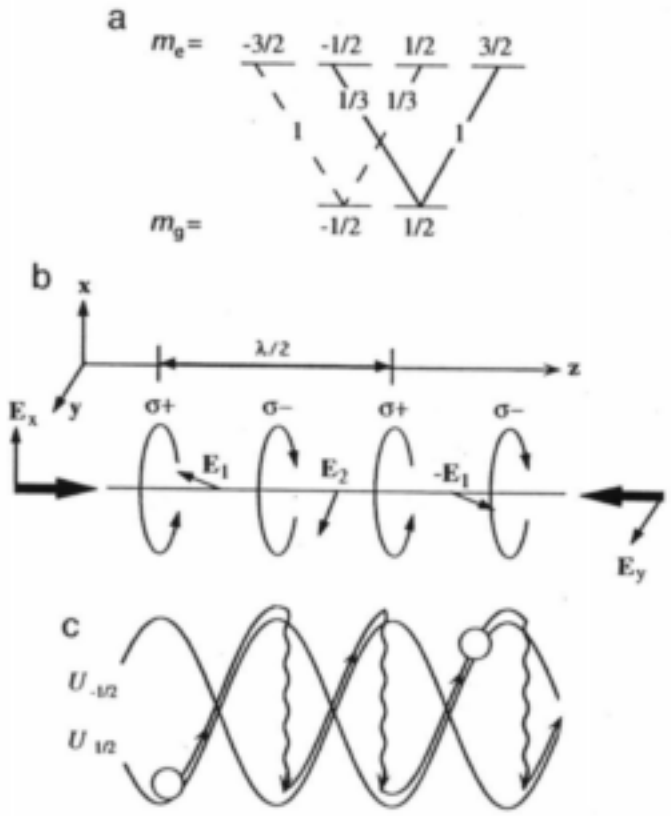

FIG. 1. Sisyphus cooling. (a) Structure of two-level atom with . The square of the Clebsch-Gordan coefficients are included. (b) Configuration of 1D OL. (c) An atom moving in a bipotential associated with two ground state sub-levels (e.g., atom depicted in (a)). The atom is optically pumped from the hills of one potential to the wells of the other, at the expanse of its kinetic energy. (Figure from [2])

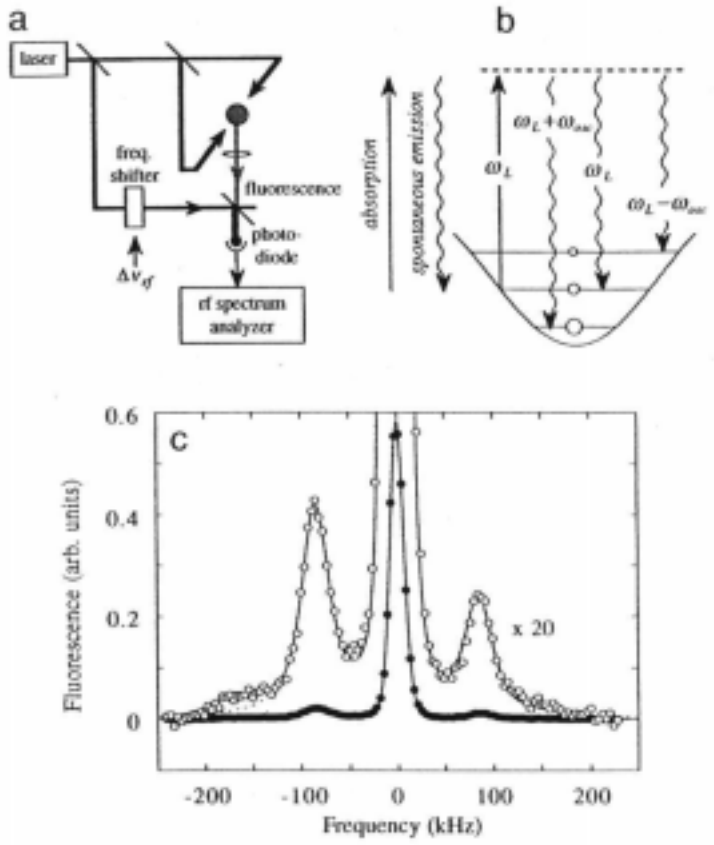

FIG. 2. Fluorescence spectroscopy. (a) Design of the experimental setup. (b) Diagram showing spontaneous Raman transitions between vibrational eigenstates of atom-potential system. Rayleigh line at the OL frequency and Raman sidebands at are shown. (c) Spectrum of fluorescence of Rb atoms in 1D OL [5]. (Figure from [2])

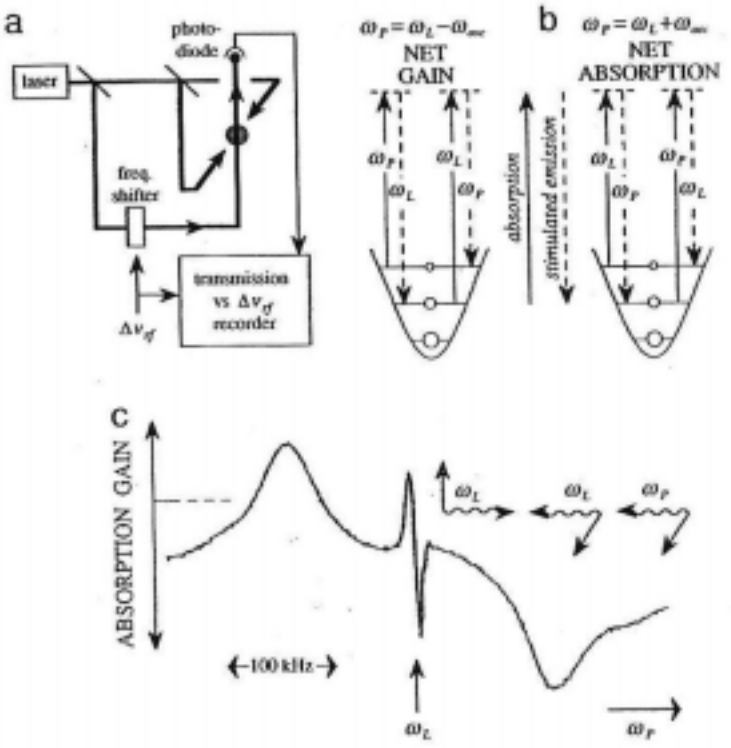

FIG. 3. Probe transition spectroscopy. (a) Design of the experimental setup. (b) Diagram showing stimulated Raman transmitions between vibrational eigenstates of atom-potential system. (c) Probe transition spectrum measured for Cs atoms in a 1D OL [7]. (Figure from [2])

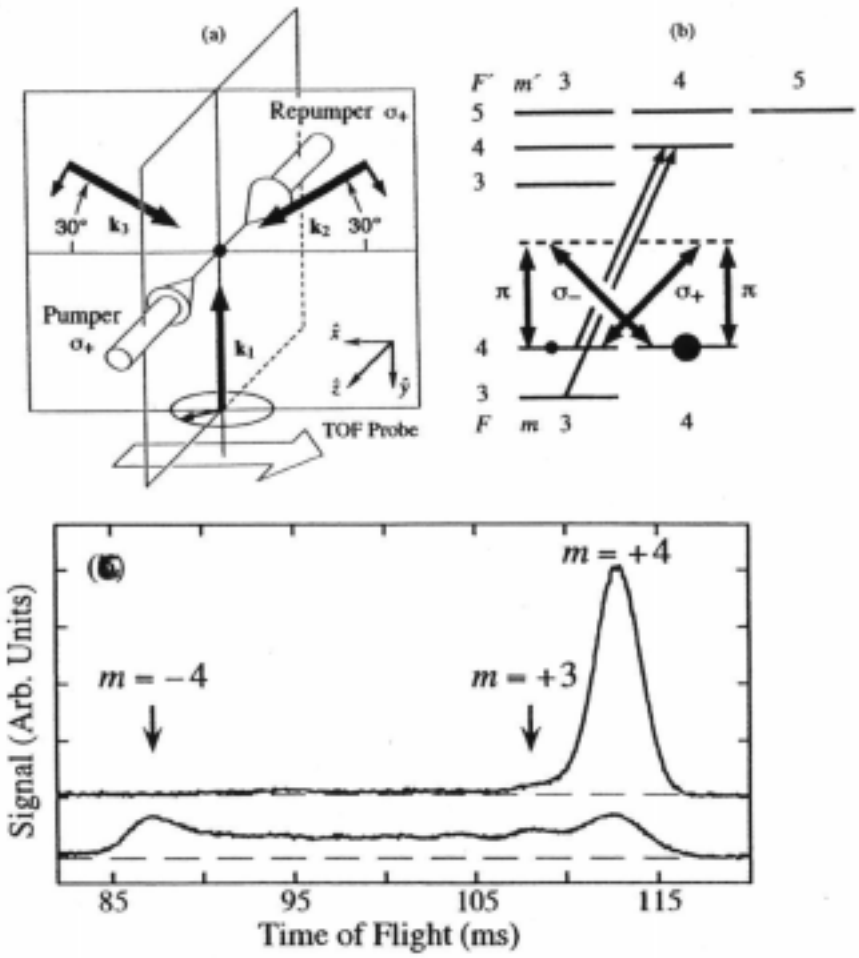

FIG. 4. (a) Experimental setup for resolved-sideband cooling. The lattice is formed by three coplanar laser beams with linear polarization in the lattice plane. Raman coupling is provided by changing one of the laser's polarization to elliptical. (b) Cooling scheme, showing Raman transitions and coupling of the magnetic sub-levels of the F=4 hyperfine ground state. Relaxation is conducted by a pair of pumper and repumper lasers. (c) Atomic internal state after sideband cooling (top curve) and before sideband cooling (bottom curve). (Figure from [8]