Quantum
Technology
PROGRAMME

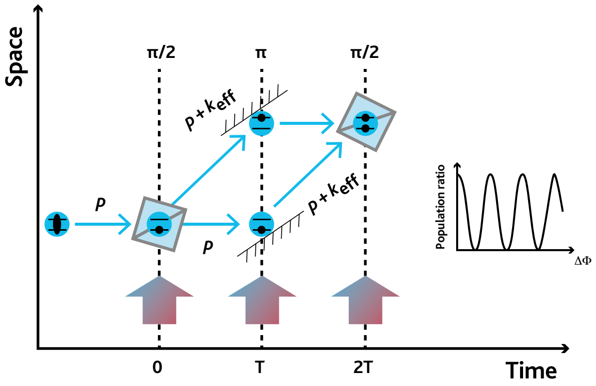
TEACHER GUIDANCE

The physics of quantum sensors – laser cooling

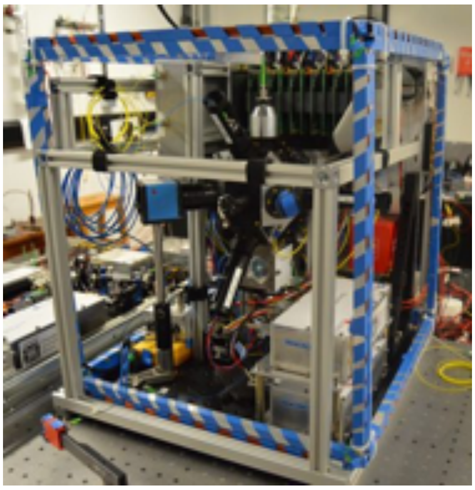
1 BACKGROUND

Many quantum sensors, for example those detecting gravity, need to slow down atoms so that they are nearly completely still. At room temperature atoms move about really fast. So fast, in fact, that their high kinetic energy makes it really hard to exploit their quantum properties for something useful. At very low temperatures the quantum properties of atoms can be observed and harnessed to detect very small changes that would be missed out otherwise, like passing over a sinkhole where the gravitational field is slightly weaker than the surrounding area.

Laser cooling can be used, for example, in an atom interferometer that works by dropping a cloud of 'cooled' atoms. To measure gravity, three pulses of light are shone onto the atoms, transferring momentum to the cloud and placing the atoms into a quantum superposition of two momentum states. The first pulse causes one half of the atoms to travel more quickly through space, splitting the cloud in two. After a time T has passed, a second pulse is used to invert the momentum difference of the two clouds, causing them to begin to move towards each other once again. Finally, after further time T a third pulse is used to close the interferometer. During the sequence the atoms accumulate a phase difference due to gravity, allowing the instrument to detect local changes in density.



Laser cooling is essential in this technology to 'cool' atoms to form the cloud needed to study their properties and take measurements.



Gravity sensor

Developing technology to miniaturise atom traps by laser cooling is an important area of development at the Quantum Technology Hubs, as it will enable us to fit powerful quantum sensors in portable devices, such as smartphones. These technologies will be developed over the next ten years or so. There will be many career opportunities in this area, such as research and development, creating applications for a new generation of smart devices that will use these quantum sensors.

But how can these atoms be slowed down and kept almost still when their tendency is to move so fast?

In this activity you will explore how laser cooling works.

2 OBJECTIVES

- Understand the principles of 'laser cooling'
- Practise A level Physics knowledge and understanding relating to properties of photons
- Link the A level curriculum to quantum sensors technology

3 ADVANCED PREPARATION

Access to YouTube for students, or at least from a projector (including speakers). Students should have previously learnt the equations and theories that will be employed in the questions below, so it is advisable to check the questions and answers before asking students to complete this activity.

4 INTRODUCTION

In this activity you will watch a video that explains the principles of laser cooling. Then, you will use your knowledge and understanding of A level Physics to answer questions about laser cooling. You will need to use ideas and equations from a wide range of A level Physics topics in your answers, so make sure you read each question carefully and keep an open mind.

5 ACTIVITY

This activity encourages students to use their knowledge and understanding of A level Physics to explore the principles of quantum sensors, in particular laser cooling. They will be solving real calculations linked to a pivotal principle common to most quantum sensors. Students will get a sense of how quantum technologies work and appreciate that these applications are not that far from their own experience and grasp.

An activity sheet with a suggested video and associated questions is included in this activity.

6 PLENARY

Discuss the answers of the students and encourage them to offer their solutions from the whiteboard, especially on the calculations in questions 9 to 12. Useful points for discussion are:

- Analysis of units
- The interlinking of all ‘branches’ of physics in the calculations and principles they had to employ in their answers
- Procedural methods and strategies adopted to solve the questions asked

7 EXTENSION

Create students’ own videos to explain laser cooling.

8 TEACHER INFORMATION

See ‘Answers’.

9 LINKS TO FURTHER RESOURCES

The following videos could be watched after the activity to introduce students to the ‘How to Make a Laser’ activity:

https://www.youtube.com/watch?v=y3SBSbsdiYg

https://www.youtube.com/watch?annotation_id=annotation_970515&feature=iv&src_vid=y3SBSbsdiYg&v=lW4Uq_2VPhE

10 ANSWERS

1. What property of light can be used to slow down atoms?

The momentum of photons

2. Why can’t we just use any light to slow atoms?

Atoms only absorb photons of specific wavelengths, so the wavelength of the light used for laser cooling needs to match the absorption frequencies of moving atoms.

3. Use your ideas about the Doppler effect to explain why lasers used in cooling are tuned to a wavelength just longer than the absorption wavelength of still atoms.

Because if the wavelength of incident photons matched the absorption wavelength of still atoms, these atoms would absorb the photons when they are still and gain momentum, hence not be still anymore. A wavelength slightly longer than that is used, so the atoms absorb the photons only when they are moving towards the source of photons (the laser), as the photons will be blue-shifted and of the right wavelength to be absorbed only when the atoms move.

4. Atoms are moving in random directions, so how do ‘laser cooling’ devices manage to slow atoms down so they are nearly still?

Six lasers are used (or three lasers and mirrors on the opposite side) along the x, y and z axes to slow atoms in all directions.

5. Atoms trapped in ‘laser cooling’ chambers are often called ‘cold atoms’. What is actually meant by the term ‘cold atoms’?

It means that their ‘thermal’ speed is very low and that the atoms are nearly still. Atoms cannot actually be cold or hot, but they have more or less energy in the kinetic store associated to them.

6. In the video they say that ‘laser cooling’ has reached temperatures in the order of μK. However, at the UK National Quantum Technology Hub (NQTH), scientists have managed to reach temperatures of pK. By how many orders of magnitude do these temperatures differ?

Six orders of magnitude smaller temperatures.

These questions can be answered through your knowledge and understanding of A level Physics and cannot be inferred from the video.

⑦ The gravity sensors at the NQTH use Rb atoms to measure their gravitational interaction with other masses. The atomic mass of an atom of Rb is 85.4678u. Calculate the gravitational force between an atom of Rb and a large boulder of rock with density $\rho = 2{,}800\text{kg/m3}$ and volume $V = 125\text{m3}$. The atom and the rock are 12m apart.

From the atomic mass of Rb we can convert $m_{Rb} = 1.419226 \times 10^{-25}$ kg

The mass of the boulder is $M_b = XV = 2{,}800 \text{ kgm}^{-3} \times 125 \text{ m}^3 = 350{,}000 \text{ kg}$

So, the gravitational force between the atom of Rb and the boulder is:

$$F = \frac{Gm_{Rb}\,M_b}{d^2} = \frac{6.673 \times 10^{-11}\text{ Nm}^2\text{ kg}^{-2} \times 1.419226 \times 10^{-25}\text{ kg} \times 350000\text{ kg}}{12^2\ \text{m}^2} = 23.018 \times 10^{-33}\ \text{N}$$

⑧ A typical speed for an atom of Rb in its gas state is 430m/s. Explain what effect the gravitational force you calculated in the previous question would have on an atom of Rb in its gas state and why it is necessary to ‘cool’ these atoms for quantum sensors to work correctly. Hint: consider the acceleration caused by the gravitational force and the speed of the atom at room temperature. What effect would this acceleration have on an atom moving at such speed?

A force so small would cause accelerations of

$$a = \frac{F}{m_{Rb}} = \frac{23.018 \times 10^{-33}\text{ N}}{1.419226 \times 10^{-25}\text{ kg}} = 16.22 \times 10^{-8}\ \text{ms}^{-2}$$

which are too small to cause significant effects in atoms at room temperature

⑨ At temperatures of the order of 2pK an atom of Rb would move at a speed of approximately $1.39 \times 10^{-5}\text{ms}^{-1}$ in any direction. The quantum properties of Rb atoms are used by quantum sensors to detect how individual atoms are interfering with each other. Calculate the wavelength associated with a Rb atom at 2pK.

According to De Broglie’s equation any particle with momentum has an associated wavelength following the relationship:

$$\lambda = \frac{h}{mv}$$

We can substitute the mass and velocity of a Rb atom to find the wavelength:

$$\lambda = \frac{6.626 \times 10^{-34}\text{ m}^2\text{ kgs}^{-1}}{1.419226 \times 10^{-25}\text{ kg} \times 1.39 \times 10^{-5}\text{ ms}^{-1}} = 3.359 \times 10^{-4}\text{ m}$$

This is the wavelength associated with a Rb atom at speeds found at 2pK.

10 For an atom of Rb the electron transition caused by the absorption of photons generated by lasers used for ‘laser cooling’ is characterised by an energy difference $\Delta E = 1.590\text{eV}$. Calculate the wavelength of the lasers used for ‘laser cooling’ of Rb atoms. In what range of the EM spectrum is this laser?

We need to convert the energy difference to joules:

$$\Delta E = \frac{1.590}{6.242 \times 10^{18}} = 2.547 \times 10^{-19}\ \text{J}$$

The energy gap between electron orbitals in an atom is linked to the wavelength of a photon of the same energy through the relationship:

$$\Delta E = \frac{hc}{\lambda} \Rightarrow \lambda = \frac{hc}{\Delta E} = \frac{6.626 \times 10^{-34}\ \text{m}^2\ \text{kgs}^{-1} \times 3 \times 10^{8}\ \text{ms}^{-1}}{2.547 \times 10^{-19}\ \text{kgm}^2\ \text{s}^{-1}} = 7.80 \times 10^{-7}\text{m} = 780\ \text{nm}$$

This laser is in the infrared spectrum.