Measurement of spatial distribution of cold atoms in an integrating sphere

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In this paper, we present an experiment to measure the spatial distribution of cold atoms in a ceramic integrating sphere. An quadrupole field is applied after the atoms are cooled by diffuse light produced in the ceramic integrating sphere, thus the shift of atomic magnetic sub-levels are position-dependent. We move the anti-Helmholtz coil horizontally while keeping the probe laser beam resonant with the cold atoms at the zero magnetic field. The absorption of the probe beam gives the number of cold atoms at different position. The results show that at the center of the integrating sphere, less atoms exist due to the leakage of diffuse light into the hole connecting to the vacuum pump. The method we developed in this paper is useful to detect cold atoms in a region where imaging is not possible.

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Cooling atoms by diffuse light has received a lot of attention recently due to its important application in compact cold atom clock, the HORACE for example [1–5]. The HORACE has reached $2.2 \times 10^{-13} \tau^{-1/2}$ short term stability [5], and is expected to be further improved in microgravity environment [3]. Cooling atoms from a background vapor in a glass cell by diffuse light was first realized in cesium in 2001 [6], and then in rubidium in 2009 [7]. Typically, diffuse light is produced by multiple reflection of laser light at the inner surface of a hollow sphere with high-reflective medium which encloses the glass cell. Such a device is similar to an integrating sphere, which is normally used for photometric or radiometric measurements.

It is quite obvious that in a completely-enclosed sphere, if the reflectivity of the inner
Fig. 1: The schematic diagram for the principle of the method.

Surface is high enough, the light field in the sphere should be homogeneous. The distribution of cooled atoms in a homogeneous diffuse laser field should be homogeneously distributed in the region where the diffuse field exists. But in fact, the light field in the sphere is not homogenized due to several reasons, including the injection of laser light, hole in the sphere for the vacuum pump, inhomogeneous reflectivity of the inner surface of the sphere, and et.al. Such an inhomogeneity leads to inhomogeneous distribution of cooled atoms in the sphere. Esnault et al. suggested that the shape of cold atom cloud in the sphere has two lobes due to the leakage of diffuse light at two holes used to connect the vacuum pump and atom reservoir [4], but no convincing results have been shown, and no direct measurement of the shape has been done so far due to the difficulties to measure the shape in a closed hollow sphere, in which imaging of fluorescence of cold atom cloud is not possible. Measuring and reshaping the cold atom cloud are very important works for the compact cold atom clock, and thus it is necessary to measure the distribution of cold atoms in the sphere.

In this work, we developed a method to measure the spatial distribution of cold atoms in a closed sphere. The principle is similar to that of magneto-optic trap (MOT), as shown in Fig. 1. In the MOT, an anti-Helmholtz coil is used to create a quadrupole magnetic field with zero at the center. With a pair of counter-propagating $\sigma^+ - \sigma^-$ laser lights, the force on an atom is position-dependent because of the position-dependent energy shift of the atomic magnetic sub-levels, and thus atoms in the MOT can be cooled and trapped [8]. In our case, the atoms are pre-cooled by diffuse light [6, 7]. The cooled atoms at different positions encounter different magnetic fields, and thus different energy shifts. By moving the anti-Helmholtz coil while keeping the probe laser resonant with the atomic transition at zero...
magnetic field, we can map the spatial distribution of cold atoms in the cell by recording the absorption signal of the probe laser. Here we give one dimensional case.

For $^{87}$Rb, the ground states have sub-levels $F = 1, 2$, and excited states $F' = 1, 2, 3$. A $\sigma^+$-circularized probe laser beam, resonant with the transition of $F = 2 \rightarrow F' = 3$, is used to detect the cold atoms around the region of zero magnetic field. Atoms aside this region are not detected due to the Zeeman splitting.

The experimental setup was discussed in Refs. [7, 9], here we briefly introduce the setup as shown in Fig. 2. A glass cell, connected to a vacuum pump through a glass tube with inner diameter of 8 mm, is filled with rubidium vapor at a background pressure around $10^{-7}$ Pa. The glass cell has an inner diameter of 43 mm, and is surrounded by an integrating sphere made of ceramic whose diffuse reflection coefficient at the inner surface is 98% at 780 nm. Two laser beams, containing both cooling and repumping lights, are injected into the integrating sphere through two multimode fibers vertically. With multiple reflection, diffuse light is formed in the sphere. When the cooling laser is tuned at appropriate frequency, the atoms can be cooled by diffuse light [6, 7].

Figure 3 gives the typical experimental sequence and result. First, the cooling laser is turned on for 6 s, which is long enough for the loading of cold atoms [10]. Then the magnetic field is turned on right after the cooling light is switched off. After 1.1 ms, when the magnetic field becomes stable, the horizontal probe beam is switched on. Since the lifetime of cold atoms in the glass cell can be longer than 40 ms [11], the change about the spatial distribution
with 1.1 ms delay can be neglected. In the experiment, the power of the injected cooling laser into the integrating sphere is 42 mW, and the cooling laser is red detuned 18 MHz (about $-3\Gamma$) to the transition of $5^2S_{1/2}, F = 2 \rightarrow 5^2P_{3/2}, F = 3$, with which the diffuse light has the top efficiency in capturing the $^{87}\text{Rb}$ atoms. The power of the repumping light is about 5 mW, which is locked to the resonant transition of $5^2S_{1/2}, F = 1 \rightarrow 5^2P_{3/2}, F = 2$.

The bottom of Fig. 3 gives a typical absorption signal, where the gradient of the magnetic field is around 1.30 Gauss/mm, as shown in Fig. 4 and the zero-point of the magnetic field
Fig. 5: The density of the cold atoms vs position when the magnetic field gradient is 1.30 Gauss/mm.

is about 12 mm from the center of the integrating sphere. The spatial distribution can be determined from the absorption signals by moving the anti-Helmholtz coil along the probe beam with the step of 5 mm.

From the absorption of the probe beam we can work out the density of the cold atoms at different positions, as shown in Fig. 5. Clearly, the spatial distribution shows that at the center of the sphere, less atoms exist, and the atoms are mostly distributed at the position around $r = \pm 14$ mm from the center of the integrating sphere (where $r = 0$). The density of the cold atoms at $r = -14$ mm is about $3.08 \times 10^4 \text{ mm}^{-3}$, while at $r = 0$ mm, is about $1.18 \times 10^4 \text{ mm}^{-3}$. This is mainly because the hole of the glass tube, which is connected to the vacuum pump, as discussed in Ref. [4]

The position resolution of our measurement is mainly determined by the spontaneous emission rate of the excited state and the linewidth of the laser. The magnetic field along the probe beam created by the anti-Helmholtz coil can be simply described as $B(\Delta r) = c\Delta r$, here, $c$ is a constant, and $\Delta r$ is the position with origin at the zero-point of the quadrupole field. For weak magnetic field, the energy levels are split linearly according to

$$\Delta E_{\text{Zeeman}} = g_F\mu_B m_F B(\Delta r) = g_F\mu_B m_F c\Delta r \quad (1)$$

As the probe beam is turned on, most of the atoms in the $F = 2, m_F = -2, -1, 0, 1$ states can be quickly pumped into $F = 2, m_F = 2$, and connecting $F' = 3, m_{F'} = 3$, such a transition system becomes closed circles. And besides that, the Clebsh-Gordan coefficient
$F = 2, m_F = 2 \rightarrow F' = 3, m_{F'} = 3$ transition is $\sqrt{\frac{1}{2}}$, which is much larger than the other transitions of $F = 2 \rightarrow F' = 3$. So we can only consider $F = 2, m_F = 2 \rightarrow F' = 3, m_{F'} = 3$.

The Zeeman shift of $F = 2, m_F = 2$ is $2 \times 0.70$ MHz/Gauss, and $F' = 3, m_{F'} = 3$ is $3 \times 0.93$ MHz/Gauss. Thus from Eq.(1) the resonance of probe beam with the $F = 2, m_F = 2 \rightarrow F' = 3, m_{F'} = 3$ transition is

$$\Delta \nu = (3 \times 0.93 - 2 \times 0.70)B(\Delta r) = 1.39c\Delta r$$

(2)

so we get

$$\Delta r = \frac{\Delta \nu}{1.39c}$$

(3)

Here, $\Delta r$ can be defined as the position resolution. Obviously, the larger gradient of the magnetic field, the higher position resolution.

The natural linewidth of $^{87}$Rb is about 6 MHz, and the linewidth of the laser is about 1 MHz, suppose $\Delta \nu = 7$ MHz, so

$$\Delta r = \frac{\Delta \nu}{1.39c} = \frac{5.04}{c}$$

(4)

For $c = 1.30$ Gauss/mm, $\Delta r = 3.88$ mm. The resolution is high enough to determine the spatial distribution of cold atoms in the sphere, which has a 43 mm diameter.

In conclusion, we have developed a method to measure the spatial distribution of cold atoms in a nearly enclosed sphere where imaging is not possible. We pointed out that the spatial resolution is as high as 3.88 mm in our measurement. With the method, we measured the spatial distribution of cold atoms in an integrating sphere, and found that the distribution has two lobes. This result is very important for developing a compact cold atom clock.

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