Stochastic cooling of atoms using lasers

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We propose a method to laser-cool atoms based on stochastic cooling, first developed at CERN to cool antiprotons. Fluctuations in the momentum distribution will be detected in a pump-probe configuration with far-detuned lasers, and the appropriate correction kick will be accomplished with optical dipole potentials. Each stage of an iterative cooling process will involve measurement and feedback, with phase space remixing in between. We discuss possible applications of this method to magnetically trapped atoms and molecules. [S1050-2947(98)05012-4]

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Laser cooling of atoms has had an enormous scientific impact in recent years [1]. The basic idea requires a closed ''cycling'' transition of absorption followed by spontaneous emission to the same state. This fundamental requirement, however, makes it difficult to extend laser cooling beyond a small set of atoms in the Periodic Table. One solution is to turn to other cooling methods that do not require lasers, such as evaporative cooling [2]. Nevertheless, it is interesting to ask whether lasers could be used in some other way to achieve phase space compression, especially when inelastic collisions preclude the use of evaporative cooling. In this paper we propose a method of laser cooling that is based on far-detuned lasers, leaving the atoms in the ground state and circumventing the need for a cycling transition.

At first sight this may seem to violate Liouville's theorem which ensures that phase space volume is preserved under Hamiltonian evolution. This question was studied by van der Meer in 1968. He was concerned with phase space compression in a particle accelerator, motivated by the possibility of increasing the luminosity of the antiproton beam at CERN [3,4]. In response to this challenge, van der Meer devised an approach, stochastic cooling, which ultimately enabled the discovery of the W and Z bosons [5]. The idea is based on the realization that the phase space distribution of a *finite* number of particles can be thought of as points surrounded by empty space. We may distort phase space so that individual particles are displaced towards the center of the distribution. To implement this idea requires a measurement and a kick that can both act selectively on particular regions of phase space. This does not violate Liouville's theorem because we are merely exchanging sections of phase space to the extent allowed by the Hamiltonian dynamics. Furthermore, the number of particles is conserved. We note that this approach is valid in a ''classical regime'' where the individual particle wave packets can be ignored compared to the separation between particles in phase space.

The simplest feedback scheme is to measure the mean momentum (or position) of the cloud, amplify the signal, and apply a kick to center the distribution to zero. After the kick, the next step is a remixing of position and momentum on some longer characteristic time scale. An extension of stochastic cooling was recently proposed [6] using finer spatial resolution, enabling a multiple subdivision of each particle bunch. The resulting sensitivity to higher-order correlations of the distribution can dramatically improve the efficiency of stochastic cooling.

We begin by demonstrating the basic mechanism as well as the advantages of spatially resolved stochastic cooling in a simple one-dimensional model. Consider pairs of numbers (q_i, p_i), $i=1, \ldots, N$, denoting the positions and momenta of N particles in phase space, chosen from *independent* Gaussian distributions. The spatial distribution is then sliced into n_p intervals of width Δq_j, $j=1, \ldots, n_p$, which may or may not be equal. Each cooling cycle consists of two stages. (i) For one or more intervals, the average momentum $\langle p \rangle_j$ is computed using only those p_i whose corresponding q_i lie in the interval Δq_j. These momenta are then shifted by $-\langle p \rangle_j$. (ii) Remixing is achieved by means of the harmonic rotation:

$$p_i' = p_i \cos\alpha - q_i \sin\alpha, \tag{1}$$

$$q_i' = p_i \sin\alpha + q_i \cos\alpha, \tag{2}$$

where the angle α (equal to or greater than ωt_m where ω is the oscillator frequency and t_m the mixing time) can be taken to be fixed or random. The procedure is then repeated and the ''time dependence'' of the emittance $\sigma_p \sigma_q$, where σ_p and σ_q are the widths in momentum and position, is used to assess the cooling. Variations of this simple scheme were also considered to optimize the cooling after a fixed interaction time. It should be noted that the remixing is needed to ensure that different particles are addressed at every iteration.

The results of a particular simulation are shown in Fig. 1, where an initial cloud of 10^4 particles was subjected to 10^4 cooling cycles. The solid line corresponds to the situation where fluctuations in the entire cloud are measured and corrected $(n_p=1)$. The calculation shows small cooling which is not evident in the figure. In contrast, even a single spatially resolved measurement and correction leads to a drastic reduction in the time scale for cooling. This is shown by the dot-dashed curve where the measurement is made in a slice of width $0.2\sigma_q$ centered at σ_q. This corresponds to a nega-

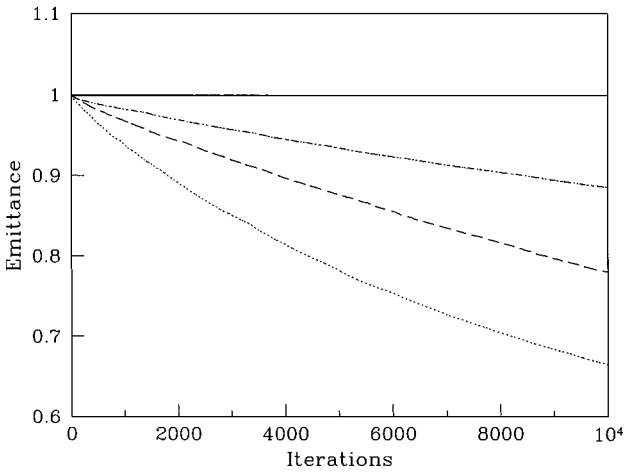

FIG. 1. Emittance (the product of position and momentum widths) as a function of the number of cooling cycles. Four cases are shown where either the number of partitions or the location of the measurement slice is varied. The solid line corresponds to addressing the fluctuations in the entire cloud and results in no significant reduction in emittance over the time shown. One spatially resolved measurement at a fixed location (dot-dashed) or variable location (short-dashed) leads to an improvement of several orders of magnitude in cooling. Increasing to two measurements (dotted) further enhances the effect. In all cases, the number of particles $N=10^4$. The single measurement considered a slice $0.2\sigma_q$ wide centered either at σ_q (long-dashed) or randomly chosen (short-dashed) between $0-2\sigma_q$. The two measurement case considered slice width $0.1\sigma_q$ centered randomly in the interval $(-\sigma_q,\sigma_q)$.

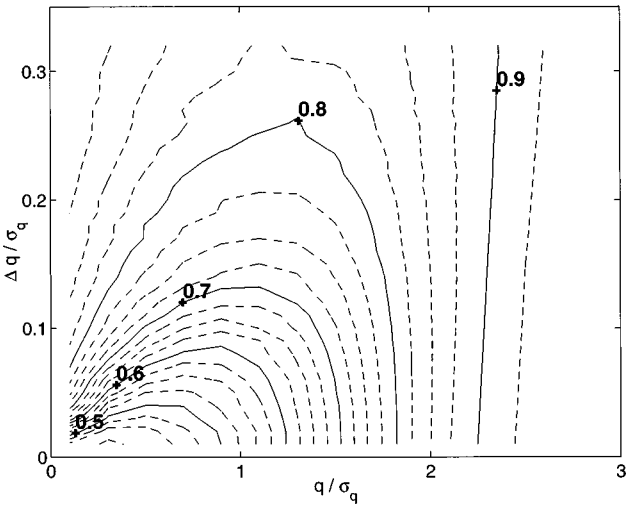

FIG. 2. Contour plot of the variation in final emittance as a function of slice location and slice width for $N=10^4$, 10^4 cycles, and 2 slices.

tive $\langle p\rangle_{j0}$ kick and zero kick for $j\neq j_0$. The result can be significantly improved by either randomly varying the location of the slice within the initial cloud (short-dashed line) or by increasing the number of measurement slices (dotted line). We believe that the dramatic improvement in cooling efficiency with spatial resolution is due to higher-order correlations that are addressed in the measurement and feedback scheme [6].

The reduction in emittance as a function of slice location and width is best displayed as a contour plot, shown in Fig. 2. The emittance at the end of 10^4 cycles is shown, starting from the same initial cloud as in the earlier figure. Equiemittance contours are drawn as a function of slice location and slice width (both measured with respect to the initial σ_q). Clearly, measuring and correcting small numbers of particles is the most efficient though not the most tractable in an experimental context. What is more significant is that, for more modest reduction in emittance, the optimal range is quite broad.

To apply stochastic cooling to atoms or molecules we must provide an iterative method to capture the essentials of the method: (a) measure the momentum distribution and detect the fluctuations, (b) apply a kick that shifts the mean to zero momentum, and (c) remix position and momentum in a harmonic (or anharmonic) potential. We present below a specific realization for each step using established experimental techniques in atomic physics [7].

For the measurement step (a) in the cooling process, we propose using a stimulated optical process with far-detuned lasers [8–11]. The basic configuration consists of two laser beams that cross at a small angle θ. The beams have equal intensity I and large detuning Δ from the atomic transition, but different frequencies. Scattering of photons from one beam (designated the pump) to the other (probe) depends on the velocity distribution of the atoms. The power transmitted in the probe beam, as a function of the frequency difference between the beams, exhibits a dispersive line shape which was shown to be the derivative of the velocity distribution. This method, therefore, should enable *in situ* velocimetry that is spatially resolved to the region of overlap of the two beams. This configuration is most natural when the atomic distribution in three dimensions is ''cigar'' shaped, with the pump and probe beams nearly normal to the long axis. The region of beam overlap then constitutes a slice of the ''cigar'' along the axis, and the velocity measurement is in that same direction.

As a first condition, it is clear that we must be able to resolve the asymmetry in the average velocity of the finite sample. This fluctuation is of order $N^{-1/2}$, where N is the number of atoms that are being measured. The fractional variation in probe power, R, must therefore be large compared with $N^{1/2}R_0$, where R_0 is the smallest detectable power variation. Using the scaling of R with I, Δ, and the temperature T, the resulting condition is

$$R\equiv\alpha I^3/\Delta^4T^2>\sqrt{N}R_0, \tag{3}$$

where the proportionality constant α depends on the details of the atomic species [9].

The measurement process leads to heating which comes from two sources. The first is due to absorption followed by spontaneous emission. The scaling of the resulting momentum transfer (measured in units of photon recoils) is

$$\beta NI\tau/\Delta^2, \tag{4}$$

where τ is the measurement time and β is again atom specific. It is clear that this contribution is negligible for sufficiently large detuning [12]. The second source of heating is due to momentum transfer from the standing wave, created

by the pump and probe beams. The small angle between the beams helps to reduce this heating effect which scales (for sufficiently short times) as [13]

$$\eta N I \theta \tau / \Delta, \tag{5}$$

where η is a proportionality constant. These two heating effects add in quadrature and the choice of parameters is governed by the condition that the heating induced by the measurement must be smaller than the asymmetry we wish to detect. To a first approximation, the fluctuations in the velocity distribution can be considered to result in a shifted Gaussian. This means that the direction and size of the asymmetry could be determined by performing two measurements of velocity groups on either side of zero momentum.

The frequency difference between two beams over the dispersive line shape is of the form

$$\zeta \theta T^{1/2}. \tag{6}$$

The inverse measurement time must be small enough to resolve this line shape placing an additional constraint on the crossing angle.

Step (b) in the cooling process consists of a spatially resolved kick that shifts the mean momentum to zero for the same set of atoms that were measured in step (a). One particular realization would be to trap atoms in a far-detuned standing wave that is accelerated [14]. The standing wave must be turned on and off adiabatically in order to avoid heating, and the acceleration must be small enough to avoid loss due to tunneling. The standing wave can be formed at an angle that is somewhat larger than in the measurement beams, using a separate far-detuned laser, and spontaneous scattering must be minimized as before.

The final step, (c), requires remixing of momentum and position so that a fresh distribution can be addressed in the next iteration. This stage allows fluctuations in momentum to emerge again and is an essential part of the cycle. The simplest configuration is a harmonic well, although correlations build up over time that inhibit cooling. This effect can be minimized by random remixing times, trap anharmonicity, or collisions. Finally, the duration of the first two steps [(a) and (b)] must be small compared with the remixing time.

Paramagnetic atoms and molecules can be magnetically trapped using cryogenic buffer gas cooling [15]. This method was successfully used to trap europium [16], and appears very promising for trapping other atomic species and molecules. The initial temperature for those experiments was below 250 mK, using a dilution refrigerator. The density was assumed to be large enough to enable further cooling by evaporation. Our method of laser cooling may be able to increase phase space density to a point where evaporative cooling could then take over.

To illustrate our method we consider the case of cesium atoms because the individual components of our proposed method have all been experimentally observed in this system, and it is therefore likely to serve as a first experimental testing ground. The laser wavelength in this case is 852 nm, and we assume that the atomic density is 10^{11} cm^{-3}. It is possible to find parameter regimes for which the above conditions are approximately satisfied, and an iterative cycle should cool the cloud, though these numbers serve only as a rough point of reference. We assume that each slice consists of 10^3 atoms with an initial temperature of 100 mK which can be magnetically confined. For the measurement stage we consider the following parameters: an intensity of 10^5 mW/cm^2 (corresponding to a power of 10 mW focused to an area of 10^{-4} cm^2), a detuning of 10 GHz from resonance, an angle of 50 mrad, and a measurement duration of 500 ns. We also assume that the minimum detectable relative power is $\delta_p = 10^{-6}$.

With these parameters, the fractional variation in probe power, R, is equal to 1.5×10^{-3}. This should be able to resolve a 3% asymmetry in the momentum distribution due to the finite number of atoms that are being measured. This asymmetry at the given temperature is approximately 25 photon recoils (the one-photon recoil velocity is 3.5 mm/s). In comparison, the heating from the measurement is estimated to be approximately three photon recoils from stimulated scattering, and 0.006 photon recoils from spontaneous scattering.

For the kicking stage a standing wave must trap the atoms in a particular slice, and accelerate them by the appropriate momentum shift. We consider the following parameters: a standing wave with an intensity of 400 mW in each beam with a spot size of 10^{-4} cm^2 (to match the measurement stage), and a detuning of 8 THz. The corresponding well depth would be 600 recoil energies, sufficient to trap the initial distribution. It should then be possible to accelerate the atoms over ten recoils in less than 1 ms, which should be considerably shorter than the remixing time, and with the probability of spontaneous scattering less than 0.25%. The exact conditions for adiabaticity must also be examined carefully for this step in order to avoid heating.

Two important questions to address are the magnitude of the cooling rate and the ultimate temperature that can be reached. We can place an upper bound on the cooling rate using the following argument. Let the average energy per particle be ϵ. If the fluctuations, at each iteration, scale with the square root of the number of particles, the amount of energy removed from the ensemble is $\epsilon/2$, independent of the number of particles that is being measured and kicked. Therefore to get significant cooling of the ensemble, the number of iterations should be at least twice the number of particles. This would suggest that the best strategy is to make as many spatially resolved measurements within a period of the trap in order to minimize the total cooling time. This is only an upper bound, because correlations can build up over time that reduce the fluctuations. It should also be noted that although the distribution may appear thermal, the iterative process leads to a complicated dependence on the history, and hence is non-Markovian. Further, the ultimate temperature achievable via stochastic cooling is limited not just by the heating associated with each measurement, but is more typically determined by other heating processes (such as trap loss) which limit the interaction time, and hence the number of iterations. These considerations make it difficult to predict a more accurate cooling rate and final temperature, since they both depend critically on experimental details and are very system specific.

Stochastic cooling has become a very successful method in high-energy accelerators, in spite of enormous technologi-

cal challenges. The application of stochastic cooling to atomic and molecular physics presents similar challenges, and appears most suited to cooling of atoms that can be magnetically trapped and cryogenically cooled to around 1 K, but that cannot be further cooled by evaporation due to inelastic collisions.

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