Circular magneto-optical trap for neutral atoms

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We propose and experimentally demonstrate a novel scheme to magneto-optically trap neutral atoms in a ring shaped trap that can be used to transfer atoms into a circular magnetic trap with high density. This in turn enables to evaporatively cool atoms and study the behaviour of ultra cold gases in a periodic 2-dimensional potential. The circular magneto-optical trap itself is also of interest to investigate the properties of magneto-optical trap of deformed shape, such as reduction of photon-reabsorption.

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I. INTRODUCTION

Ultra cold gases tightly confined in a 2-dimensional (2-D) potential are expected to exhibit various features which are not seen in a bulk 3-D system, and are extensively investigated both theoretically and experimentally. These features include anomalous quantum fluctuations of quasi-condensate, the fermionic behaviour of a bosonic gas in the Tonks-Girardeau regime, or the quantized conductance through such a confining potential. In most experimental studies linear magnetic traps (MT) or optical traps of finite length are used and small changes of the potential in the longitudinal direction are unavoidable. A ring MT on the other hand has in principle a flat potential along the trap ring, and because it is a periodic system, additional phenomena such as persistent currents or Josephson effects are expected to be observed. For the practical side, the study of evaporative cooling process in 2-D potential is of importance to achieve a continuous atom laser. Several groups have so far realized magnetic storage rings that are mainly aimed to construct a Mach-Zehnder type interferometer for the high precision gyroscope application and thus the atomic density should be kept low to avoid the unwanted atom-atom interaction. In fact, these traps are loaded from a conventional 3-D MOT or 3-D MT and the density of atoms is insufficient to start evaporative cooling when atoms are uniformly spread in the trap. In this letter we propose a new type of MOT in which atoms are trapped along a circle. Because of the large trapping volume and the trap shape matching, an efficient loading of circular MT from this ring MOT should be possible, which will enable the evaporative cooling of atoms in the circular MT. We also expect that the problem of fragmentation of the condensate due to the irregularities of the trap potential will be reduced by rotating atoms in the circular trap, that is not possible for the linear (box-like in the longitudinal direction) 1-D potential.

As an MOT of reduced dimension, suppression of photon-reabsorption and high density trap are also expected.

II. BASIC IDEA

A ring MOT is realized by modifying the magnetic field of a conventional 3-D MOT. Fig. 1(a) is a schematic drawing of the popular 6-beam MOT. An anti-Helmholtz coils pair generates a quadrupole magnetic field at the center and the trapping laser beams approaching the center of the trap parallel (anti-parallel) to the magnetic field have (−) polarization so that the atoms are trapped at the zero of the magnetic field. Now we add a small inner quadrupole coils pair (fig. 1(b)) to this system. By putting appropriate currents to this coils pair in the opposite direction, the original zero of the magnetic field is expelled from the center to form a ring. With the trapping laser beams unchanged, atoms are now pulled toward this ring (fig. 1(c)). Because the atoms are trapped at the zero of the magnetic field, we can switch to the ring MT just by turning off the laser beams. In MT, spin-flip of trapped atoms can be avoided by using TORT (time-orbiting ring trap) technique proposed in [10], or by putting a current carrying wire on the symmetry axis (z-axis) which generates an azimuthal magnetic field Bθ. When the trap with this current carrying wire is operated as an MOT, Bθ causes imbalance in the scattering force along the trap ring and atoms begin to rotate. The final rotation speed (mean velocity vrot) is determined by the balance between the Zeeman shift by Bθ and the Doppler shift by vrot. This can be used to generate a laser cooled atomic ensemble that has finite mean velocity, which might be useful for some applications, such as the observation of the glory scattering.

III. SOME MATHEMATICS

In vacuum (i.e. in the absence of currents) a static magnetic field B is derived from a (magnetic) scalar potential \( \phi \): \( \vec{B} = -\nabla \phi \). Let us consider the magnetic field generated by a set of coils which has rotation symmetry around z-axis and anti-symmetry for z-axis inversion.
Now we expand $\phi$ this, we calculate the 5th order in $z$ $\phi$ with $\partial$.

Again field gradients on these points are calculated as of zero magnetic field of radius $a$.

Thus $\phi = \phi(z, r)$, $\phi(-z, r) = \phi(z, r)$ with $r \equiv \sqrt{x^2 + y^2}$.

Now we expand $\phi$ near the origin (center of the trap) to the 5th order in $z$ and $r$:

$$\phi = a_2 \phi_2 + a_4 \phi_4$$

with $\phi_2 = z^2 - \frac{1}{4} r^2$, $\phi_4 = z^4 - 3r^2z^2 + \frac{3}{8} r^4$ [14]. From this, we calculate

$$B_r(0, r) = -\frac{3}{2} a_4 r (r^2 - \frac{2a_2}{3a_4}),$$

$$B_z(z, 0) = -4a_4 z(z^2 + \frac{a_2}{2a_4}).$$

If $a_2a_4 > 0$, from [2], we see that there is a circle of zero magnetic field of radius $r_{trap} = \sqrt{\frac{2a_2}{a_4}}$. Field gradient on this ring is calculated as $\partial_r B_r|_{(0, r_{trap})} = -\partial_z B_z|_{(0, r_{trap})} = -2a_2$. From [4] on the other hand, in case $a_2a_4 < 0$, there will be two additional points of zero magnetic field on $z$-axis at $z_d = \pm \sqrt{\frac{a_2}{2a_4}}$.

Again field gradients on these points are calculated as $\partial_r B_r|_{(z_d, 0)} = -\sqrt{\frac{a_2}{2a_4}} \partial_z B_z|_{(z_d, 0)} = -2a_2$. Because the field gradients are the same for both points, we can simultaneously trap atoms on these points (“double MOT”) by appropriately choosing the direction of currents, or the helicity of the trapping laser beams.

The profile of the magnetic field is depicted in fig. 2 for $a_2a_4 > 0$, $a_2 = 0$ (octapole field [12]), and $a_2a_4 < 0$ [12].

In a more general case where the system has no antisymmetry under the inversion of $z$-axis, odd order terms in $z$ also come in the equation [11]. This will rotate the principal axes of the quadratic field in $zr$-plane, and if rotated by $\pi/4$ (which is the case when the system is symmetric under $z \rightarrow -z$), the restoring force toward the ring disappears.

**IV. EXPERIMENT**

We have performed a preliminary experiment to prove the principle of this trap. A sodium dispencer (SAES Getters) is placed 15cm away from the center of the trap, and atoms are catched directly by the MOT without using Zeeman slower. We use a ring dye laser (Coherent CR699-21 with Rhodamine 6G) for the trapping laser (about 50mW in each arms with diameter ~15mm) and an electro-optical modulator to generate a 1.77GHz sideband for the repumping. The design of the trapping coils is shown in fig. 4. Parameters of these coils in [11] are given by

$$a_2 = A_{out2} I_{out} - A_{in2} I_{in}$$

$$a_4 = A_{out4} I_{out} - A_{in4} I_{in}$$

with $A_{in2} = 6.5$ Gauss cm$^{-1}$A$^{-1}$, $A_{out2} = 2.0$ Gauss cm$^{-1}$A$^{-1}$, $A_{in4} = 1.7$ Gauss cm$^{-3}$A$^{-1}$, $A_{out4} = 0.0$ Gauss cm$^{-3}$A$^{-1}$ ($I_{out}$ and $I_{in}$ are the currents flowing in the outer and inner coils, respectively). Maximum currents for the both coils are $I_{max} = 18$A. In fig. 4 we show pictures (fluorescence images) of MOTs under the normal and the circular MOT conditions. The inhomogeneity of the atomic cloud density of the circular MOT can be explained by the insufficient beam quality of the trapping lasers. Another possible account for the inhomogeneity comes from the fact that the circle of zero magnetic field can easily be destroyed by an external stray magnetic field (or by the small misalignment of the trap coils). For example, consider the perturbation by a small uniform magnetic field in $+x$-direction (a slice of the magnetic field in $xy$-plane is shown in fig. 5). On $x$-axis, the points of zero magnetic field are just shifted by the external field in $+x$-direction. In the other area, however, there are no local zero points and points of local minima form again a circle, along which atoms are accumulated toward the point of zero magnetic field on the right handside of the circle. We also note in fig. 4(b) that the axis of the trap ring is tilted slightly. This is due to the mismatch of the centers of the vertical trapping beams, which was not a serious concern for the conventional MOT.
FIG. 2: Profile of the magnetic field. Magnetic field lines are shown for (a) \(a_2a_4 > 0\) (ring MOT), (b) \(a_2 = 0\) (octapole field), and (c) \(a_2a_4 < 0\) (“double MOT”).

FIG. 3: Design of the trap coils. A trap glass cell is sandwiched between pairs of outer and inner coils. The coils are cooled by water.

V. CONCLUSION AND OUTLOOK

We have proposed and experimentally demonstrated a novel method to magneto-optically trap neutral atoms in a circular trap that can be used to load laser cooled atoms into a circular magnetic trap. This method opens up a path to generate and investigate 1-dimensional cold gas with periodic boundary condition. We are now working on constructing a new setup using electromagnets to achieve much tighter confinement.

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[14] Generally, nth order term is given by \(\phi_n = \sum_{n=0}^{\infty} (-1)^n \binom{2\nu}{n} \frac{n!}{(n-2\nu)!} z^{n-2\nu} \left(\frac{r}{z}\right)^{2\nu}\).
[15] It is known that a 3-D MOT with 2n-pole magnetic field is possible only for \(n = 2\).
[16] In a cylindrically symmetric system, field lines can be drawn as contour lines of the function \(f(z,r) = \int_0^r \rho \partial_\rho \phi(z,\rho) \, d\rho\).
FIG. 4: (a) Normal MOT ($I_L = 9\, \text{A}, I_S = 0\, \text{A}$, and $\frac{\partial}{\partial z} B_z(0, 0) = -2\frac{\partial}{\partial r} B_r(0, 0) = 18\, \text{Gauss/cm}$). (b) Circular MOT ($I_L = 18\, \text{A}$, $I_S = 6\, \text{A}$, and $\frac{\partial}{\partial z} B_z(0, r_{\text{ring}}) = \frac{\partial}{\partial r} B_r(0, r_{\text{ring}}) = 4.5\, \text{Gauss/cm}$ with $r_{\text{ring}} = 3.8\, \text{mm}$).

FIG. 5: A slice of magnetic field in $xy$-plane under the perturbation by a constant external field in $+x$-direction.