Seeing from One to One Million Atoms

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Application Note

Introduction

Electron Multiplying CCD (EMCCD) scientific digital camera technology is used very effectively to image an extremely cold ‘nano-climate’, found in the laboratories of Professor Mike Chapman at the School of Physics, Georgia Institute of Technology. Prof Chapman and his group focus on investigating the quantum behavior of atoms and photons, often at the single particle level. Cooling bosonic atoms to a very low temperature, to beyond a „critical temperature“ for the atom, causes them to condense into the lowest available quantum state, resulting in a new wavelike form. In this state, a cloud of atoms will form a macroscopic quantum state in which all the atoms share the same space and have phase coherence in their wavefunctions. Lasers are employed to confine and cool such atoms to nano-Kelvin temperatures (colder than the most remote regions of deep space, which are pervaded by cold microwave radiation - the afterglow of the big bang), which are used for studies including fundamental atom-photon interactions, atom optics and interferometry, and quantum computing (towards a future generation of supercomputers) and communication. Recent achievements of the Chapman lab include the first all-optical Bose-Einstein condensation (BEC), the first storage ring for neutral atoms, and cavity QED with optically transported ultracold atoms.

Laser Cooling

Laser cooling has become a very important tool of atomic physics research, a fact that was recognized by the awarding of the Nobel Prize in 1997 for its discovery and advancement. The techniques of optical molasses and magneto-optical trapping have allowed ultra-cold temperatures of µK’s (millionths of a degree above absolute zero) to be reached with arguably much greater ease. In 2001 the Nobel Prize for Physics was presented for the long sought after achievement of Bose-Einstein Condensation.

Laser cooling and trapping of atoms makes use of the mechanical effects of light on atoms. Atoms have specific resonance frequencies at which they interact strongly with light by absorbing photons which are subsequently re-emitted by spontaneous emission.

By using a laser beam with a frequency detuned by a small amount (typically tens of MHz) to the red of an atomic transition (i.e. the photons in the laser have a lower energy than the atomic transition), the atoms will absorb more photons if they move towards the light source, due to the Doppler effect. In each scattering event the atom loses a momentum equal to the momentum of the photon. If the atom, which is now in the excited state, emits a photon spontaneously, it will be kicked by the same amount of momentum but in a random direction. If the system is then extended to six circularly polarized laser beams, with three pairs of beams in opposite directions, cooling in 3D can be achieved. This is the result of the directional absorption of photons and the spatially random emission process. Averaged over many of these events the net force due to the emission averages to zero, meaning that the atom loses one unit of the laser photon momentum per scattering event. The temperature – which is related to the kinetic energy – of the atomic cloud can be reduced to temperatures on the order of 100 µK by this mechanism.

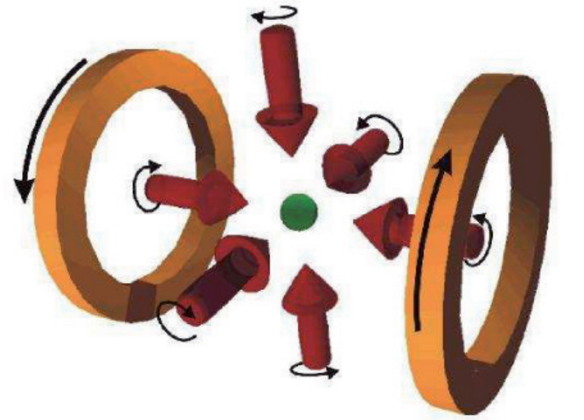

Figure 1

Schematic of a magneto-optical trap. Six laser beams (in red) cool the atomic cloud in all directions. A magnetic field, created by the circular coils, provides a position dependant force, keeping the atoms trapped.

Bose-Einstein Condensation

Bose-Einstein condensation describes the collapse of the atoms into a single quantum state. This phenomenon was predicted in the 1920’s, and derived originally from Satyendra Bose’s work on the statistical mechanics of photons, and subsequently formalized by Albert Einstein. Governed by the Bose-Einstein statistics, a Bose gas describes the statistical distribution of certain types of identical particles known as bosons. „Bosonic particles“, are allowed to share quantum states with each other.

Einstein speculated that cooling bosonic atoms to a very low temperature, to beyond a „critical temperature“ for the atom, would cause them to condense into the lowest available quantum state, resulting in a new wavelike form. In this state, a cloud of atoms will form a macroscopic quantum state in which all the atoms share the same space and have phase coherence in their wavefunctions.

Thus, as the value for momentum becomes more certain, the position of the atoms becomes more uncertain or (in quantum mechanical terms), the wavepacket that describes an individual atom becomes „delocalized". As the atoms cool down, their kinetic energy and hence their momentum reduce, as required by Heisenberg's uncertainty principle,

where,

$$\Delta x \, \Delta p \geq \frac{h}{2}$$

Δx = the uncertainty in the measured value of position
Δp = the uncertainty in the measured value of a component of momentum along x
h = reduced Planck constant.

Another quantum effect that becomes important at low temperatures is that of waveparticle duality, a concept advanced by Louis de Broglie in 1924. He suggested, following from the successful earlier theory that light can behave both like a wave and a particle, that particles can behave like waves in certain situations. The wavelength of a particle, λ_{dB} is related to its momentum, p by

$$\lambda_{dB} = 2\pi \frac{h}{p}$$

Within 3 years of this proposal physicists in the UK and the USA observed the wave-like nature of electrons.

In terms of the wave-like properties of the atoms the transition to a Bose-Einstein condensate, or BEC, occurs when the de Broglie wavelength of the atoms becomes comparable to the inter-atomic spacing. The individual behavior of each atom is then lost as each atom becomes indistinguishable. The entire cloud of atoms is then describable by a single wavefunction.

While laser cooling can achieve extremely low temperatures, it is insufficient to cool all the way to BEC. The atoms from the MOT are loaded into a separate trap and the hottest atoms are preferentially removing by lowering the trap depth. By allowing the remaining atoms to re-thermalize the temperature of the cloud is lowered, eventually all they way to BEC. This environment created in the laboratory is even colder than the most remote regions of deep space, which are pervaded by cold microwave radiation - the afterglow of the Big Bang.

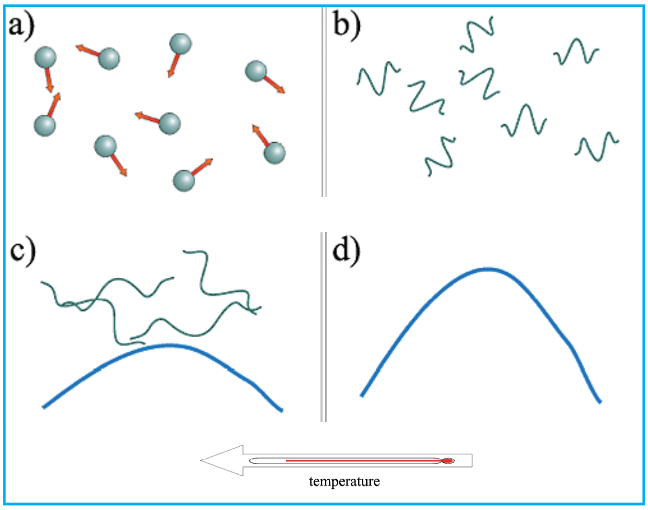

Figure 2

The transition to a Bose-Einstein condensate, as atoms are cooled from particle-like behavior to behaving as a single 'giant matter wave'.

Bose-Einstein Condensation at Georgia Tech

The original experiments on Bose condensates involved using large magnetic fields to trap magnetically sensitive states of an atom after the MOT. A different technique allows a condensate to be created without bulky, water cooled magnetic coils by using a tightly focused, high powered laser. The electric field of a laser causes a shift of the energy levels of an atom. By focusing the laser a spatially localized trap can be created at the focus; known as an optical dipole trap. In order to prevent the atom absorbing energy from the laser beam the laser must have a wavelength far from any atomic resonances. A CO_2 laser provides the deal case of an optical dipole trap as high power, ultra-stable designs are available. Furthermore, a CO_2 laser has a wavelength of 10.6 µm, which is approximately 14 times longer than any transitions from the ground state of rubidium (or any of the other alkali atoms). At this extremely long wavelength, a rubidium atom scatters light from the trapping laser at a rate of single photons per hour, mean that the trap does not cause unwanted heating effects.

Using 25 W of CO_2 laser power focused down to 50 µm, Mike Chapman and his group were able to create a BEC without using any magnetic traps. Due to the nature of the alloptical trap BEC can be achieved in only a few seconds, as compared to the tens or hundreds of seconds that were previously needed.
A separate advantage is that essential all atoms and many molecules can be trapped in a CO_2 laser trap as it does not distinguish between magnetic states.

Optical traps for quantum gasses are interesting as many trap geometries can now be formed by using one or more trapping laser beams. A single focus laser provides a quasi- 1D trapping potential whereas crossed lasers provide more uniform 3D confinement. By using interfering lasers much more complicated potentials can be formed.

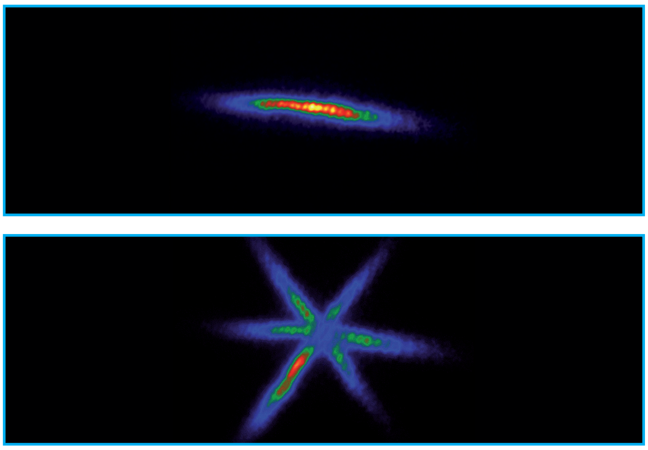

Figure 3

Optical dipole traps allow different trapping potentials, such as a 1D optical lattice (above) and a 3D optical lattice (down).

Probing a BEC

A BEC is typically only tens of microns across, and additionally the experiments described are conducted in ultra-high vacuum, to prevent collisions with background vapor destroying the BEC. To probe the condensate non-contact methods must then be used. Instead, information is obtained from the interaction of a laser with the atoms. Two main types of probe are used; absorption imaging and fluorescence imaging, i.e. measuring the optical power absorbed or radiated by the atoms, respectively. Both these methods allow the experimentalist to obtain both the spatial and momentum distributions of the BEC.

Fluorescence Imaging

Probing an ultracold atomic cloud by capturing scattered fluorescence is a widely used technique due to the simplicity of interpreting the data with a few pieces of information, such as the rate an atom scatters photons, Γ_{sc}, the collection efficiency of the imaging system, $\Omega/(4\pi)$, and the imaging camera conversion efficiencies, β. The number of atoms, N can then be found as

$$N = \Gamma_{sc} \cdot \frac{\Omega}{4\pi} \cdot \beta \cdot \delta t$$

where δt is the duration of the imaging probe.

Absorption Imaging

The intensity of light passing through an absorptive medium decreases according to the Beer-Lambert law

$$\frac{\partial I(x, y, z)}{\partial z} = -n(x, y, z) \cdot \sigma \cdot I(x, y, z)$$

with n and σ are the cloud density and the absorption cross section, respectively. An image of the probe beam, $I(x,y)$ will then contain information about the column density, $\tilde{n}$ of the medium along the probe, z axis,

$$I(x, y) = I_0 \exp(-\tilde{n}\sigma) .$$

The optical depth of a BEC can be extracted by comparing the laser beam profile with and without a condensate present – the relative transmission, T,

$$\tilde{n}\sigma = -\ln T(x, y) .$$

By comparing images of the probe beam with and without the atomic cloud present the spatial optical density, and hence spatial number density can be extracted. The spatial momentum of the cloud can be measured by repeating the process after a time of flight.

Any movement of the entire optical system or fluctuations of the probe beam will result in noise in the final image. This effect can be minimized by taking the probe and reference signals as close to each other as possible. By masking part of the EMCCD and using the camera in ‘fast kinetics mode’ (see below for description) then the separate images of the beam can be taken within 200 μs of each other, which eliminates many of the sources of noise.

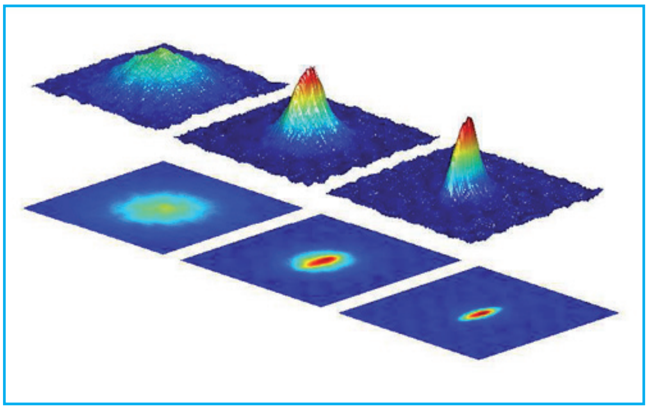

Figure 4

Surface plots of the transition from a thermal gas (left) to a Bose-Einstein condensate. The sharp, bimodal peak in the right figure is a signature of a BEC

Detecting Atoms with Ultra-Sensitive EMCCDs

High-performance EMCCD cameras from Andor Technology have been a key component to dedicated set-ups throughout the world, for creation and detection of Bose-Einstein Condensates.

EMCCD is an innovative technology that offers single photon sensitivity without the need for an intensifier tube. As such it enables optimization of the key parameters of sensitivity: low Noise Floor and high Quantum Efficiency. The readout noise detection limit is completely overcome through a process of on-chip amplification of signal, rendering the device single photon sensitive *at any readout speed*. Furthermore, since an intensifier tube is not required, the full QE of the silicon sensor can be harnessed, enabling QE up to ~ 95%. Through effective thermoelectric cooling of the sensor (down to -100 °C in Andor cameras) and careful control over clocking electronics, the remaining camera noise sources of Darkcurrent and Clock Induced Charge can be minimized and the cameras can be used even for single photon counting with high QE. In the current context, the ultrasensitive nature of EMCCD cameras has been highly effectively harnessed for dynamic measurement of weak fluorescence from small numbers of trapped atoms, recorded over a time series.

The challenging detection requirements associated with typical optical configurations for laser-cooling and atom detection have been further addressed through a number of particular operational modes, including combinations of the following:

- **Rapid charge „purging":** crucial to eradicate bright signal, e.g. from magnetooptical traps, prior to absorption or fluorescence measurement. For example, with the iXon^{EM}+ DU-885, the anti-bloom structure inherent to the frame transfer sensor has been adapted to „flush" charge from the sensor when not exposing. The time to switch to an exposure is in the order of a microsecond. The end of an exposure begins the shift of the image underneath the FT mask.
- **External Trigger:** capture synchronous with probe laser pulse. This functionality has been extended to 'bulb mode' acquisition. In bulb mode, the beginning and end of exposure is determined by the rising and falling edges of an external trigger. This trigger can be synchronized to coincide exactly with the probe pulse.
- **Fast Kinetics acquisition mode:** offers sub-microsecond time resolution from rapid parallel shifts. In this configuration, the imaged area is focused onto a userdefined number of rows at the very top of the sensor. The „dark rows" beneath are subsequently used for storing the images shifted down from the exposed area, reaching time resolution down to 0.4µs/row. A new unique feature enables the user to keep signal accumulated in the exposed area also, provided the probe pulse can be rapidly switched off prior to readout, hence affording an extra image - this can be important if only dividing the entire image area into 4 segments for example. Vertical shift timings can either be driven by camera or by external trigger pulses.
- **Cropped Sensor:** If your experiment dictates that you need fast time resolution but cannot be constrained by the storage size of the sensor, then it is possible to readout the EMCCD in a „cropped sensor" mode, as illustrated on the left. In this mode, we can „fool" the sensor into thinking it is smaller than it actually is, and readout continuously at a much faster frame rate.

Further information on use of EMCCD cameras in Bose Einstein Condensation labs can be accessed through this web site: http://www.andor.com/physics/?app=176#h2188

Single Atoms Traps

A new experiment being conducted is to laser cool and trap individual atoms. This experiment incorporates new challenges; a first issue is that the MOT used for laser cooling is very efficient at trapping atoms. For example, the BEC experiment begins by capturing >10^8 atoms in 5 seconds. This issue is circumvented by making the trapping region very small. This is done using a high magnetic field gradient (350 Gauss/cm) and an extremely low Rb vapor pressure. A second, perhaps more fundamental, issue is how to "see" a single atom. (By way of a naive comparison, a single grain of salt contains approximately 10^{18} atoms of chlorine and sodium).

Atoms scatter light at a rate that varies proportionally with the intensity of the light, I and inversely with the square of the detuning, Δ from an atomic resonance,

where Γ_{sc} is the single atom photon-scattering rate. In a typical experiment for laser intensities of approximately

$$\Gamma_{sc} \quad \frac{I}{\Delta^2} ,$$

25 mW/cm^2 and detuned by -12 MHz from the strongest transition in Rb (the famous D2 line) a single atom scatters 4x10^6 photons per second.

A high numerical aperture lens allows the collection of 2% of this scattered light for imaging onto an iXon EMCCD camera, giving a measured count rate of 8x10^4 photons per second per atom. Imaging the MOT in video mode allows the scatter vs. time to be monitored. A typical data run, shown in Fig. 1 shows a MOT with between zero and five atoms trapped. The background level of 10^4 counts is due to scatter of the cooling and imaging beams from the vacuum chamber into the imaging system. On top of this background discrete scatter levels are clearly seen as atoms enter or leave the MOT. For the data presented the MOT was optimized for trapping either one or two atoms.

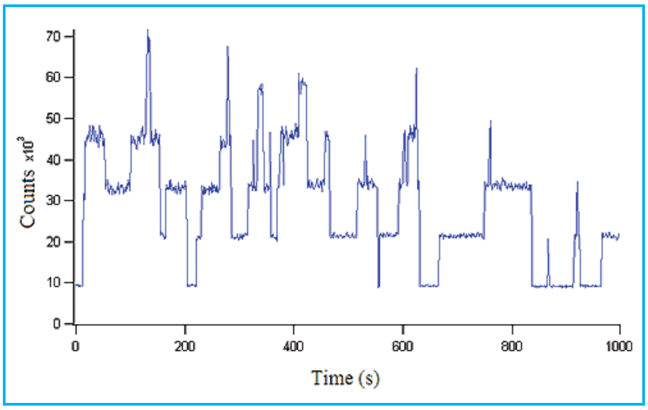

Figure 5
Fluorescence from a few-atom MOT vs time, showing the discrete steps characteristic of single atoms entering and leaving the trap.

A Single Atom Quantum Register

In the rapidly developing field of quantum computation, neutral atoms have been recognized as a candidate for storing and exchanging quantum information. Hyperfine energy states of rubidium (for example) can be used as a quantum bit, or qubit. In classical computer information, data is composed of bits; typically a 0 or 1 but this may correspond to an on or off, an up or down – essentially any two fully distinguishable states of the system being used (microprocessor, capacitor, abacus, etc). Another counterintuitive part of quantum mechanics is that of quantum superposition; that a system can be in two states at the same time. This concept was so surprising that Erwin Schrödinger – himself a founder of quantum mechanics – was prompted to ask if this could apply to everyday objects: for example, could a cat be simultaneously alive and dead? Whether or not quantum effects affect macroscopic object is a much discussed problem of physics and, to a greater extent, philosophy. However quantum superposition has been shown to be an experimental fact of atomic physics. By this principle of quantum superposition, a single qubit can be in every possible single bit state at the same time. Incorporating this idea, a completely new type of computer, a quantum computer can be built that can solve certain problems exponentially faster than a classical computer.

A MOT is a dynamic system, due to the cycles of absorption and spontaneous emission, described previously. Spontaneous emission is necessary for laser cooling as it is this irreversible process that provides the mechanism for energy loss for the system. However the random nature of spontaneous emission means that the state of the atom after the emission is itself randomized. If an atom is to be a candidate for a qubit it must be trapped in an environment which does not destroy the coherence of its states. The state independent, focused laser trap previously described in the section on BECs is such a trap.

If more than one atom is held in a single trap then these atoms can collide. Incoherent events like this can change the atomic states and destroy the qubit information. If instead two counter-propagating lasers are used, a standing light wave will be formed. Each antinode of this standing wave, known as an optical lattice, will form an atom trap. The individual traps will be separated by half the optical wavelength, $\lambda/2$.

An optical lattice formed by a Nd:YAG laser (λ=1.06 nm) was loaded from a MOT. Through careful alignment many atoms can be loaded into the optical dipole trap with at most a single atom per site. The lifetime of the trapped atoms has been measured to be as high as 35 s. This timescale is extremely large, when compared with the atom-photon interaction time, which is on the order of tens of nanoseconds. In Figure 6 below an optical lattice containing only 4 atoms is shown. The spacing of these atoms is large enough to allow additional laser beams to be used to address the atoms individually to carefully manipulate the atomic qubit state. More recently a second optical lattice was aligned parallel to the first such that both are sparsely loaded with atoms. By axially translating the lattices with respect to each other it should now be possible to interact atoms in the separate lattices through induced long range interactions, such as by using high energy, Rydberg atomic states.

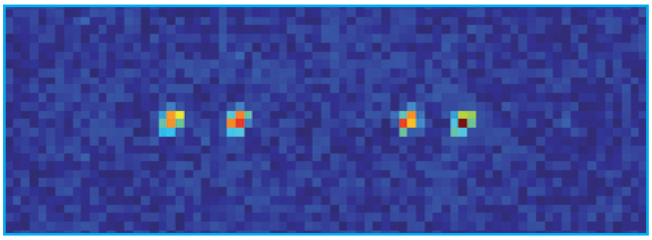

Figure 6 a
EMCCD images of single atoms trapped in an optical lattice

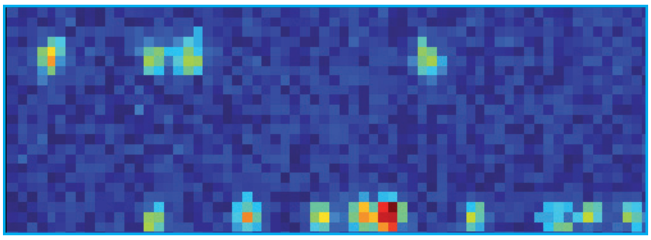

Figure 6 b
EMCCD images of single atoms trapped in parallel optical lattices.

Bose Einstein Condensation and laser cooling is clearly a progressive and exciting field of atomic scale manipulation and ultra-sensitive detection that will lead to increasingly profound discoveries and eventually, next-generation technology developments. You don't even need a quantum super-computer to predict that!

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