Quantum Computing

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Laser Cooling of Atoms Down to Doppler Limit: A Step Towards Atomic Qubit

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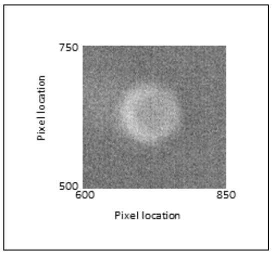

A typical photograph of cold atom cloud at steady state recorded by CCD camera

ABSTRACT

Atoms can serve as quantum bits (qubits) when trapped and controlled in predefined locations in space without undesired disturbances. Temperature of the atomic cloud needs to be lowered significantly to few microkelvin to efficiently trap the atoms in optical or magnetic micro traps. In an effort to demonstrate atomic qubits, we have recently trapped and attained the Doppler limited lowest temperature (~130μK) of Caesium cold atom cloud using a magneto-optical trap. The temperature was measured by release and recapture technique. Our next goal is to reduce temperature further below by sub-Doppler cooling techniques up to ~5μK so as to trap the atoms in optical lattice where entanglement of the qubits can be achieved.

KEYWORDS: *Quantum computing (QC), Magneto optical trap (MOT), Caesium (Cs)*

Introduction

Quantum computing (QC) has numerous future potential applications such as simulation of quantum processes, complex molecules, development of new drugs, storage and fast processing of huge data, secure communication, artificial intelligence etc. [1]. Different architectures are being explored for the experimental realization of quantum computing like superconducting qubit, ions traps, photons, nitrogen vacancy centers in diamond and neutral atoms [2]. Among these, atom based approach inherently offers scalability which is an important criterion of QC [3]. In this approach, thousands of ultra-cold atoms are loaded to optical or magnetic micro traps to create large array of individually controllable quantum system [4-5]. The quantum state is manipulated using laser or microwave pulses. In the atom-based quantum technology, the prerequisite is to cool the atoms by means of Doppler cooling technique and then trap them in a magneto optical trap (MOT). MOT is realised by overlapping three pairs of opposite polarization laser beams along with a quadrupole magnetic field [6]. In MOT, atomic gases can be cooled down to its Doppler limit which is typically ~100μK for alkali atoms [7]. In all these applications of MOT, the knowledge of the characteristic parameters including the temperature and number of trapped atoms is indispensable. Many specialized techniques have been developed for the measurement of temperature of cold atom cloud in MOT. Among these, Release and Recapture method [8] and Time of flight method [9] are used most frequently.

In ATLAD, BARC, we are developing an experimental facility with an ultimate target of generation and manipulation of Caesium (Cs) atomic qubit. As an initial step, we have cooled and trapped Cs atoms in MOT and have estimated the temperature of the cold cloud by Release and Recapture method. The observed temperature has been found to be close to theoretically lowest possible temperature i.e. Doppler limit of the cooling process.

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Experimental Method and Results

The schematic and photograph of our experimental set up for cooling of the Caesium atoms in Magneto Optical Trap are given in Fig.1 and 2 respectively. The cooling laser is locked at a frequency red shifted by ~2.5 MHz from the cyclic transition $6s_{1/2}$ $F=4 \rightarrow 6p_{3/2}F'=5$ (resonant frequency v_0=351.7219605 THz) of Cs. The re-pump laser is locked at $6s_{1/2}$ $F=3 \rightarrow 6p_{3/2}F'=4$ transition (resonant frequency v_0=351.7309022 THz) of Cs. Magnetic field gradient is maintained at ~ 10 Gauss/cm. All the cooling and re-pump laser beam diameters are fixed at 5 mm. The optical power of the cooling laser and re-pump laser are kept at ~1.3 mw/beam and 0.3mW/beam respectively.

When the lasers are 'ON', cold atom cloud starts to build up in the trapping region due to the trapping force. Typically, within 500ms the cloud reaches to its steady state value where the momentum diffusion rate and the trapping rate balance each other. The fluorescence from the cold atom cloud at the trapping region is monitored by a CCD camera. Only the

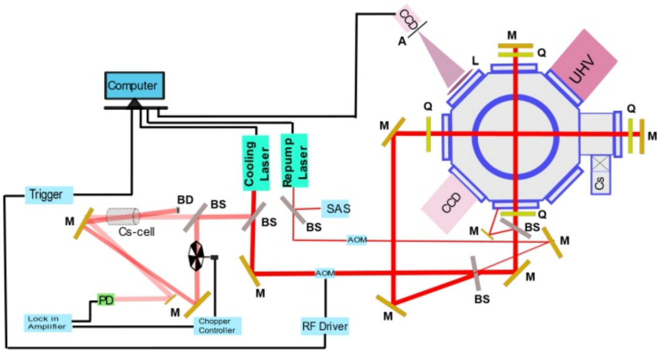
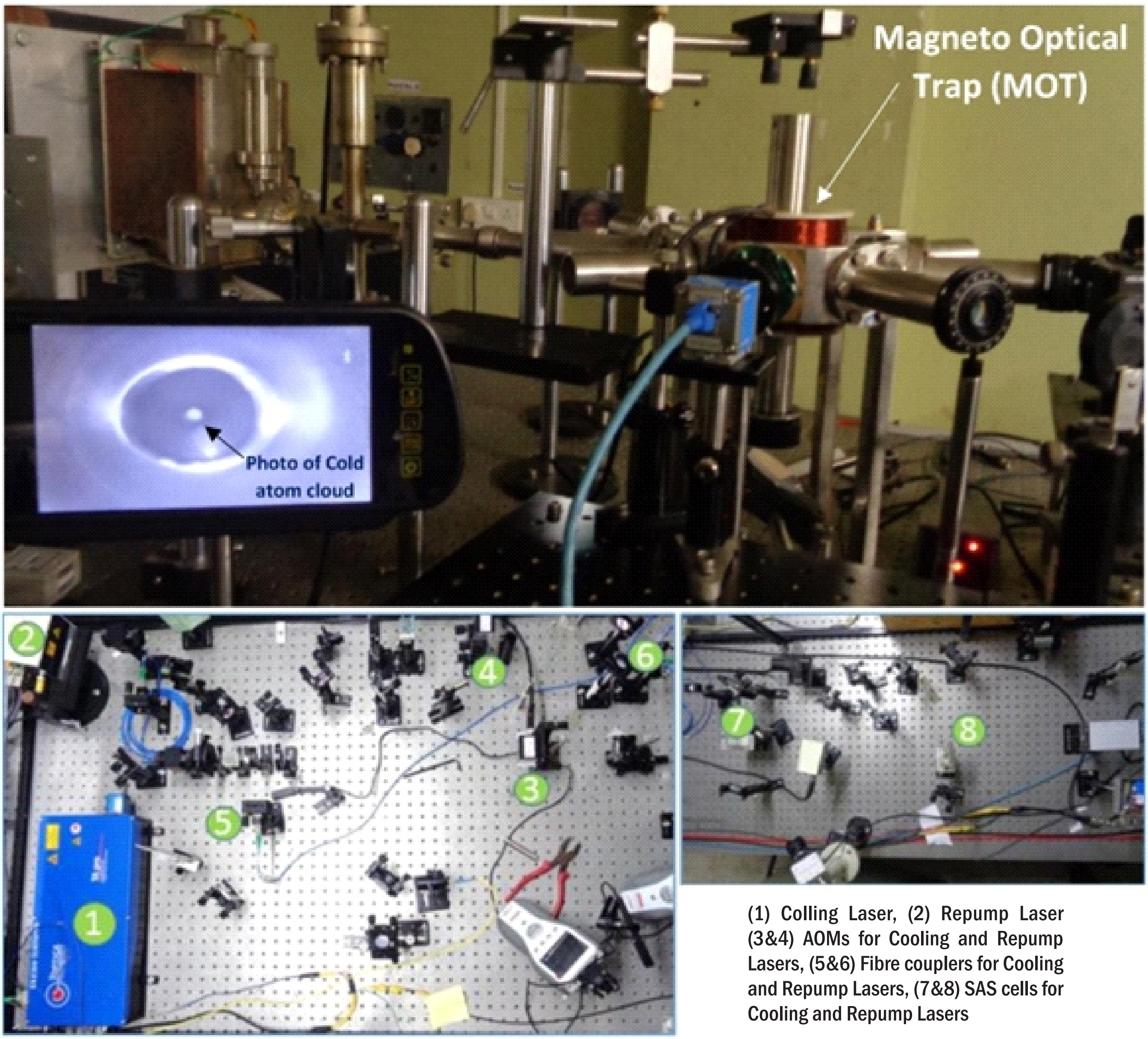


Fig.1: Schematic of experimental set up for cooling and measurement of temperature of Cs cold atom cloud in Magneto Optical Trap (MOT). UHV: Ultra high vacuum, Cs: Caesium atoms reservoir, Q: Quarter wave plate, AOM: Acoustic Optic Modulator, BS: Beam Splitter, M: Mirror, BD: Beam dump, L: Lens, PD: Photodiode, CCD: Charged coupled device. A: Aperture.



(1) Colling Laser, (2) Repump Laser (3&4) AOMs for Cooling and Repump Lasers, (5&6) Fibre couplers for Cooling and Repump Lasers, (7&8) SAS cells for Cooling and Repump Lasers

Fig.2: Photographs of Magneto Optical Trap (MOT) and Laser systems.

trapping region is focussed on the CCD sensor. Fluorescence from rest parts of the MOT is blocked from falling on the CCD sensor by an aperture. From the pixel count of the CCD, the total number of the cold atoms in the trapping region is measured [10].

Measurement of the temperature of cold atom cloud in MOT by Release and Recapture (RR) method is based on repeated release and recapture of atoms from the trapping region of the MOT. This is achieved by sequential 'ON' and 'OFF' state of the cooling beams. The duration of 'ON' and 'OFF' are adjusted by controlling the RF driver of AOM using a trigger module. Just before the 'OFF' period of the cooling beams, the cloud is in steady state. From the fluorescence image in CCD, the steady state number N_{ss} was evaluated and it was found to be 2.1×10^6 atoms and diameter of atomic cloud was ~ 0.65 mm. A typical steady state image is shown in Fig.3. Then the cooling beams are kept 'OFF' (i.e. releasing the cloud from trapping force) for a duration of t_{off}. There is no trapping force during this period and the cloud expands. As a result, the atoms are lost from the trapping region. After time t_{off} the cooling beams are brought back i.e. recapture of the remaining atoms occurs, and the florescence image is taken in CCD. From this image, the number of left over atoms t_{off} is given by [8],

$$f_r = \frac{N_{t\_off}}{N_{ss}} = \left(\frac{m}{2\pi kT}\right)^{3/2} \int_0^{v_c} 4\pi . e^{-\frac{mv^2}{2kT}} v^2 dv \qquad (1)$$

where m is the mass of Caesium atoms, k is the Boltzmann constant, T is the temperature and $v_c = R_c / t_{off}$ is the velocity at which atoms reach the position R_c at time t_{off}. The value of integration is a function of t_{off}.

For different t_{off}, a plot of f_r vs t_{off} is experimentally generated as shown in Fig.4. Then, it is compared with the theoretically expected plots corresponding to different temperatures 'T'. Our experimental data matches with the theoretical plot at temperature T~130μK. Thus, the measured temperature is very close to the Doppler limit of temperature of Cs which is 125μK.

Conclusion

As temperature plays a critical role for controlling and manipulating the atomic qubits, we have attained the Doppler limited lowest temperature (~130μK) of Caesium cold atom

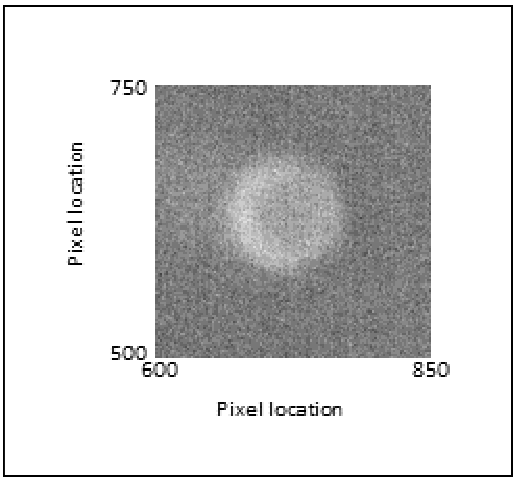


Fig.3: A typical photograph of cold atom cloud at steady state recorded by CCD camera.

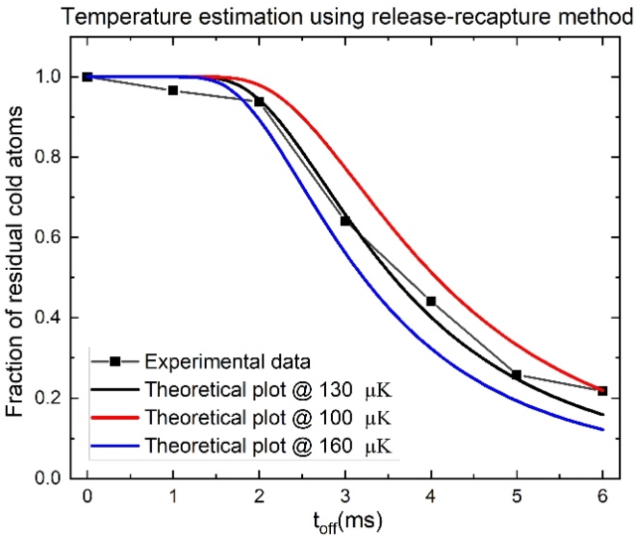


Fig.4: Variation of residual fraction of atoms in the trapping region of the MOT with 'off' period of cooling laser beams.

cloud trapped in a magneto-optical trap. We have measured the temperature by release and recapture technique. Since, lowering of temperature further below the Doppler limit up to about ~ 5μK is required for trapping of single atoms in optical microtraps, we are at present in the process of implementing experimental techniques such as Sisyphus or polarization gradient cooling mechanism for obtaining sub-Doppler temperature of cooled Caesium atoms.

Acknowledgments

The authors would like to thank Dr. Someswar Rao and Sandeep Agarwalla of ATLAD, BTDG for providing optical components and support during the course of experiments.

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