Single atoms and single photons: probing the quantum world

Thejesh N. Bandi,[1,2] Michael Morrissey,[1,2] Kieran Deasy,[1,2] and Síle Nic Chormaic[2,3]

[1] Department of Applied Physics and Instrumentation, Cork Institute of Technology
[2] Photonics Centre, Tyndall National Institute, Cork
[3] Physics Department, University College Cork, Cork.

1. Introduction

Cavity quantum electrodynamics is concerned with the interaction of single atoms and single photons confined within a cavity and is *the* textbook example for quantum optics.

Optical nanofibres provide a means of probing single atom plus photon interactions. The optical field in guided modes is tightly confined in the fibre, with an evanescent component extending outside the fibre. Photons contained within the evanescent field can interact with atoms in the vicinity of the fibre, thereby providing a means of controlling and manipulating the atoms using photons.

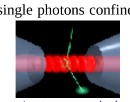
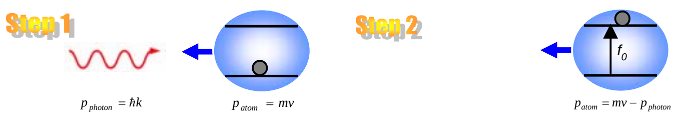


Figure 1: Atom and photons in a cavity

We investigate the use of nanofibres passing through a laser-cooled cloud of rubidium atoms. Laser-cooled atoms provide a novel tool for advanced technologies, such as atomic clocks and atom interferometers, and are ideal candidates for the realisation of quantum computers based on the engineering of quantum states for quantum information.

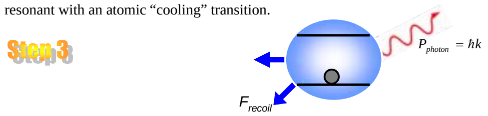
2. Laser Cooling

The cold atomic cloud of ^{85}Rb is produced by the technique of *laser cooling*.



Initially, the cooling laser photons and atoms are moving towards each other. The photons are resonant with an atomic "cooling" transition.

Each time the atom absorbs a photon the atom is forced to slow down by *conservation of momentum*.



Next, the atom decays spontaneously by emitting a photon in a random direction causing a recoil force, which averages to zero over time. The cooling cycle is repeated and the atom velocity is further reduced for each photon absorption. This is equivalent to a reduction in the average thermal temperature of the atoms.

The typical cooling time for Rb is ~ 100 µs. The first experimental realization of laser cooling was done by Steve Chu and co-workers in 1985 (*Phys. Rev. Lett.* 55, 48, 1985).

3. The Magneto-Optical Trap (MOT)

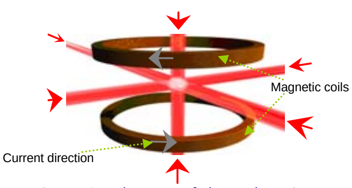


Figure 2: Schematic of the six laser beams and anti-Helmholtz coils.

Three circularly polarised *counter-propagating* laser beams give the six beams used for the cooling field.

A pair of coils in an anti-Helmholtz configuration (current flows in opposite directions) provides the magnetic field to confine the atoms at the centre, where all the six laser beams meet (figure 2).

Our experimental setup for Rb^{85} MOT includes:

- Rubidium source: SAES getters
- Ion pump speed: 55 l/s.
- Cooling laser: Tiger ® Sacher, extended cavity.
- Free-running Sanyo laser is used as re-pump.
- Axial magnetic field gradient: 14 G/cm

Typical parameters we have achieved:
Base pressure : 10^{-10} mbar
Atom temperature: ~100 µK
Number of atoms: ~ 10^7
Cloud radius: ~ 1 mm

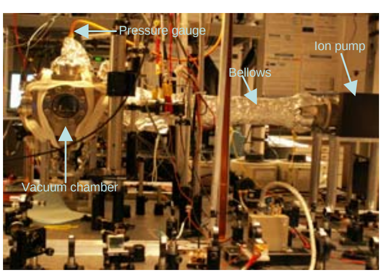


Figure 3: The experiment (nobody said it was easy!!)

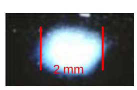
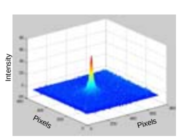


Figure 4: CCD image of cloud of cold ^{85}Rb atoms



Intensity profile
Figure 5: Intensity profile of the cold cloud

Now that we have the cold atoms, what can we do with them?
Manipulate them using photons!

4. Tapered Nanofibres

Tapered nanofibres are fabricated by heating and pulling a single mode optical fibre in a controlled manner.

For a tapered fibre of diameter 0.3 μm, 46% of the total input power is distributed into the evanescent field, shown in figure 6.

The evanescent field at 1/e distance extends up to 0.03 µm from the fibre surface.

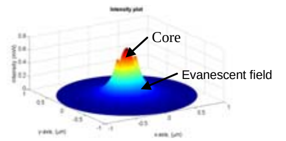


Figure 6: Evanescent field outside the fibre

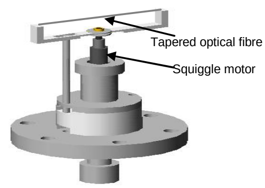


Figure 7: UHV fibre mount

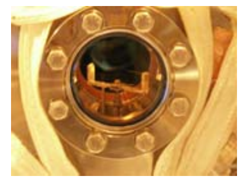


Figure 8: Nanofibre mounted inside the vacuum chamber

The fibre is placed into the vacuum chamber on a nanometer precision positioning Squiggle motor (figures 7 and 8).

By moving the squiggle, we ensure that the tapered region passes through the centre of the cloud of ^{85}Rb atoms.

5. Atom Interaction with Evanescent Field

The interaction between laser-cooled rubidium atoms and the photons in the evanescent field of the tapered optical fibre is studied.

A probe beam, modulated ± 15 MHz across the absorption line of ^{85}Rb, is coupled into the fibre.

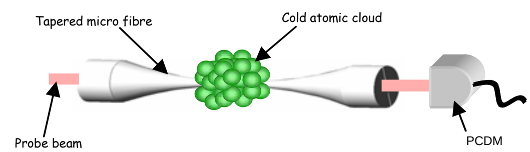


Figure 9: Schematic diagram of the experiment, showing the tapered optical fibre, cold cloud of ^{85}Rb atoms, probe beam and a PCDM.

By comparing the measured density of the MOT to the numerically calculated interaction area of the evanescent field, at any given time there will be approximately **five** atoms interacting with the evanescent field.

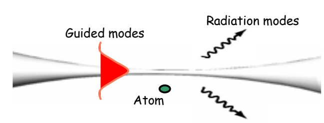


Figure 10: An atom interacting with guided and radiation modes in the vicinity of a thin optical fibre.

The input probe beam produces an evanescent field that can be absorbed by the atom and re-emitted into the surrounding environment.

The scattered photons which are coupled into the guided modes are detected by a photon counting detector module (PCDM).

Three conditions will be investigated as illustrated in figure 11:

(1) Both MOT laser beams and B-fields are switched off,
(2) MOT laser beams are switched on, and
(3) Both MOT laser beams and B-fields are switched on.

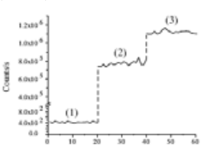


Figure 11: Photon count through the optical fibre *(from K.P. Nayak et al)*

6. Future Prospects

Atoms can be trapped along the tapered fibre (off-resonance condition).

An optical potential can be created by a two colour detuning (blue and red), as shown in figure 12.

Total potential $U = U_{red} + U_{blue} + V$,

where V is the van der Waals potential.

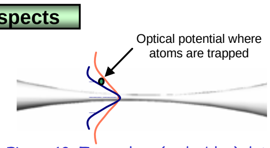


Figure 12: Two-colour (red + blue) detuning.
Attractive force: red
Repulsive force: blue

The input probe beams can be circularly polarized to trap the atoms around the tapered part of the fibre.

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