Cooling Neutral Atoms in a Magnetic Trap for Precision Spectroscopy

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A configuration of magnetic fields is exhibited which can harmonically trap paramagnetic particles in a shallow field minimum, superposed on a nearly uniform field which simplifies spectroscopic interactions with the particles. The potential energy of a trapped neutral particle depends on the particle's internal quantum number, as well as its position in the trap, permitting a combined rf-laser optical pumping cycle which can cool particles by a factor of 2 per cycle. Application of these ideas to the trapping of Na atoms is discussed.

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Electromagnetic traps for neutral particles open new possibilities for precision spectroscopy and for the study of collective behavior among the trapped particles or between the particles and radiation, and may have applications as polarized targets in atomic scattering. Numerous schemes for such traps have been proposed including magnetic-field traps,[1-4] electrostatic traps,[5] and traps using near-resonant radiation.[1,6] A magnetic trap has been realized for neutrons.[7] In this Letter, we propose two new ideas which make such traps more attractive, particularly for precise spectroscopy: a trapping field configuration which has a large nearly uniform field at the center of the trap, and an efficient cooling scheme which offers the possibility of ultimate temperatures as low as 10^{-5} K.

The trap proposed here employs magnetic fields and relies on the energy $-\vec{\mu}\cdot\vec{B}$ to trap paramagnetic atoms. For moments of 1 Bohr magneton and laboratory fields of 10^5 G, this interaction energy is greater than 4 cm^{-1} (about 7 K): much deeper than other types of traps for atoms in their ground energy level[5,6] (although polar molecules in electrostatic traps have comparable interaction energies[8]). The fact that this energy exceeds the kinetic energy of atoms recently produced by laser cooling[9] and also by cryogenic techniques[10] suggests that it may be possible to fill such a trap.

The proposed trap is particularly suited for spectroscopic applications because the trapping fields are superposed on a large uniform field. This simultaneously defines a useful quantization axis and suppresses the possibility that time-varying magnetic-field components due to the particle's motion will cause transitions between Zeeman sublevels (Majorana flops).[3]

The novel cooling scheme exploits a key feature of neutral-particle traps which has not, in our opinion, been sufficiently emphasized: The energy levels of the trapped particle(s) must vary with position in order to confine the particles and since this variation will generally depend on the quantum numbers, the energy spacing between the levels will also vary with position. (This is unlike the trapping potential of electromagnetically confined ions, which, to an excellent approximation, depends only on the charge.) This variation permits the use of rf transitions to lower the potential energy of the particles—typically by a factor of 2 in a single transition—thus affording the possibility of rapid cooling of the particles. The spatial variation of the energy levels also introduces a form of (inhomogeneous) broadening as will be discussed.

A charge- and current-free region of space cannot sustain a field maximum, but can have a field minimum.[11] Thus, we expect to trap "weak-field seeking" particles whose potential energy is $U = \mu B$. The proposed trap consists of a uniform magnetic field along $\hat{z}$ with a bottle field added:

$$\vec{B}_b \simeq B_0[1+(k^2/2)(z^2-\rho^2/2)]\hat{z} - (B_0/2)(kz)(k\rho)\hat{\rho},$$

where k^2 is the fractional strength of the bottle and ρ is the radial coordinate in the x-y plane. For $k^2 > 0$ the origin $\rho = z = 0$ is a field strength minimum along $\hat{z}$, but a maximum in the ρ-φ plane. To make the origin into a minimum for motion in any direction, one can add a quadrupole field in the ρ-φ plane,

$$\vec{B}_q = b_q\rho[\cos 2\varphi\hat{\rho} - \sin 2\varphi\hat{\varphi}].$$

A particle of moment μ whose kinetic energy is less than $\frac{1}{2}\mu B_0 k^2 z_m^2$ will now be confined to $|z| < z_m$ and will be radially confined if (for small k) $[b_q - \frac{1}{2}B_0k^2z_m]^2 - B_0^2k^2/2 > 0$, i.e., if $b_q > \frac{1}{2}B_0k[2 + kz_m]^{1/2}$.

This field configuration has several advantages for spectroscopic manipulation of the atoms: For small k and b_q the total field will always make a small angle with respect to $\hat{z}$, so that circularly polarized light propagating along z, for example, will have a very small probability of causing $\Delta m = 0$ transitions for particles anywhere in the trap. Moreover, under these conditions the field strength (and hence the particle's energy) will vary quadratically with z and ρ, causing the trapped particles to exhibit simple harmonic motion, albeit with different frequencies of motion for oscillations along z, along $\varphi = 0$, and along $\varphi = \pi/2$. The existence of terms which couple the z motion to the ρ-φ motion may be beneficial for cooling: Quite possibly a cooling scheme which works along only one axis will cool all motions in the trap.

Before discussing the new cooling scheme, I first consider the effects of transitions between two quantum levels 1 and 2 which have different field-independent magnetic moments, μ_1 and μ_2.

Assume that the field strength varies as a function of z between $B_<$ and $B_>$ as shown in the lower part of Fig. 1; then the potentials for motion in states 1 and 2 are $U_{1,2} = \mu_{1,2}B$. If the particle is initially in state 1 with total mechanical energy (kinetic plus potential) E_1, then it will oscillate in z out to where $U_1 = E_1$, i.e., to where $B_> - B_< = E_1/\mu_1$. Since we took $\mu_2 > \mu_1$ in this example, the separation between U_2 and U_1 is not constant, leading to a broadening of the transition by the amount $\hbar\Delta\omega = (B_> - B_<)(\mu_2 - \mu_1) = E_1(\mu_2 - \mu_1)/\mu_1$. This is an inhomogeneous broadening which depends on the details of the particle's orbit in a trap of low symmetry like the one proposed.

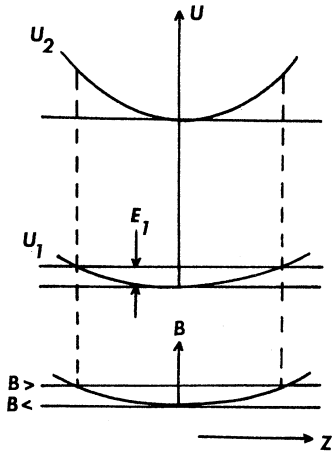

FIG. 1. The magnitude of the field B as a function of z is shown at the bottom; the corresponding energy $\mu_{1,2}B$ of neutral particles in states 1 and 2, respectively, depends on z as shown directly above. The particle in state 1 has total energy E_1.

This inhomogeneous broadening also affects any coherences involving the two quantum states of the trapped particle. A superposition of states ψ_1 and ψ_2 (produced, for example, by a very short pulse of radiation at $t = 0$) will decay in a time $\sim 1/\Delta\omega$. If μ_1 or μ_2 is < 0, then the particle will be unbound in that state, causing an even more rapid decay of any superposition. These considerations make us pessimistic concerning spectroscopy experiments on atoms trapped in electric-field traps (but see Ref. 11 for a possible way out). The above situation bears considerable similarity to molecular spectroscopy; in particular the last case is analogous to transitions from a bound to a repulsive potential curve, and the inhomogeneous broadening discussed previously results from the population of many vibrational levels.

The fact that the potential energy depends on the state can be used to generate very efficient cooling, essentially because the inhomogeneous broadening allows one to make rf transitions which change the total mechanical energy (kinetic plus potential) of the particles by a factor of typically 2. Combination of rf with optical pumping by a laser (which provides population imbalance necessary for the rf transitions to operate in the cooling direction) then results in a cooling cycle of great efficiency. I give a specific example of such a scheme applied to a three-state system in a trap whose energy levels vary as shown in Fig. 2. The quantum numbers of the states may be taken to be the magnetic quantum numbers for concreteness.

Imagine that the objective is to produce cold atoms in state 2, and that initially the particles have total mechanical energy E_0. Their maximum excursion is to z_0. If radio-frequency radiation is now applied at frequency rf_0 it will equalize the populations in levels 1 and 2. On account of the classical Franck-Condon principle, the kinetic energy at z_0 will be the same in states 1 and 2 (nearly zero as shown); therefore the total energy of the particles in state 1 will be reduced to $E_1 \sim U_1(z_0)$ which is much less than their former energy, $E_2 \sim U_2(z_0)$. Assume that the atoms are now irradiated by a laser tuned to ω_L and polarized so that atoms in level 1 will undergo transitions to 2′ but atoms in 2 will not be excited. Assume that the atoms may decay spontaneously back to

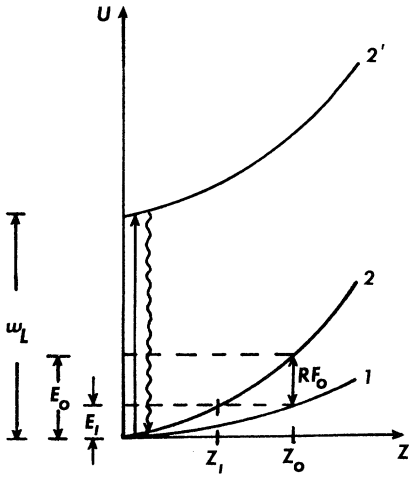

FIG. 2. Combined rf-laser optical pumping cooling cycle. Particle initially in level 2 with total energy E_0 makes an rf transition to level 1 with new E_1. Laser optical pumping then takes it, via level 2', back to level 2, but with energy still $\sim E_1$, restricting its motion to $z \leq |z_1|$, as shown.

2 in time T_N. Neutral-particle traps frequently operate in the regime where $T_N \ll$ the period of oscillation in states 1 and 2—under these conditions there will be little change of kinetic energy in the laser-induced cycle (except from the momentum transferred by the light) if the laser beam is tuned and/or positioned in the trap to cause transitions only near $z=0$. Thus the combined rf-laser cycle has reduced the mechanical energy of the atoms in state 2 by a factor of ~2, which restricts their motion to $|z| < z_1$. If the rf frequency is now lowered slowly, it will eventually come into resonance with the atoms a second time, cooling them again. This type of cooling cycle is very efficient, and has an ultimate lower momentum limit of a few times $\hbar\omega_L/c$ corresponding to an energy $(\hbar\omega_2)^2/(2mc^2)$. For Na atoms, the velocity corresponding to three photons is 9 cm/sec, and the corresponding kinetic energy is 8×10^{-6} cm^{-1} (0.2 MHz). This is at least a factor of 10 smaller than Doppler cooling schemes for trapped ions, where the limit is $\sim\hbar\Gamma_N$.[12] I note that schemes of the type outlined here are also applicable to ions trapped in inhomogeneous fields.

Use of neutral-particle traps for high-resolution spectroscopy requires a method of eliminating the inhomogeneous broadening which arises when $\mu_2 \neq \mu_1$. A straightforward way to do this is to bias the trap at a magnetic field B_0, where $\mu_2^{\rm eff} = \mu_1^{\rm eff}$. The effective moment is $\mu(B)^{\rm eff} = -\partial U(B)/\partial B$ so that at this field the transition frequency is field independent. (Useful field-independent transitions exist in many paramagnetic atoms with nuclear spin $I \geq 1$ as a result of the hyperfine structure.) If we now assume that some of the trapped particles have mechanical energy kT, it is clear that they will make excursions to regions of the trap where the field exceeds B_0 by the amount $\Delta B = kT/\mu^{\rm eff}$, shifting the transition energy by the amount $\frac{1}{2}(\Delta B)^2[d^2(U_2-U_1)/dB^2]$. For a typical field-independent transition $d^2(U_2-U_1)/dB^2 \sim \mu_{\rm eff}{}^2/\Delta U$ (ΔU is the hyperfine separation), and hence the transitions will be broadened by the order $(kT)^2/\Delta U$. Taking kT to be the cooling limit obtained previously and ΔU to be ~1 GHz (a typical hfs separation) gives a broadening ~40 Hz. This limit can be improved by choosing a field-independent transition with a smaller value of $\partial[\mu_2^{\rm eff} - \mu_1^{\rm eff}]/\partial B$ or by cooling the atoms further using adiabatic techniques (e.g., a slow reduction of k and b_q in the trapping field). However, even 40 Hz represents a spectroscopically useful linewidth for laser stabilization. Moreover, this broadening is comparable to the frequency of oscillation of the trapped particles, raising the possibility of obtaining narrower lines by techniques analogous to recoilless emission, sideband cooling, etc.

Let us now investigate the specific application of these ideas to the trapping and cooling of Na atoms. Starting with laser-slowed Na atoms with 2 K translational energy[9] it seems not impossible to switch them into the weak-field–seeking hyperfine ground state with $m_F = 2$ in such a way that they would be trapped in a field configuration like the one proposed. (This could be accomplished by optically pumping the atoms to a strong-field–seeking state at a field maximum of ~15 kG near the end of the trap, and pumping them back to $F=2$, $m_F=2$ near the trap minimum.) If this were accomplished without heating the atoms, the trapped atoms would have a temperature of ~0.05 K,[9] and be confined in a ~1-cm^3 volume in a trap with $B_0 = 200$ G, $k=0.63$, and $b_q = 300$ G/cm. The Na atoms could then be cooled to an energy less than $\hbar\Gamma_{\rm nat} \sim 0.5\times10^{-3}$ K by use of Doppler cooling in the weak-trapping limit.[12] Conveniently, the red tuned laser interacts with the $(^3S_{1/2}, m_F=2) \rightarrow (^3P_{3/2}, m_F=3)$ atoms most strongly at the center of the trap where their kinetic energy is highest (since there the transition frequency is lowest).

Now we consider the application of the proposed rf-optical cooling scheme to the trapped atoms. We shall let the states 1 and 2 in Fig. 2 refer to the hyperfine states $F=2$, $m_F=1$ and 2, respec-

tively. The upper state 2′ refers to the $F=3$, $m_F=2$ hyperfine state of the $p_{3/2}$ manifold. These assignments prevent loss of the atoms by spontaneous decay to untrapped hyperfine states of the ground level (e.g., $F=1$, $m_F=1$). In order to assure that F is a relatively good quantum number in the excited state, the field B_0 must be reduced to just a few gauss prior to the application of the rf. Since the kinetic energy of the atoms has been cooled below $\hbar\Gamma_N$ previously, they will be confined to a region in which the magnetic field increases by less than $\hbar\Gamma_N/(g_s\mu_0)\sim 6$ G so that the excited-state hyperfine structure will not be unduly decoupled.

The limiting temperature produced by the cooling cycle in the preceding example is determined by several considerations. The branching ratio from $F'=3$, $m_F=2$ to $F=2$, $m_F=2$ is only $\frac{1}{3}$, hence it will take ~six photon absorptions plus emissions on the average to pump from state 1 to state 2. As the atoms cool, the laser frequency can no longer be adjusted preferentially to excite atoms with zero potential energy; at worst the position of the laser becomes ineffectual in this respect also, and the average potential energy of the excited atoms is $\frac{1}{2}$ of their total energy (virial theorem). Hence ~six photon momenta will be necessary to reduce the atom's total energy by 25%, implying a lowest achievable thermal energy of $\sim 12(\hbar k)^2/m_{\mathrm{Na}}\sim 10^{-5}$ K, roughly 100 times lower than attained by Doppler cooling. The ultimate temperature may be further limited as a result of heating by absorption on $F=2$, $m_F=2$ to $F'=3$, $m_F=3$ transition or of precautions necessary to counteract the pull of gravity; however, it can be lowered by creative inclusion of the $F=2$, $m_F=0$ state in a more complicated pumping cycle.

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