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Observation of single neutral atoms in a large-magnetic-gradient vapour-cell magneto-optical trap*

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Single caesium atoms in a large-magnetic-gradient vapour-cell magneto-optical trap have been identified. The trapping of individual atoms is marked by the steps in fluorescence signal corresponding to the capture or loss of single atoms. The typical magnetic gradient is about 29 mT/cm, which evidently reduces the capture rate of magneto-optical trap.

Keywords: single atoms, magneto-optical trap, large magnetic gradient, loading rate
PACC: 3280P, 3280, 4250

1. Introduction

Individual particles have been always a vital concept in microscopic physical theory. With the advance and the development of scanning tunnelling microscope (STM), one begins to observe and control individual particles, such as single atoms and single molecules which are manipulated in the solid surface by STM. The interaction between light field and atoms is a standard tool for controlling motion state of atoms. In recent decades, one has been able to cool neutral atoms in gas phase down to a nano-Kelvin level by combining laser cooling/trapping[1,2] with other cooling techniques of atoms. Utilizing this, one has achieved Bose-Einstein condensation (BEC) and Fermi degeneration gases (DFG), and also can realize the preparation of a few atoms or single atoms.[3−12] Therefore, we can attain so much longer coherent time that is beneficial to the study on a single-atom level. For example, it is possible to investigate optical manipulation on internal and external degrees of freedom of single atoms.[13−19] In addition, one can study the radiation characteristic of single atoms which is separated sufficiently from the background, the preparation and the domination of quantum state of single atoms,[20] triggered single photon source by exciting single atoms,[21] the interaction between light field and single atoms which are trapped in a free or a confined space (e.g. cavity QED), the entanglement between single atoms and photons,[22] quantum register[23] and so on. All the above-mentioned points are significant to quantum information processing on a single-atom level and a single-photon level.[24−26]

We experimentally observe single caesium atoms in a large-magnetic-gradient vapour-cell magneto-optical trap (MOT). The MOT works remarkably well in collecting and trapping atoms, and a standard MOT usually can trap 10^5–10^9 atoms. In order to reduce this number down to a single trapped atom, we have to lower the capture rate. There are many ways to do this, operate in a good vacuum condition, reduce the diameter of laser beams, and increase the gradient of quadrupole magnetic field.

2. Experimental setup

Figure 1 shows the experimental setup. A glass cell is evacuated by a vacuum pump system (not shown here) down to a pressure of about 2×10^{-8} Pa

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while caesium atoms are released from a caesium ampoule. The lower pressure could remarkably reduce the capture rate. A standard $\sigma^+ - \sigma^-$ polarization configuration with three pairs of counter-propagating cooling/trapping beams is provided by a diode laser, which is frequency locked to the crossover transition of caesium $6S_{1/2}F_{\rm g} = 4$–$6P_{3/2}F_{\rm e} = 5$ with a red detuning of 51.5 MHz. The beams double pass the acousto-optical modulator (AOM) system to conveniently control the detuning between –20 MHz and –2 MHz from $6S_{1/2}F_{\rm g} = 4$–$6P_{3/2}F_{\rm e} = 5$ transition. Some atoms are optically pumped to the $F_{\rm g} = 3$, which is compensated by a repumping beam from another diode laser stabilized to the $6S_{1/2}F_{\rm g} = 3$–$6P_{3/2}F_{\rm e} = 4$ transition and superimposed with cooling/trapping beams. The confluent beam of repumping and cooling/trapping beams with a polarizing beam splitter (PBS) is spatially filtered by a polarization-maintained (PM) optical fibre to obtain a good mode. Then the diameter of the combined beam is expanded to about 2 mm by a telescope system. Two pairs of beams in the x–y plane intersect into an angle of 60° in a glass cell. On the one hand, the MOT is close to the detection system. On the other hand, this configuration will suppress stray light entering the detection system. Another one pair of beams, which is perpendicular to a horizontal plane, is not indicated in Fig.1. The power of each cooling/trapping beam and repumping beam is about 200 μW and 30 μW respectively.

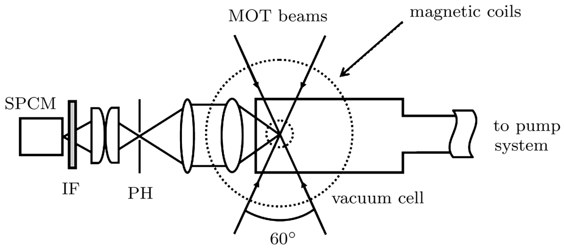

Fig.1. Schematic diagram of the single atoms MOT. A glass cell is evacuated by vacuum pump system (not shown) to keep the pressure at about 2×10^{-8} Pa while caesium atoms are released from a caesium ampoule. The four of MOT beams in the horizontal plane are shown, and the other two beams which are perpendicular to the horizontal plane are not indicated here. The dotted circles show the positions of quadrupole magnetic coils which are mounted outside the vacuum cell. A single-photon counting module (SPCM) is used to detect the collected fluorescence photons scattered by the trapped atoms in MOT. IF stands for interference filter and PH for pin hole.

The dotted circles in Fig.1 show the positions of quadrupole magnetic coils that are mounted outside the vacuum cell. The quadrupole magnetic field is produced by two anti-Helmholtz coils mounted above and beneath the glass cell separately. For obtaining a small number of well-localized atoms in our MOT, we use a large-magnetic-gradient field of $\mathrm{d}B/\mathrm{d}z = 29\,\mathrm{mT/cm}$. It works at a necessary current of 18 A. The power supply and the coils are connected via an electronic control circuit. The switching time of the magnetic field which is controlled by a transistor-transistor logic (TTL) signal is about 4 ms limited by an eddy current effect.

Typical lifetime of cold atoms in the MOT is about 28.2s (Fig.2). It is measured in a conventional vapour-cell MOT with a moderate power of laser beams and a low magnetic field gradient of 1 mT/cm.[2,19,27] Because the life time of atoms in the vapour-cell MOT is limited by the background pressure, we can deduce the pressure around the MOT regime from it. The vacuum pressure calculated from the lifetime is about 2×10^{-8} Pa which accords with the reading of a vacuum gauge.

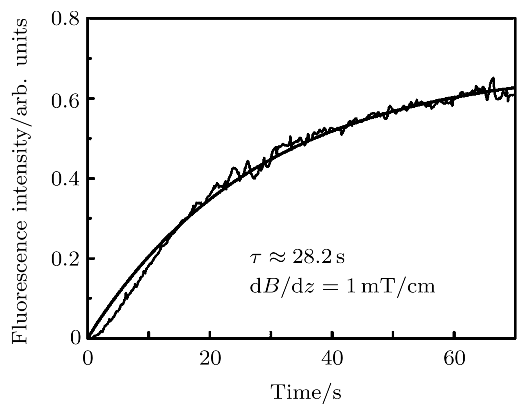

Fig.2. The typical loading curve of MOT with an axial magnetic gradient of 1 mT/cm. The fluorescence intensity of trapped atoms in the MOT is approximately proportional to the number of cold atoms. Fitting gives a time constant of loading process as $\tau \approx 28.2\,\mathrm{s}$, which confirms the measured vacuum degree of about 2×10^{-8} Pa.

In our experiment, we detect trapped single atoms in the MOT by collecting its fluorescence light. Since the fluorescence emitted from single atoms is weak, we detect it by single photon count module (SPCM) which is sensitive to weak signals. Otherwise, the key points are to suppress stray light and improve the collection efficiency. The fluorescence from the single atoms emits randomly into a 4π solid angle. It is advantageous to collect the fluorescence light from a solid angle that is as large as possible. We use an objective lens system of which the numerical aperture is about 0.29. It covers a solid angle of about 2.1% of the total solid angle in the whole space. In order to guide the collected fluorescence light to the detector while keeping stray light away, we use a pinhole to block the light rays which are not originating from a region around the MOT. It demands a high quality of lens system, which is optimized into a diffraction limited resolution. Finally, a lenses assembly focus the light rays onto the sensitive area of the SPCM that works under the Geiger mode and produces TTL pulses with a quantum efficiency of about 50% at 852 nm when the incident photons arrive there. The number of pulses is counted by a multi-channel scaler (MCS) within a time bin of 50 ms. The computer records all the data as the count versus time.

3. Experimental results

The average number $\bar{N}$ of atoms in a typical vapour-cell MOT is given as $\bar{N} = R\tau_s$. R is the capture rate, and $1/\tau_s$ is the loss rate of atoms in the trap due to collisions with background atoms. The capture rate in the vapour-cell MOT is $R = 0.5nV^{2/3}V_c^4(m/2k_BT)^{3/2}$,[2] in which n is the density of background C atoms, m is the atom mass, T is the temperature of background gas, and V is the trapping volume, V_c is the maximum capture velocity of the trap. In the vapour cell, atoms with velocity less than a capture velocity V_c are slowed sufficiently after entering the intersecting laser beams, and these atoms can be loaded into the MOT. If we want to acquire single atoms, an effective way is to decrease the capture rate R. First, the good vacuum condition evidently can keep n small. $n = p/(k_BT)$ is limited only by the pressure p in the chamber. n is proportional to R. A small number density of background gas could reduce the capture rate. Second, we also know that the laser beam diameter d is related to V. The estimated volume V is proportional to d^3. A smaller d could acquire a smaller R. But too small diameter is not applicable because it will increase the difficulty in alignment. An optimal diameter is related to the real experimental environment. Third, the capture velocity V_c is a function of quadrupole field gradient. While for an axial gradient $\mathrm{d}B/\mathrm{d}z$, the function is analytically expressed as $V_c \sim (\mathrm{d}B/\mathrm{d}z)^{-2/3}$.[6] Consequently for a steep magnetic field, $R \approx (\mathrm{d}B/\mathrm{d}z)^{-8/3}$. The main influence of a large gradient is a significant reduction in capture rate and thereby leading atoms to be highly localized. Summarizing the three aspects of suppressing the capture rate shows that, all the parameters mentioned above in our experiment meet the requirements for trapping only a few atoms as compared with traditional MOT parameters (vacuum pressure is about 10^{-7} Pa, magnetic field gradient is about 1 mT/cm, and the diameters of laser beams each are about 10 mm).

Figure 3 shows typical photon counting signals of MOT with a large magnetic gradient versus record time. The discrete steps indicate the capture or loss of single atoms. At the beginning of this figure, the count level C_0 is for the case in which no atoms are in the MOT. It is calibrated by switching off magnetic field. The C_1 above the background level is interpreted as the trapping of a single atom. Since atoms each contribute the same quantity of fluorescence, the number of atoms in the trap can be deduced directly from the discrete level of the count rate C_2.

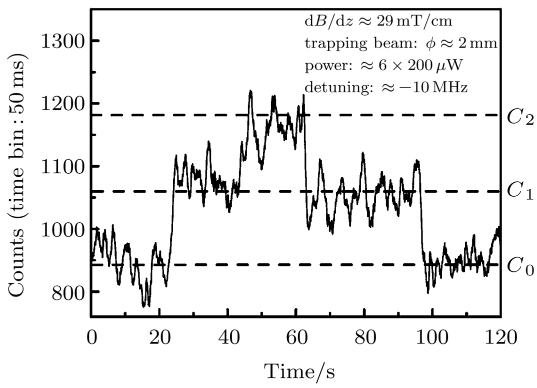

Fig.3. Typical photon counting signals from MOT with a large magnetic gradient versus record time. The steps indicate individual atoms entering into or escaping from the trap. C_0 is the count rate level without any atoms in MOT and can be calibrated by switching off magnetic field. C_1 and C_2 denote the counting rate levels for one atom and two atoms in MOT respectively.

Figure 4 shows the statistics of the observed fluorescence counts. The largest peak is associated with the absence of trapped atoms. Another two peaks in the histogram correspond to the fluorescence counts of one and two atoms, respectively. The emitted photons from single Cs atoms into space can be calculated from the formula $\gamma = \frac{\Gamma}{2}\frac{I/I_s}{1+I/I_s+4\Delta^2/\Gamma^2} = 1.15\times10^7$ photons/s, where Γ is the spontaneous emission rate of single Cs atoms; $I = 45.8\,\mathrm{mW/cm^2}$ is the total intensity of six cooling laser beams; $I_s = 1.12\,\mathrm{mW/cm^2}$ is the saturation intensity of Cs atoms; $\Delta \approx 2\pi \times (-10)$ MHz is the detuning to transition frequency of

$6S_{1/2}Fg = 4$ - $6P_{3/2}Fe = 5$. From the collection efficiency of objective lens, the quantum efficiency, and the total transmission of the detection system, we can obtain the counts of single atom fluorescence in 50 ms to be about 120 counts.

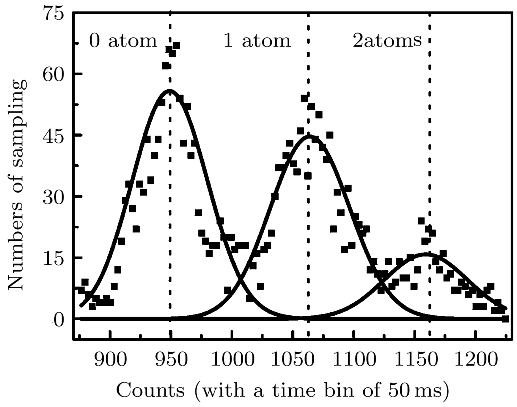

Fig.4. Occurring times statistically derived from Fig.3 versus count rate with a time bin of 50 ms, where the black squares denote the experimental data, the solid curves are Poisson fitting curves for the three peaks respectively, correspond to atom numbers of 0, 1, and 2.

4. Discussion

In order to improve the ratio of signal to background, we must adjust the position of each component accurately, especially the pinhole in the detection system. In addition, we can reduce the detuning of cooling/trapping laser beams to intensify the scattering rate of single atoms for the purpose of enhancing the count rate of the fluorescence emitted from single atoms. Keeping the total intensity unchanged and changing the detuning from –10 MHz to –5 MHz, we can acquire 30% improvement on the fluorescence count rate of single atoms. With an optimized detection system and experimental parameters, in next step we are going to use a self-made laser diode pumped single-frequency 1064 nm Nd:YVO_4 laser to form far-off-resonance dipole trap (FORT) and then transfer single atoms from MOT to FORT to keep coherence of atoms. The experiment is expected to open the way for investigating the triggered single photon source and the entanglement between atoms and photons based on a single atom system.

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