An effective method of accelerating Bose gases using magnetic coils*

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Based on the experimental device which is a non-uniform magnetic field to trap an atom, we show how to obtain a certain velocity of a Bose gas by controlling the magnetic coils. By comparing the relationship of the different current supply and delay time versus the ultimate velocity of the atom, we theoretically predict the method of accelerating the gases to an expected velocity. This method is of great convenience and significance for the applications in cold atom physics and precision measurements.

Keywords: magnetic control, Bose–Einstein condensation

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1. Introduction

The realization of Bose–Einstein condensation (BEC) has rendered studies of quantum phenomena at ultra-cold temperature possible. It has become a very powerful tool in the fundamental research such as atomic interferometry,[1] Bragg diffraction,[2] atomic clock,[3,4] and quantum phase transition.[5] For all these research areas, manipulating the external state of a cold atom, i.e., its momentum, is a key technique. So far, most of the experimental studies have been implemented by accelerating atoms. In Ref. [6], Bragg diffraction that indicates the long-range coherence of BEC was studied by using a moving atom cloud. The condensate was accelerated and the transition from the pure super-radiant regime to the Bragg scattering regime appeared. Bloch oscillations of Bose–Einstein condensates with a certain velocity in the one-dimensional optical lattice was observed in Ref. [7]. However, the average velocity of the BEC was derived from the occupation numbers of the different momentum states after a flight time, which was not directly seen from the imaging picture.

There are several methods driving neutral atoms to move. The usual way is using a pair of counter-propagating Raman laser beams with a proper frequency difference to illuminate atoms. The energy generated from the light frequency difference is absorbed and then transferred to the atom's kinetic energy. For driving atoms, complicated optical accessories are applied to shift the light frequency and an additional light path is needed. With two designed light pulses, which were also produced by two counter-propagating light beams with the same frequency, a BEC cloud can be split into several momentum parts. However, pure momentum is impossible to achieve by using this kind of pulse and strong light power is necessary.[8] Here we present an approach to accelerate the cold atoms to a certain velocity by utilizing a dynamic magnetic field. First we elaborate the interactions between neutral atom and magnetic field. Then by adjusting the parameters of the magnetic system, we can control the acceleration of the atom to an expected velocity. Our theoretical and experimental results agree well. Finally, we give the maximal values of atom velocity with different conditions under this method, in theory.

2. Experiment

The common procedure to generate a BEC is transforming atoms that are in magnetic–optical traps (MOT) into magnetic trap. After loading the cold atoms into the magnetic trap, evaporation cooling is used to remove the high kinetic energy atoms. About one-thousandth of atoms can be kept which finally become the BEC. In our experiment, we use quadrupole coils (anti-Helmholtz coils) and an Ioffe coil[9] to constitute a quadrupole-Ioffe-configuration (QUIC) trap[10] (Fig. 1). All the coils are settled around an ultra-vacuum glass container on a copper supporter that can be cooled by water. To prevent the eddy current in the copper frame when being energized, some crucial parts in the holder are fabricated with gaps.

The potential energy of atoms in the QUIC trap $U(r,z)$ can be written as

$$U(r,z) = U_0 + \frac{1}{2}m\omega_{\rm r}^2 r^2 + \frac{1}{2}m\omega_z^2 z^2, \tag{1}$$

where r is the radial direction, z is alone axial of the Ioffe coil, and $\omega_{\rm r}$ and ω_z are the radial frequency and axial frequency in the QUIC trap, respectively. The BEC in such a gradient magnetic field will be stressed by a force

$$\boldsymbol{F} = -\boldsymbol{\nabla}(-\mu\cdot\boldsymbol{B}) = -\boldsymbol{\nabla}(m_{\rm F}g_{\rm F}\mu_{\rm B}\boldsymbol{B}) = -\nabla(\mu_{\rm B}\boldsymbol{B}) \tag{2}$$

for an atom in $|F=2,m_{\rm F}=2\rangle$ state, where μ is the atomic magnetic moment and $\boldsymbol{B}$ is the magnetic intensity in the trapping area. When turning off the current in coils, the current is not perfectly decreased to zero immediately but with a decay

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time. In principle, we can choose different decay times of the currents in Ioffe and quadrupole coils to get a certain magnetic field that can accelerate atoms by gradient force $\boldsymbol{F}$. If the current in the Ioffe coil decays faster than in the quadrupole coil, then the atoms will move in a region where the quadrupole magnetic field has the major effect. In that case, atoms should be projected towards to the center of the quadrupole trap.

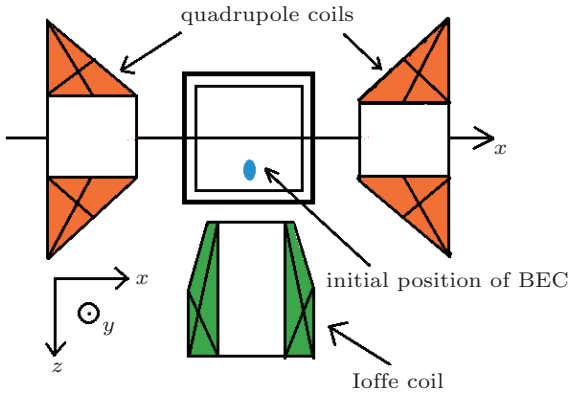


Fig. 1. (color online) The structure of the QUIC trap. The coils in orange are the quadruople coil, which consists of two coils with the same structure but inverse current (anti-Helmholtz coils), while the coil in green is called the Ioffe coil. The blue dot shows the initial position of BEC which is also the bottom of the static QUIC trap ($z_0 = 8.025$ mm).

With the force at direction z alone, the axial of the Ioffe coil[13] is

$$\begin{aligned}\boldsymbol{F}(z,t) &= m\ddot{z}(t) = -\mu_{\mathrm{B}}\frac{\partial B(z(t),t)}{\partial z}\\ &= -\mu_{\mathrm{B}}\left[I_i\frac{\partial}{\partial z}f_i(z)\,\mathrm{e}^{-t/\tau_i} + I_{\mathrm{q}}\frac{\partial}{\partial z}f_{\mathrm{q}}(z)\,\mathrm{e}^{-t/\tau_{\mathrm{q}}}\right], \quad (3)\end{aligned}$$

so we can get the expected atom velocity, where m is the atomic mass, f_{i} (f_{q}), I_{i} (I_{q}), and τ_{i} (τ_{q}) are respectively the structure function, driven currents, and decay time of the Ioffe-type (quadrupole) trap.[14] We achieved it by optimizing the discharging loop of the current control circuit. When shutting down the power supply system, the oscilloscope detected that the quadrupole current I_{q} and Ioffe current I_{i} attenuate in a pattern like exponent. The characteristic time of I_{i} is approximately 66 μs while I_{q} is 87 μs. In the whole process, there are magnetic zero points, which will cause the abscondence of an atom if approaching the points (Majorana transition). What we can assure is that the response of an atom to the external field is so retardant that most of the atoms are far from the bottom of the trap. With our calculations, when the current in both the Ioffe coil and the quadrupole coil is 21 A ($I_{\mathrm{i}} = I_{\mathrm{q}} = 21$ A), an atomic velocity of 1.7 mm·s^{-1} (corresponding to $0.5\hbar k$) can be achieved.

To make the trap work steadily, we need a stabilized power supply or constant current source controlled by digital or analogue signals. One of the advantages of the QUIC trap is that the current normally required is merely 21 A, so the power dissipation is merely 520 W, provided that the impedances of the quadrupole coil and the Ioffe coil are 0.7 Ω and 0.2 Ω, respectively. Using QUIC trap apparently makes the control and cooling much easier compared to using other traps. The power source is TAKASAGO's GP 35–50R. It has two operating modes: a constant voltage mode, in which the stability can reach 10^{-4}, and a constant current mode, in which the stability can reach 10^{-3}. We chose a constant voltage mode, and adopted self-made circuits to control the current in both the quadrupole coil and the Ioffe coil. By applying the negative feedback system, the stability of the circuit can reach 10^{-5}.

In our experiment, we prepared a cigar-shaped BEC sample of 10^5 ^{87}Rb atoms in the quadrupole-Ioffe configuration trap, of which the axial frequency is 20 Hz, the radial frequency is 220 Hz and the quantum state is $|F = 2, m_F = 2\rangle$. Before releasing, the atoms stay still in the bottom of the trap. Then we shut down the current of the QUIC trap that leads a horizontal projectile motion of BEC. In order to detect the location of atoms, after switching off the magnetic trap, we imaged the expanding cloud at releasing time Δt by using resonant probe light propagating along the x axis. The CCD camera[15] recorded a slight movement from left to right for approximately 3.67 μm within 1.8 ms, as well as an anti-parabola distribution of the condensate with the radial length vibrating periodically (Fig. 2). We study the atomic velocity from the center of the distribution movement within a certain time period Δt. After measuring the locations of the atom at different times, we can detect from (Fig. 3) that the atom, regardless of its acceleration which is not prominent in early time, travels in a constant velocity of 1.7 mm·s^{-1}.

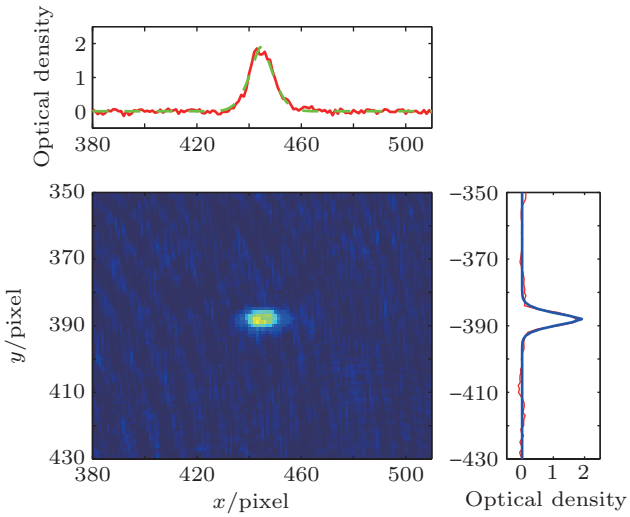


Fig. 2. (color online) The atomic number distribution in two dimensions after 1.8 ms, described by optical density. The subplot in the figure collects the data from the digital picture (red line) and fits into the anti-parabola distribution (green dash line and blue line) which indicate the Bose–Einstein condensate. (1 pixel≈ 6.8 μm).

By using this method of accelerating cold atoms, we are able to generate high enough atomic velocity theoretically. There are several factors influencing how atoms run in the trap,

which consequently contribute to the condition of the bottom and its vicinity, thus determining how an independent (without interaction) atom responds to the change of external field. We compared the two eminent factors, the current supply and the discrepancy of characteristic times of two parts of the coils.

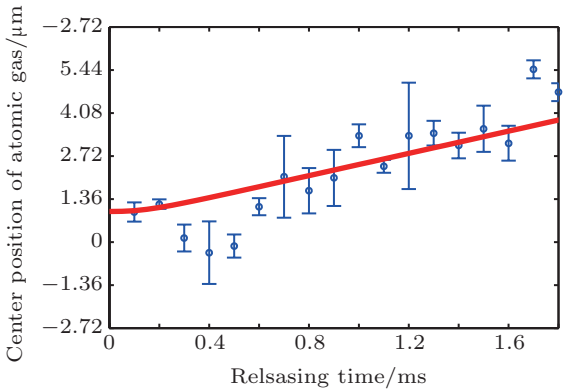


Fig. 3. (color online) The movement of atomic gas via different releasing time Δt. The blue dots show the experimental results, and each dot indicates the mean value of the data collected from the three repeated experiments. The red line is the theoretical curve with our experimental parameters as inputs, where $I_i = I_q = 21$ A, $\tau_i = 66$ μs and $\tau_q = 87$ μs.

Firstly, we study the difference of coils' current in both the Ioffe coil and the quadrupole coil with a fixed decay time (Fig. 4) (1000 μs for quadrupole, 1 μs for Ioffe). From the picture, we can sketchily see that the initial behaviors of the velocity are mutually different and the final velocity of the atom depends linearly on the current supply. The current only changes the shape of the bottom linearly, derived from the linear relationship of the current and magnetic intensity. However, it is hasty to conclude that the linear relationship of the final velocity and the current for the reactions of an atom are not linear. Fortunately, we already know that an atom like Rubidium responds so sluggishly that in the whole process, it is far from catching up with the movement of the bottom. With this approximation and the fugacity of the field, by judging the initial effect posing to the atom, the final velocities linearly depend on the current supply. With this condition at a maximal current value of 30 A, a velocity of 35$\hbar k$ can be achieved.

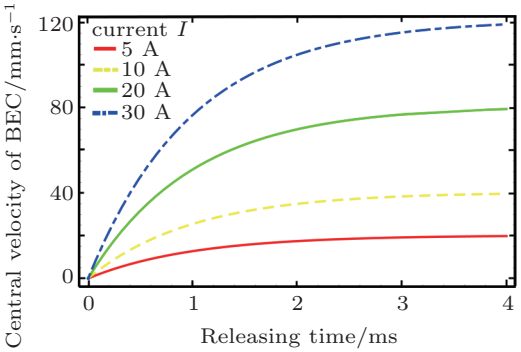


Fig. 4. (color online) The relations of velocity and time with different initial currents and with the same characteristic time of the Ioffe coil, 1 μs, and of the quadrupole coil, 1000 μs.

Then we calculate another situation. The current in both the Ioffe coil and the quadrupole coil is 30 A with $\tau_i = 1$ μs. By changing the characteristic time of quadrupole τ_q , we change the speed of the bottom of the trap. The initial accelerations are identical for the four curves, which means this factor does not affect the conduct at the beginning of shutting down the power due to the fact that it does not change the intensity but the position. Subsequently, this non-linear factor results in disparate accelerations at the point of the atom experience and the times the velocities become asymptotically flat. Unlike the first factor whose fives velocities almost end up a constant simultaneously, a larger discrepancy of the two characteristic times will exert a longer effect on the atom. The red curve ($\tau_q = 0.5$ ms) (Fig. 5) only experiences a millisecond reaching only 15$\hbar k$, whereas the purple curve($\tau_q = 5$ ms) has a much larger velocity of 97$\hbar k$ within 4 ms. Usually, it is more convenient to take advantage of this factor to accelerate atomic gases to an expected velocity. However, we should carefully choose parameters of the current delay time in order to make the accelerating duration time within a certain valid time. As in the gravitational field, after 5 ms the atoms will drop 123 μm from the center of the magnetic trap, this calculation model would no longer simulate the real condition.

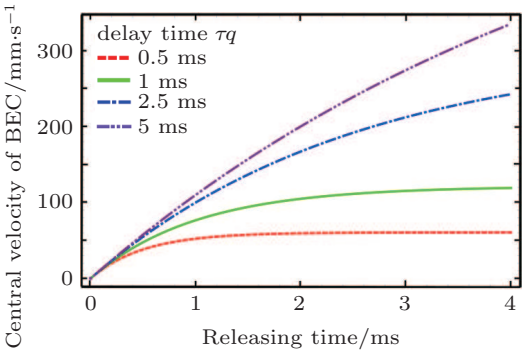


Fig. 5. (color online) The relations of velocity and time sharing the same initial current 30 A and the characteristic time of the Ioffe coil 1 μs, but with different characteristic time of the quadrupole.

3. Summary

In summary, we have both experimentally and theoretically studied the behavior of cold atoms in the magnetic trap. As the QUIC trap is a common trap generating BEC, it is very convenient to use this method without adding or changing the coil. With the current control electric circuit, we can generate a low-noise rapid-response quadrupole-Ioffe configuration trap. By using a different designed current delay time, that leads to a gradient magnetic field, atoms can be accelerated to an expected velocity. According to our calculations, an atomic velocity of 97$\hbar k$ can be achieved. In the subsequent experiment, we accelerated atomic gases within 400 ms to reach to a velocity of 0.32$\hbar k$ and observed a magneto-optical diffraction of ultra-cold atom.[16] In that case, this method can be taken

as an effective and convenient tool for moving BEC into the QUIC trap.

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