ISSN 1054-660X, Laser Physics, 2007, Vol. 17, No. 7, pp. 1–4.

Single-Photon Atomic Cooling

G. N. Price, S. T. Bannerman, E. Narevicius, and M. G. Raizen

Center for Nonlinear Dynamics and Department of Physics, The University of Texas at Austin, Austin, TX 78712, USA
e-mail:
Received March 1, 2007

Abstract—

PACS numbers:
DOI: 10.1134/S1054660X0707@@@@

This paper is dedicated to the memory of Professor Herbert Walther, an outstanding scientist and an exceptional person. He has served as an inspiration to all of us and has set a standard of excellence to follow.

The backdrop of this work is the field of laser cooling and trapping, which has been a major area of study for the past 30 years [1]. One of the key requirements for laser cooling is an available cycling transition so that many photons can be scattered. The cooling is accomplished by momentum transfer from photons to atoms. Examples of laser cooling techniques include Doppler cooling, optical molasses, Sisyphus cooling, lattice cooling, VSCPT, and Raman cooling [1]. All of these methods rely on a cycling transition and on photon momentum transfer. However, these same requirements also have limited laser cooling to a small set of atoms in the periodic table, and have excluded molecules. The extension of cooling methods to other species is a topic of intense interest, both from the standpoint of fundamental science as well as possible applications. This area is especially relevant with the development of new nonlaser-based methods to produce cold (mK) atoms and molecules that can be trapped. These methods include buffer gas cooling [2], Stark decelerator [3], optical decelerator [4], moving nozzle [5], and atomic paddle [6, 7]. One elegant laser cooling method that relies on photon momentum transfer but does not require a cycling transition is "cavity cooling," originally proposed by Ritsch [8] and later by Vuletic and Chu [9] with subsequent experiments performed in cesium [10].

The starting point for the present work is the development of a new approach to phase space compression based on a one-way barrier for atoms. We showed that a combination of resonant and nonresonant light can be used to make such a barrier, which can be thought of as an "atom diode" [11–13]. An atom crossing this barrier scatters only one photon in order to get through. In a series of papers, we showed how this barrier can be used to compress atomic phase space [11, 12]. We also showed that the cooling mechanism is not based on photon momentum, but is, instead, informational cooling [14]. This provides the physical realization of a proposal by L. Szilard to use information theory to resolve the controversy of Maxwell's demon [15]. While our previous papers established the general method, only toy models were considered. In the present paper, we move beyond the toy model to show how a single-photon cooling scheme can be implemented in practice with real atoms. We also show how this same method can be extended to other atoms and to diatomic molecules.

We consider a magnetic quadrupole trap for rubidium-87. This is the simplest trap configuration and consists of two coils with currents in opposite directions, forming an anti-Helmholtz pair [1]. Atoms in a low-field seeking state will be trapped in a potential well, as illustrated in Fig. 1.

This trap is characterized by a large trap volume that is very deep (as high as 1K). While the zero magnetic field in the center will cause trap loss, it is negligible at sufficiently high temperatures. There are three ground-state levels that can be magnetically trapped: $F = 2$, $m_F = 2$; $F = 2$, $m_F = 1$; and $F = 1$, $m_F = -1$. Suppose we

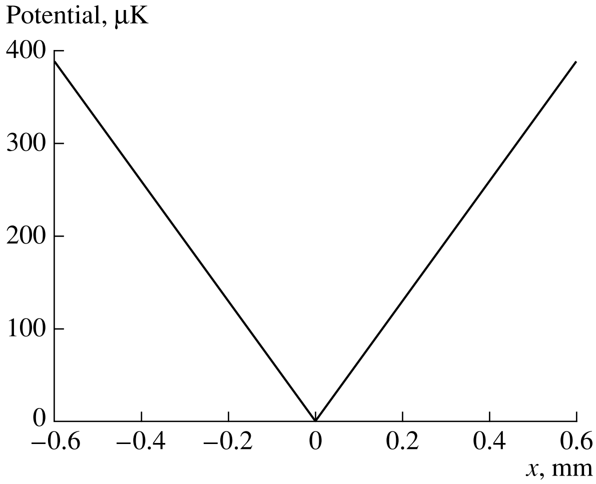

Fig. 1. Potential energy of a low-field seeking state in a magnetic quadrupole trap.

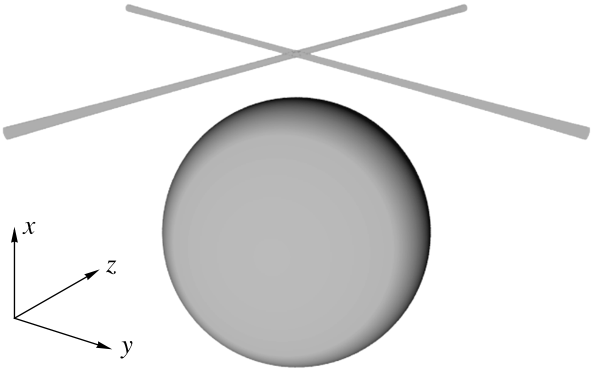

Fig. 2. Schematic of crossed laser beams above a cloud of magnetically trapped atoms. Gravity is in the x direction as shown in the figure.

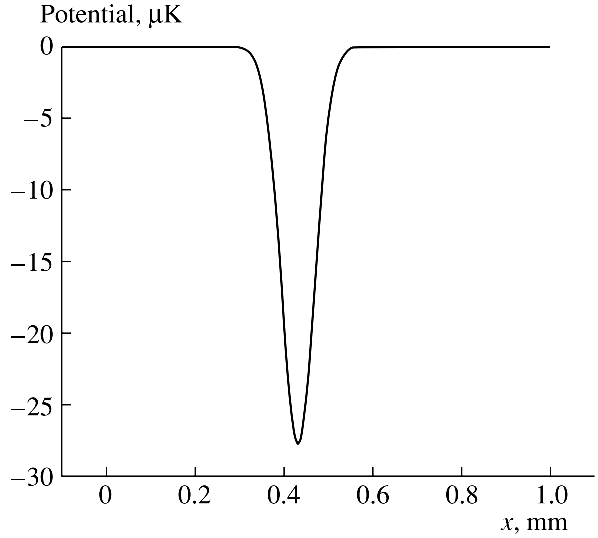

Fig. 3. Potential created by the crossed laser beams using realistic parameters.

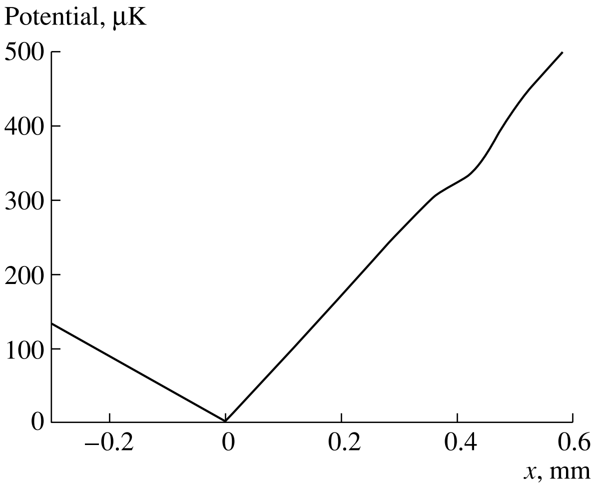

Fig. 4. Effective potential for the combined magnetic and optical traps.

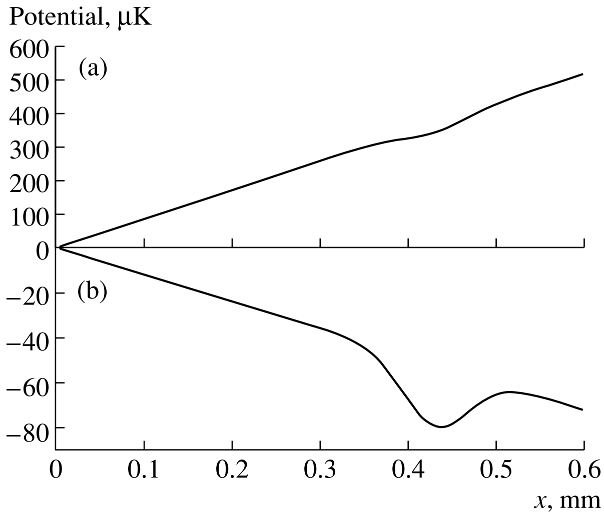

Fig. 5. (a) Effective potential for the combined magnetic and optical traps, for atoms in the $F = 2$, $m_F = 2$ state; (b) effective potential for the combined magnetic and optical traps, for atoms in the $F = 1$, $m_F = 1$ state.

start with all the atoms trapped in the $F = 2$, $m_F = 2$ state and we want to compress phase space further. The standard method to date has been evaporative cooling, whereby hot atoms are removed from the trap by driving an RF spin-flip transition, and the remaining atoms equilibrate by collisions. We propose, here, a different approach using optical transitions. Consider an optical dipole trap that consists of two crossed laser beams at 1064 nm, as illustrated in Fig. 2. These beams create an attractive conservative potential for the atoms, as shown in Fig. 3.

Such traps are characterized by a small trap volume and depth (typically 10 mK or less). Can we find a way to load atoms from the large magnetic trap into the small dipole trap? Let us assume that the dipole trapped is positioned in the wings of the magnetic trap. The combined magnetic and optical potential is shown in Fig. 4 (gravity is also included). A small dimple on the right side is evident, but it is too small to create a bound state. We, next, observe that another state, $F = 1$, $m_F = 1$, has a bound state in the optical trap, although the gradient of the magnetic trap is reversed compared with the $F = 2$, $m_F = 2$ state, indicating that the former is a high-field seeker. The potentials for the two states are shown in Figs. 5a and 5b. The reason for the formation

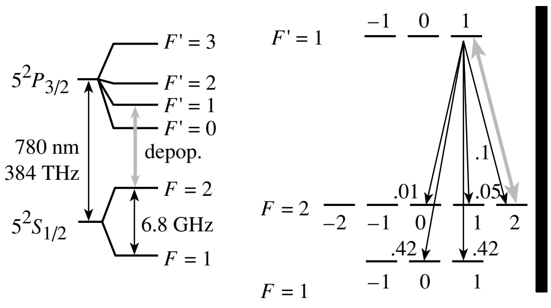

Fig. 6. Schematic of the energy levels in Rb-87 showing the branching ratios of the decay of the excited $F' = 1$ state. The energy level diagram of the D_2 transition is shown on the left side (not to scale).

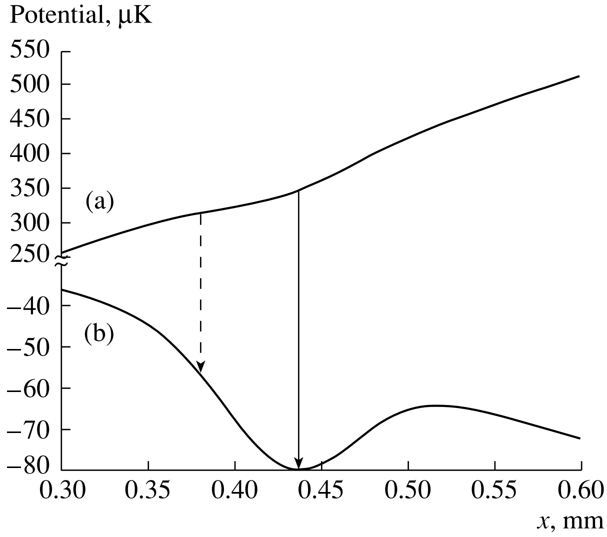

Fig. 7. Transitions induced by the depopulation beam, depending on the spatial location of the beam. The solid line is the preferred location, and will lead to less heating than the dashed line.

of the bound state is that the magnetic tilt is only half of the value of the $F = 2$, $m_F = 2$ state.

This observation leads to the following idea: suppose we align a resonant beam with one of the 1064 nm beams, such that it is tuned from $F = 2$, $m_F = 2$ to the excited state $F' = 1$, $m_{F'} = 1$. This beam, which we call a depopulation beam, leads to absorption of one photon followed by spontaneous emission. The branching ratio for the decay is shown in Fig. 6. We can optically pump 42% of the atoms into that state with a single cycle of absorption and emission.

As atoms reach the region of the tweezer, they will encounter the depopulation beam. It is clear that the location of that beam within the optical tweezer beam is crucial. Two possible configurations are shown in Fig. 7. The ideal situation is when the atoms are transferred to the bottom of the potential well. In order to accomplish this goal, the depopulation beam must be more tightly focused than the tweezer beam.

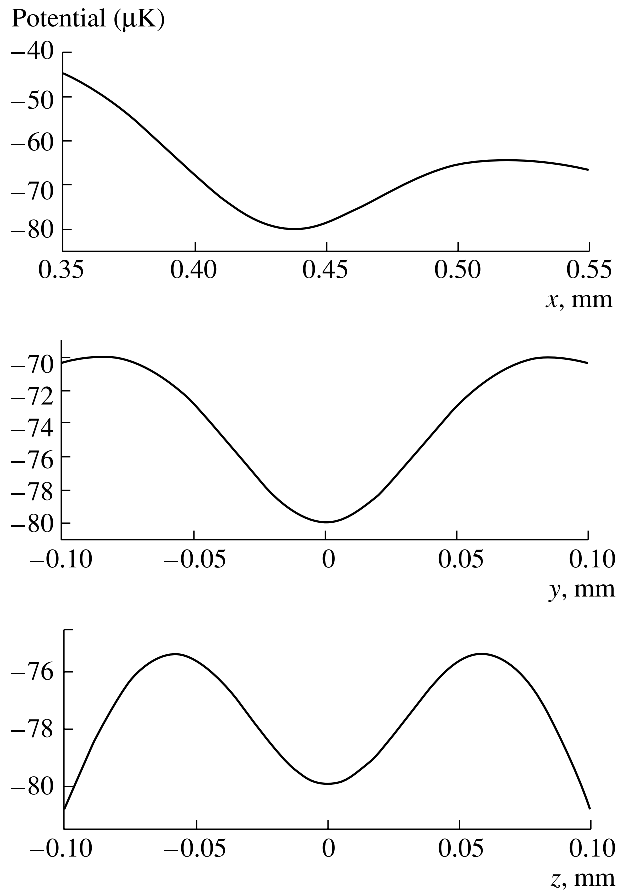

Fig. 8. Effective three-dimensional potential in the combined optical and magnetic trap for atoms in the $F = 1$, $m_F = 1$ state.

To complete the scheme, we must sweep the magnetic trap across the optical trap, so that we can catch atoms near their classical turning points where they have removed most of their kinetic energy. In practice, we can displace the magnetic trap with a magnetic field bias, and, then, raise the trap slowly. We must also consider gravity in a realistic analysis. The magnetic force on the $F = 1$, $m_F = 1$ atoms will tend to push the atoms upward, counteracting gravity to some extent. The resulting potential in the three directions is shown in Fig. 8 and the weakest direction is z, which is along the axis of symmetry of the quadrupole coils.

We now discuss some realistic parameters. The lowest temperature is limited to approximately 2 photon recoils, which is 800 nK for the case of rubidium. The heating rate in the optical dipole trap due to the depopulation beam is estimated to be 0.1 Hz. This heating is due to atoms in the $F = 1$ state absorbing a photon from the depopulation beam, tuned approximately 6.8 GHz away. If 10^6 atoms can be loaded into such a crossed dipole trap, the resulting density will be 1012 atoms/cm^3 and the phase space density will be 1/500. This should enable rapid evaporative cooling of the sample to Bose–Einstein condensation. The timescale for the accumulation of atoms in the smaller trap also needs to be understood. It clearly relies on sufficient ergodicity to provide mixing of the three degrees of freedom, and this question will be investigated in a future publication.

Beyond a first demonstration in rubidium, our basic technique should be widely applicable to other species, because only one photon, on average, is scattered. Application to the cooling of atomic Ca and Yb follows along similar lines to the method outlined in this paper and will be discussed in a future publication. Another possible application is the cooling of polar molecules. A recent paper describes ongoing efforts to trap polar molecules in a microwave trap [16]. This trap has many advantages, including a large trapping volume and depth, and the fact that it can trap high-field seekers. The microwave frequency is tuned close to a molecular rotational line, leading to resonant enhancement of the induced dipole. The $J = 0$ state experiences the largest dipole potential, with $J = 1$ and $J = 2$ successively smaller. The proposed loading of the molecules from a beam involves electronic excitation of incoming $J = 2$ molecules, with some fraction falling into the deeply bound $J = 0$ state. Once the molecules are in the trap, a similar method of crossed dipole beams (with visible lasers) together with a depopulation beam can be used to trap the molecules. The depopulation beam would excite molecules in the deeply bound $J = 0$ state and
1 some would decay into the more weaky bound $J = 1$ or $J = 2$ states.

ACKNOWLEDGMENTS

We acknowledge support from the R.A. Welch Foundation, the National Science Foundation, Michigan FOCUS Center, and the Sid. W. Richardson Foundation.

REFERENCES

1. H. J. Metcalf and P. van der Straten, Laser Cooling and Trapping, Springer Verlag, 1999.
2. J. M. Doyle, B. Friedrich, J. Kim, and D. Patterson, Phys. Rev. A **52**, R2515 (1995); J. D. Weinstein, R. deCarvalho, T. Guillet, et al., Nature **395**, 148 (1998).
3. H. L. Bethlem, G. Berden, and G. Meijer, Phys. Rev. Lett. **83**, 1558 (1999).
4. R. Fulton, A. I. Bishop, and P. F. Barker, Phys. Rev. Lett. **93**, 243004 (2004).
5. M. Gupta, and D. Herschbach, J. Phys. Chem. **105**, 1626 (2001).
6. A. Libson, M. Riedel, G. Bronshtein, et al., New J. Phys. **8**, 77 (2006).
7. E. Narevicius, A. Libson, M. F. Riedel, et al., submitted to Phys. Rev. Lett., physics/0701003.
8. P. Horak, G. Hechenblaikner, K. M. Gheri, et al., Phys. Rev. Lett. **79**, 4974 (1997).
9. V. Vuletic and S. Chu, Phys. Rev. Lett. **84**, 3787 (2000).
10. H. W. Chan, A. T. Black, and V. Vuletic, Phys. Rev. Lett. **90**, 063003 (2003).
11. M. G. Raizen, A. M. Dudarev, Q. Niu, and N. Fisch, Phys. Rev. Lett. **94**, 053003 (2005).
12. A. Dudarev, M. Marder, Q. Niu, et al., Europhys. Lett. **70**, 761 (2005).
13. A. Ruschhaupt and J. G. Muga, Phys. Rev. A **70**, 261604 (2004).
14. A. Ruschhaupt, J. G. Muga, and M. G. Raizen, J. Phys. B **39**, 3833 (2006).
15. L. Szilard, Z. Phys. **53**, 840 (1929).
16. D. DeMille, D. R. Glenn, and J. Petricka, Eur. Phys. J. D **31**, 375 (2004).

SPELL: 1. weaky