Imperial College London

# D2. Laser Spectroscopy

***Head of Experiment: Prof Jing Zhang***

*The following experiment guide is NOT intended to be a step-by-step manual for the experiment but rather it provides an overall introduction to the work and outlines the important tasks that need to be performed in order to complete the experiment. Additional sources of documentation may need to be researched and consulted during the experiment as well as for the completion of the report. This additional documentation must of course be cited in the bibliography of the report.*

# Doppler free saturated absorption of rubidium using a diode laser

**3rd Year Lab Module, Version 2.1: Revised September 2021.**

**James McGinty,**
**Photonics Group, Imperial College**

## 1. Overview

This experiment is designed to introduce some modern atomic and laser physics techniques currently used in research labs around the world. Many of these techniques are essential to laser cooling, Bose-Einstein condensation and precision measurements.

You are provided with a commercial grating-stabilised diode laser source. This will be used to probe the internal structure of rubidium through Doppler free saturated absorption spectroscopy enabling you to investigate the hyperfine structure in more detail. The experiment consists of the following parts:

- Section 2: Take the online 'Introduction to Laser Safety' training course and perform maximum permissible exposure (MPE) and nominal ocular hazard distance (NOHD) calculations.
- Section 3: Send the laser beam in the rubidium cell and measure the absorption spectrum with a photodiode.
- Section 4: Set up the optical beam path and detectors for recording of Doppler free spectra.
- Section 5: Determining the laser frequency with a Fabry-Perot etalon.

## 2. Laser Safety

Before you begin ensure that you have read and familiarised yourself in detail with the safety information outlined in this section and that you have taken the online laser safety course and signed the risk assessment documentation.
Any student in contradiction of these safety notices will be removed from the lab immediately.

- **The laser you will be working with is class 3B. The output is therefore hazardous can potentially damage your eyes if exposure occurs.**

- **The laser operates at a wavelength of 780 nm. The response of the human eye at this wavelength is poor. This means that the beam intensity is far higher than it appears. Your blink reflex will not be triggered at this wavelength (the visible spectrum is 400-700 nm).**

- **Remove wristwatches and any other jewellery that may unintentionally cross the beam path (this includes rings, long necklaces, earphones, etc).**

- **Always wear the safety goggles provided when the laser is operational.**

- **Ensure that the external laser lamp is illuminated and that the laser screens are in place when the laser is on.**

- **In order to observe the beam and perform minor alignment always use the camera provided.**

- **Ensure that all beams remain horizontal and contained with the optical table.**

- **Leave all optical components secured where they are. If you think that any component requires moving to achieve appropriate alignment then speak to a demonstrator. Never move any of the optical components unsupervised.**

- **Never lower your face anywhere near the beam height. If you have to pick something from the floor block the output of the laser first.**

- **Only students who have signed the appropriate risk assessment forms are permitted to enter room 406A while the laser on light is illuminated.**

- **In an emergency contact the nearest lab demonstrator or technician.**

## 2.1. Introduction to Laser Safety

Before commencing any practical work you must both undertake the online Introduction to Laser Safety course. This can be found at

http://www.imperial.ac.uk/staff-development/safety-training/safety-courses-/

selecting “Introduction to Laser Safety - e-Learning”.

If asked to provide the name of a Principal Investigator (PI), enter James McGinty. You are required to pass the short online test after the training to proceed.

### 2.1.1 Laser safety calculations

The laser used in this experiment operates at a wavelength of 780 nm, a beam divergence of 1.5 mrad and a power of 91 mW. Using these values and the tables in the laser safety folder, calculate the maximum permissible exposure (MPE) and the Nominal Ocular Hazard Distance (NOHD) in your lab books. Ensure that the correct laser properties have been completed on the Laser Expose Grab Card.

Why are laser goggles required to be worn by everyone when the laser is in operation?

**Before you proceed with the experiment ensure that you have**

- Completed the online course ‘Introduction to Laser Safety’ and passed the test
- Completed the MPE and NOHD calculations
- Completed the Laser Exposure Grab Card
- Read and signed the experimental risk assessment

Now with the Head of Experiment, sign the laser user registration form in the laser safety folder.

## 3. Energy level structure of Rubidium

In this experiment you will be measuring the hyperfine structure of two isotopes of Rubidium, $^{87}$Rb and $^{85}$Rb. A representation of hyperfine structure of these two isotopes is shown in figure 1 (the energy level spacing are not to scale).

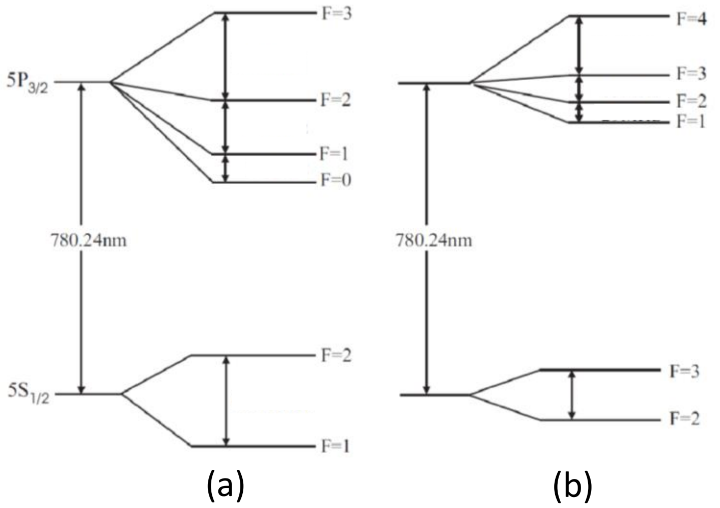


Figure 1: Energy level diagrams indicating the hyperfine structure of the ground $5^2S_{1/2}$ and excited $5^2P_{3/2}$ energy states in (a) $^{87}$Rb and (b) $^{85}$Rb (not to scale).

The full theoretical treatment of this atomic energy level structure is beyond the scope of this experiment, but you should research the mechanism for this splitting, what governs the magnitude of the splitting and what are the allowed transitions (i.e. what you can expect to measure. For the mechanism try chapter 9 in [1].

## 4. Fluorescence and Doppler-Broadened Absorption

### 4.1 The Laser

This experiment uses a commercial tuneable laser diode. The output wavelength of the laser depends on 3 parameters: laser temperature, laser current and the position/orientation of a grating. The laser temperature and current set the wavelength range over which the diode laser will operate (coarse tuning) and within this range, the laser wavelength can be continuously scanned using the grating (fine tuning). Fine tuning of the laser frequency is accomplished by a piezoelectric transducer (PZT) located in the grating mount. The PZT expands in response to a voltage from the PZT controller, which can be adjusted manually or scanned by the controller.

The laser will be switched on before the start of the lab sessions, so you will only need to make minor adjustments on the front panel to the scan amplitude and offset (i.e. the width of the scan range and the central wavelength). **Do not touch any of the optics or put anything into the central area of the bench** – there are high power beams in this region and therefore an increase laser hazard.

### 4.1.1 Initial optical set-up

The initial optical set-up will be similar to that depicted in figure 2 (depending on the set-up it may be a mirror image of figure 2). The laser beam enters through a hole in the screen and is reflected off two mirrors – **do not adjust these first two mirrors**. The beam is then incident on a wedged beam splitter, BS1 - **do not adjust this beam splitter**. This beam splitter transmits ~90% of the intensity, which is then terminated at a beam block, BB. The other ~10% of the intensity is reflected into two beams, one from the front and one from the back surface of BS1. These beams propagate through the glass cell containing the Rubidium mixture. One of the beams should be incident on a second 50:50 beam splitter, BS2, while the other should just miss it.

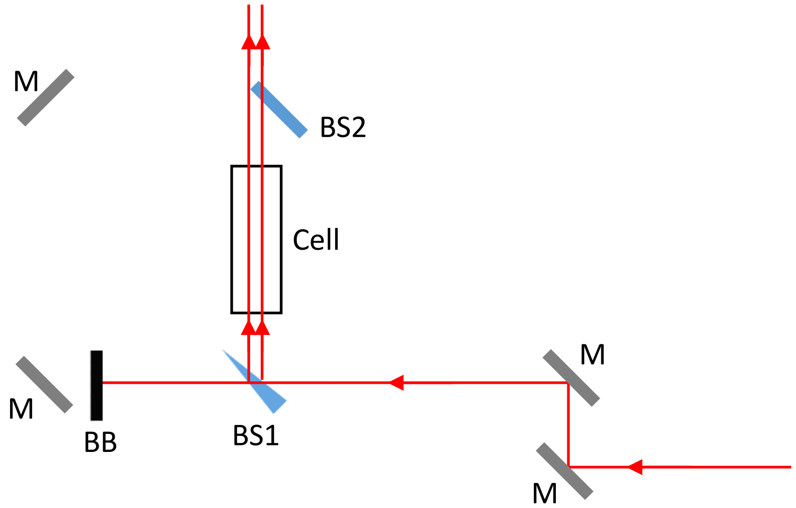


Figure 2: The initial optical set-up. M – mirror, BS1 – 90:10 wedged beam splitter, BB – beam block and BS2 – 50:50 beam splitter.

Trace the path of the beam through the system using the infrared viewing card or the camera. Does it follow the paths describe above? If not speak to a demonstrator.

With the laser wavelength being scanned, what can you observe in the cell when viewed with the camera?

The first task is to insert two pick-off mirrors and photodiodes to measure the intensity of the beams transmitted through the cell. Ask a demonstrator to guide you through this procedure and demonstrate how to insert optical components in a safe way – **optical components should not be placed in the beam path without first blocking the beam**. The optical configuration should look similar to figure 3.

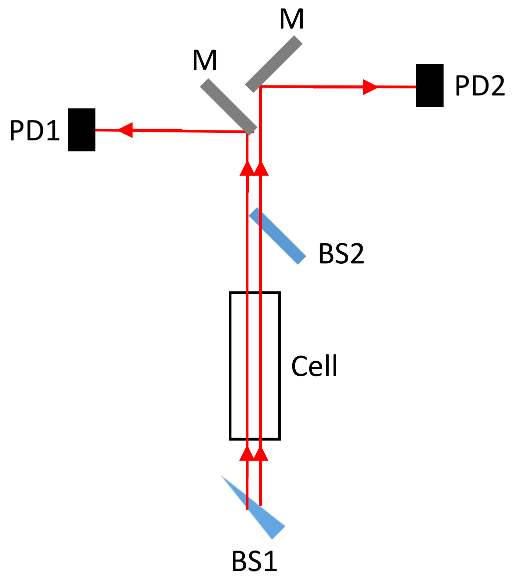


Figure 3: Optical configuration to measure the Doppler-broadened absorption spectrum.

Connect PD1 and PD2 to channels 1 and 2 of the oscilloscope. Then make fine adjustment to the tip-tilt of each mirror to observe and then maximise the signal from each of the photodiodes.

### 4.1.2 Doppler broadened absorption spectroscopy

The cell contains naturally occurring Rubidium (72% $^{85}$Rb and 28% $^{87}$Rb). Since the cell contains two isotopes, each of which have two ground states, you should be able to observe four resolvable absorption features in the spectrum if the wavelength scan range is large enough (two dips for each isotope and two dips for each ground state).

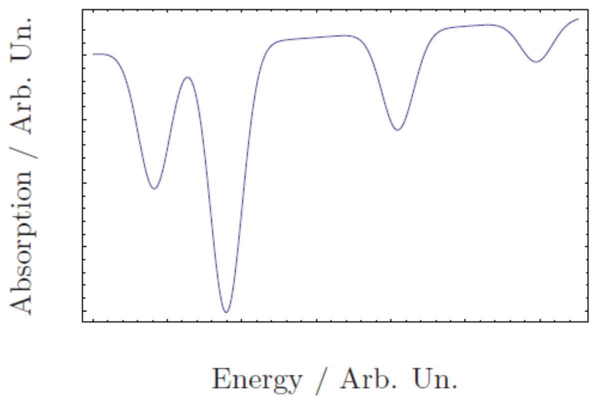


Figure 4: Schematic representation of absorption spectrum for naturally occurring Rubidium.

Using the scope provided, record and identify all four absorption dips. They should look similar to those displayed in figure 4. Using the literature values for the main transitions, estimate the width of each feature by fitting an appropriate curve or otherwise. Estimate the temperature of the gas from these values.

Why is the hyperfine structure larger for the $5^2S_{1/2}$ state compared to $5^2P_{3/2}$? Can you propose a simple physical reason for this?

Calculate the FWHM of the expected Doppler broadened absorption line using the independently measured room temperature. How do these calculations compare to the experimental measurements?

## 5. Doppler-Free Saturated Absorption Spectroscopy

The calculations and absorption measurements made should have convinced you that the excited state hyperfine structure is being masked by Doppler broadening. This will be addressed by introducing a more intense “pump” beam to the cell.

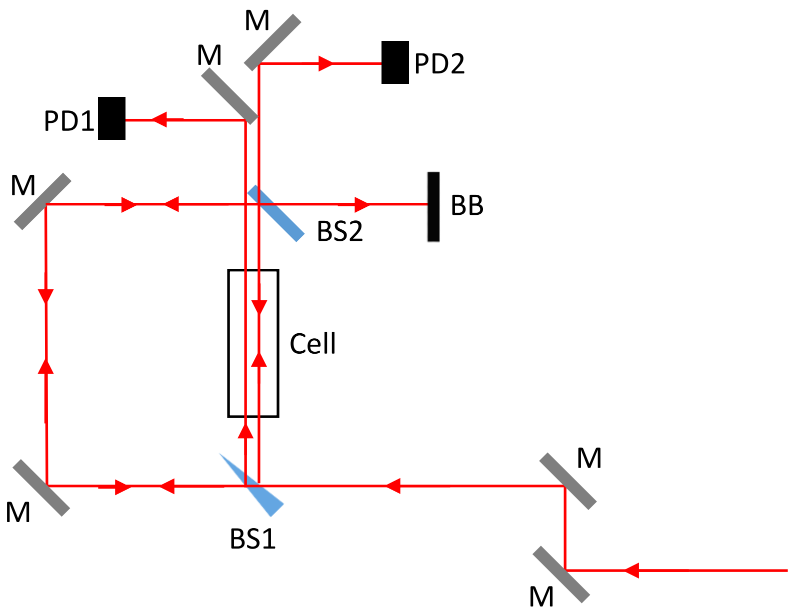


Figure 5: Optical configuration to measure both Doppler-broadened and Doppler-free absorption spectra.

With the laser beam blocked, move the beam block from beside BS1 and place it beside BS2, as indicated in figure 5. When the laser beam is unblocked the higher intensity beam transmitted by BS1 will be directed off two mirrors to BS2. By viewing the beams using the camera, make fine adjustments to these two mirrors to make the counter-propagating pump beam collinear and overlapped with the weaker probe beam. As the overlap increases you should observe a change in the relevant absorption trace (e.g. PD2 in figure 5) – what do you observe? By further fine adjust try to optimise this effect.

By reducing the laser scan range and adjusting the offset, acquire some initial test data from both photodiodes. Combine the signal from both photodiodes to try and minimise the effect of Doppler broadening and produce Doppler-free spectra.

Why does the addition of a counter-propagating pump beam change the measured spectrum? What populations of atoms contribute to this signal?

How many spectral features do you observe at each of the original four absorption lines? Does it match the expected number of transitions? If not can you explain this discrepancy (consider your answer to the previous question)?

From your earlier approximate calibration can you assign values to the hyperfine splitting? How do these compare to the literature values? By fitting or otherwise can you also determine the FWHM of the spectral features?

## 6. Wavelength Calibration using a Fabry-Perot Etalon

While the scan range and central wavelength of the tuneable laser can be adjusted, the scan rate remains constant at 11 Hz. Therefore the calibration between wavelength and time-base on the recorded oscilloscope traces varies as the laser settings are adjusted and the course calibration performed earlier is approximate at beat (as you probably determined from your subsequent analysis). Therefore a method to determine this calibration more accurately is required – this is provided by the Fabry-Perot etalon.

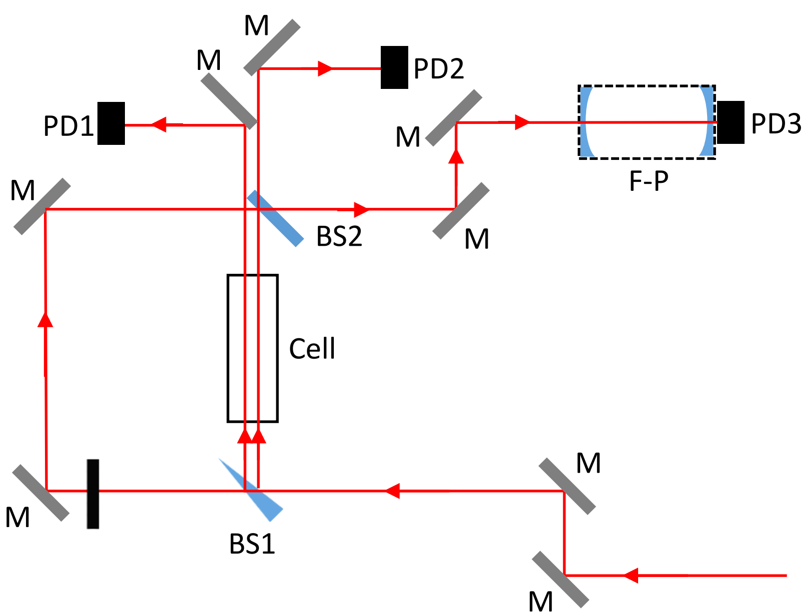


Figure 6: The final optical configuration, including the Fabry-Perot etalon. Using this all the required data to determine the hyperfine energy level structure of naturally occurring Rubidium can be acquired simultaneously.

Remove the BB from beside BS2 and insert two mirrors to steer the laser beam. Insert the Fabry-Perot etalon after these mirrors, as indicated in figure 6. To see a trace on the oscilloscope from PD3, the beam has to be centred and collinear with the central axis of the etalon. Consider how you can try to achieve this alignment and discuss it with a demonstrator.

The mirrors that make up the Fabry-Perot etalon have a radius of curvature of 20 cm and a nominal separation of 20 cm – this is described as a confocal cavity. By considering the ray diagram in figure 7 and the fact that the cavity length, L, must be an integer number of half wavelengths for constructive interference, derive an expression for the optical frequency separation of neighbouring peaks. The peaks observed in the trace from PD3 then provide a relative optical frequency scaling.

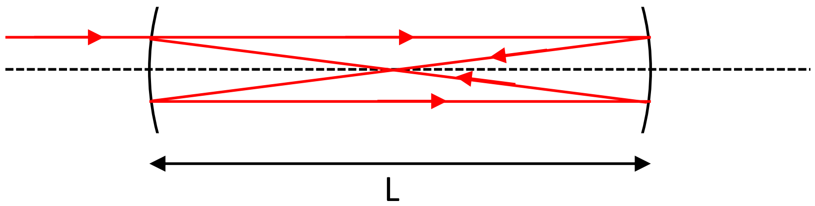


Figure 7: Ray diagram representation of the beam path within the confocal Fabry-Perot etalon.

To further improve the calibration, a radio frequency generator can be used to modulate the current of the laser diode, which results in the appearance of sidebands next to the main interference peaks from the Fabry-Perot etalon. The separation of the sidebands from the main peaks will be a function of the radio frequency applied.

**References:**

[1]G. K. Woodgate, Elementary Atomic Structure, 2nd Ed., (Oxford University Press, 1980).

Imperial College London

**RISK ASSESSMENT AND STANDARD OPERATING PROCEDURE**

| **1. PERSON(S) CARRYING OUT THIS ASSESSMENT –** The assessment should be carried out as a joint exercise between the student(s) and the supervisor. | |
|---|---|
| Name (Demonstrator/Supervisor) | James McGinty |
| Name (Student) | |
| Name (Student) | |
| Date | 07/10/2019 |

| **2. PROJECT DETAILS –** Delete building as applicable. You can fill in the room location once you know exactly where your project will be based. | | | |
|---|---|---|---|
| Project Name | Laser Spectroscopy | Project Code | D2 |
| Brief Description Of Project Outline | 3rd undergraduate laboratory experiment (~30 hours of experimental work).<br><br>Imperial College hosts the largest concentration of high-power laser research in the UK, and we develop a broad range of new laser sources for which no commercial solution exists. Elements of this work therefore requires open beam working on high power laser systems. As part of our mission to train the next generation of researchers, we therefore include safe use of Class 3B laser systems, development of laser safety cases and selection of appropriate PPE as part of our undergraduate training, in order to prepare students for project work in laser laboratories. One element of this is to provide students with hands on experience of working on open beam systems under carefully controlled conditions. For the Rb spectroscopy experiment, we have also carried out a technical assessment that highlights that a Class 3B source is required to deliver sufficient signal-to-noise. | | |

**LaserBee Laser Safety Report**

Licensed to: Imperial College London, Safety Dept
Report produced: Mon Oct 07 14:10:38 BST 2019

**Laser Details**

unsaved laser

| | | | |
|---|---|---|---|
| wavelength: | 780.0 nm | beam type: | Freespace |
| beam diameter: | 1.000 mm | divergence: | 1.500 mrad |
| power type: | CW | power: | 91.00 mW |

**Laser Classification: Class 3B**

**Small source Class 3B AEL**

| | | | |
|---|---|---|---|
| exposure time: | 100.0 s | | |
| power: | 500.0 mW | energy: | 50.00 J |

**Corneal MPE (small source)**

| | | | |
|---|---|---|---|
| exposure time: | 100.0 s | | |
| irradiance: | 14.45 W/m$^2$ | radiant exposure: | 1.445 kJ/m$^2$ |
| aperture: | 7.000 mm | | |

**NOHD calculation**

| | | | |
|---|---|---|---|
| NOHD: | 59.03 m | NOHD beam diam.: | 89.55 mm |

**ENOHD calculation**

| | | | |
|---|---|---|---|
| objective diam.: | 50.00 mm | magnification: | 8 |
| ENOHD: | 425.7 m | ENOHD beam diam.: | 639.6 mm |

**BS EN 207 calculation**

| | | | |
|---|---|---|---|
| distance: | 100.0 mm | exposure time: | 10.00 s |
| OD from MPE: | 3.78 | | |

Filter Marking: 780 D L4

LaserBee is produced by
Lucid Optical Services Ltd.
Garsdale UK

| | | | | | | |
|---|---|---|---|---|---|---|
| Location | Campus | South Ken | Building | Blackett/Huxley | Room | 406A |

| **3. HAZARD SUMMARY –** Think carefully about all aspects of your project and what your work could entail. Write down any potential hazards you can think of under each section – this will aid you in the next section. If a hazard does not apply then leave blank. | | | |
|---|---|---|---|
| Manual Handling | | Electrical | Use of mains-powered electrical equipment. |
| Mechanical | | Hazardous Substances | Rubidium vapour ($^{85}$Rb and $^{87}$RB) contained in glass cell. |
| Lasers | Commercial c.w. laser operating at 780 nm and maximum power of 91 mW (class 3B). | Noise | |
| Extreme Temperature | | Pressure/Steam | |
| Trip Hazards | | Working At Height | |
| Falling Objects | | Accessibility | |
| Other | Data acquisition requires room lights to be switched off. | | |

| **4. CONTROLS –** List the multiple procedures which you may carry out during your project along with the controls/ precautions that you will use to minimise any risks. Remember to take into consideration who may be harmed and how – other people such as students, support staff, cleaners etc will be walking past your experimental setup even when you aren't around. | |
|---|---|
| **Brief description of the procedure and the associated hazards** | **Controls to reduce the risk as much as possible** |
| Use of a c.w. class 3B infrared laser (91 mW at 780nm) | -All students taking this experiment are required to become registered laser users before commencing any experimental work, including calculating the MPE and NOHD for the laser<br>-The perimeter of the optical bench is fully screened to contain the laser beam<br>-All laser beam paths are horizontal and remain at the same fixed height in the experiment (i.e. no periscopes)<br>-Laser goggles are provided and must be worn by anyone entering the lab when the laser warning light is on. Based on LaserBee calculation, goggles have an OD>4 at 780nm (LG5, Thorlabs Inc).<br>-The laser itself and initial beam steering/conditioning optics are within a separate screened-off section of the optical bench. The students are specifically told not to touch any components in this area. The optical power entering the 'measurement' region of the optical bench (i.e. area the students make adjustments and measurements) is <0.5 mW. |
| Fine alignment of laser beam paths: The students are required to insert and adjust mirrors steering the beam through the experiment and on to detectors. | -The main optical components are in place, so only minor adjustments of the mirror tip/tilt controls is required. 4r mirrors and 3 detectors are added by the students after being trained in SOPs.<br>-The optical power in the 'measurement' region of the bench where the mirrors are situated is <0.5 mW<br>-A camera and monitor are provided to view the beam |
| Glass cell containing Rubidium vapour mixture | -Low pressure cell is used (~$1.3\times10^{-6}$ Pa)<br>-The cell is mounted in place so does not need to be moved/adjusted by the students |
| Working with room lights off | |
| Mains powered equipment | |

| | |
|---|---|
| Distribution boards providing power to central optical bench | -Task lighting is provided on the optical bench<br>-Floor is kept clear of potential trip hazards (e.g. bags, stools, etc)<br><br>-All electrical equipment is PAT tested<br>-All electrical equipment is mounted off the floor<br><br><br>-Distribution board cables from wall sockets to the optical bench are secured onto the floor under cable covers<br>-Distribution boards are not ‘daisy-chained’<br>-Distribution boards are mounted off the floor |

| **5. EMERGENCY ACTIONS –** What to do in case of an emergency, for example, chemical spillages, pressure build up in a system, overheating in a system etc. Think ahead about what should be done in the worst case scenario. |
|---|
| If a suspected laser injury has occurred immediately tell a demonstrator/technician and follow the instructions detailed on ‘Laser Grab Card’ found on the back of the lab door and in the laser safety folder.<br><br>If a glass cell containing Rubidium is damaged/broken immediately evacuate the room, close the door and inform a demonstrator/technician. Do not re-enter the room. |

| **6. TRAINING RECORD –** As your project work evolves your experimental strategy/procedures may change. Therefore it is important that you review this risk assessment on a weekly basis and update it as necessary. Please sign and date below to indicate that all person(s) have been trained in this risk assessment and associated procedures. | | |
|---|---|---|
| Names (Supervisor + Students) | Sign | Date |

| | | |
|---|---|---|
| James McGinty | J. McGinty | 07/10/2019 |