Projects

The general objective with the course is to provide knowledge helpful for designing and setting up experimental schemes for measuring spectroscopic properties in order to extract information useful for science and industry. Theoretical background is provided through the lectures and the book. Practical laboratory exercises illustrate selected key concepts and provide practical hands-on experience. The demonstrations give examples of the range of measurements that can be carried out and provide opportunity to see real-world equipment in operation.

The projects are, as for the labs, meant to activate the course participants and also in part to let you explicitly formulate how different measurements could be carried out, which can be expected to significantly help fulfilling the goals of the course. The information needed to solve the tasks can be found in the text book, from lecture notes or from the internet. For several of the projects there is also the opportunity to have a quite applied approach in the sense that one can choose to identify possible providers of the equipment and estimate costs for the equipment needed to carry out the measurements described.

For the projects you are supposed to work in pairs. Each student pair will choose one project (A, B, C or D), each consisting of three separate but connected subprojects. The written project reports for each of the subprojects are maximum 3 pages, excluding figures and tables. Each subproject is presented orally and will be commented and analyzed by two other students, but it is the lecturer who will decide if a subproject is approved or whether it needs to be complemented.

You choose your project in connection with the lecture Tuesday September 6th. Each project consists of three subprojects which are to be reported according to the schedule below. On Friday one week before your oral report of your subproject you can obtain assistance with your project from the lecturers. Before 13.00 on Wednesday the following week you need to submit the written subproject report to the *Report group* (see below) and then on Friday afternoon you have the oral report. If your project needs to be complemented the corrected report should be submitted by noon the next Tuesday.

The oral report is held for one of the lecturers and some of the other students. Together with you and your project partner, these persons form the *Report group* and the project report should be sent to all of these at the written report due date and time. Two of the students in the *Report group* will give feedback on the written and oral report and so will the lecturer. You are also yourself obliged to give feedback on one of the other student reports. The oral report should be done on blackboard/whiteboard and not by using a Power point presentation and have a maximum duration of 15 minutes. There is no lower limit but you should explain the project objective and results.

	Project assistance Friday 13.15-15	Written report due Wednesday 13.00	Oral presentation Friday	Corrected report due Tuesday 12.00
Subproject 1	9/9	14/9	16/9	20/9
Subproject 2	23/9	28/9	30/9	4/10
Subproject 3	7/10	12/10	14/10	18/10

Things to think about when preparing for the oral presentations

Preparing computer-based oral presentations can be quite time consuming, so to save you some time we instead have chosen to have black/white board presentations. However you of course still will have to prepare your presentations carefully. Below we have listed some points which should be useful for you to consider when preparing your presentations.

1. Suppose that you had not done this project and someone else would have presented the project for you. Think about what would have been the most useful/important/interesting for you to know about the project in that case. This is then also what you want to tell the others about.

2. When you prepare your presentation take some time to reflect on the material and identify things that you find the most difficult to comprehend. There is a high probability that many listeners will find these concepts difficult too. Now, put a particular focus on how to explain these difficult parts in the most educational way possible. This might of course not be an easy task, but at least the awareness of what might be difficult to understand is an important and valuable preparation.

3. Be careful to give a proper background such that the audience understands the objective of the overall project and how the part that you are telling about relates to the overall project.

4. Calculations are in general appropriate and often necessary for your written report and the audience will always be able to read your report and get all these details. In your oral presentation you would typically wish to omit any detailed calculations. It is often more useful to just write the defining equations and explain these. The order of magnitude of the answers can however also be interesting. For example, it can be relevant to know that 2000 cm^{-1} could be a typical value for a vibrational energy separation. But listening to the oral presentation it is probably completely uninteresting to know that this vibrational energy separation is exactly 2329.9 cm^{-1}, but this can of course important in your written report.

5. Have at least one complete rehearsal of your presentation. Decide what you will write on the board and who will write it (you are two persons so, if that makes things more efficient, one person can write/draw while the one talks and vice versa). It is often also good to think about where on the board things should be written. Also remember that “one figure can say more than a thousand words”.

Short comment regarding the feedback in connection with the presentations

For your feedback on the written and oral presentations please prepare/consider the things below

1. Comment in writing on the report and have your questions regarding the report written down so you remember them.

2. After the presentation comment on whether the topic and objective of the report was clear? Further ask about things you felt were unclear or you did not understand (in the written or oral presentation).

3. Give constructive feedback on style of presentation both written and oral. Particularly focus on anything that you think would be helpful for the persons to think about in the future, including their next presentation.

4. Ask about things you think would be interesting in relation to the presented material. It is generally good to aim at creating an interesting discussion, on or connected to, the presented topic.

5. Hand over your commented file/document to the pair that presented.

Project A

Projects A and C both analyze aspects related to an experiment on Rydberg atoms and quantum information carried out at University of Wisconsin-Madison [1]. However, the techniques, methods and equipment are in general common in laser-based measurement and in particular for many experiments in modern laser-based atomic physics research, making this experiment a suitable basis for projects in the Atomic & molecular spectroscopy course.

Atoms where an electron is excited to a high principal quantum numbers, *n*, so called “Rydberg atoms”, have been of interest over a very large number of years due their unique properties. For example Rydberg atoms were used for demonstrating interaction between single atoms and single photons in the Nobel Prize winning work in the group of Serge Haroche [2].

Rydberg atoms have among other things recently been used to demonstrate logical gates between single pairs of atoms, such that the quantum state of one atom controls in which quantum state a nearby atom ends up in when it is subjected to light pulses. Gate operations such as those mentioned above are of interest in investigations towards the possibility to carry out computations based on quantum mechanical systems, which can provide improved performance for certain tasks since they are not limited by the laws of classical physics[1]. The project will address properties of Rydberg atoms and examples of equipment and experimental methods used to carry out the investigations of interacting Rydberg atoms.

Incidentally there is also a historical connection to Lund since the designation Rydberg atoms was chosen after Janne Rydberg, who was a professor in Lund at the beginning of the 20th century.

Some references are given below: Additional references and links are also given in connection with each subproject.

References

[1] “*Rabi oscillations and excitation blockade between ground and Rydberg states of single optically trapped Rubidium atoms*”, Todd Johnsson, Phd Thesis http://hexagon.physics.wisc.edu/papers%20and%20pubs/theses/TAJthesis.pdf

[2] http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/popular-physicsprize2012.pdf

[3] S. Svanberg, Atomic and Molecular Spectroscopy – Basic Aspects and Practical Applications

[4] Atoms molecules and photons, W Demtröder, Springer

[5] “*Rubidium 87 D line data*”, Daniel Steck, http://steck.us/alkalidata/rubidium87numbers.pdf

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[1] The areas quantum information and quantum computing are covered more extensively in the course FYST30, “Quantum information”.

Project A1

Please answer/address the following questions in your report.

What is a Rydberg atom?

How do e.g. size, dipole moment and lifetimes, scale as a function of the principal quantum number? Provide examples of some specific values. How large are they (in meters (m))? What could be their lifetimes (in seconds (s))?

How can Rydberg states be long-lived although they have allowed transitions to so many different states?

The break down field in air is about ~30 kV/cm. Rydberg atoms get ionized at much lower voltage. In Ref [1] experiments are carried out with Rydberg atoms of principal quantum number 43 and 79. What fields would be needed to ionize these atoms? Briefly describe your calculations!

Why might Rydberg atoms be sensitive to thermal radiation?

Suggest a reasonable value for the Black body radiation induced decay rate (s^{-1})?

Useful additional references may include

Rydberg atoms, Thomas F Gallagher, Cambridge monographs on atomic molecular and chemical physics, Vol 3 (1994)

Rydberg Atoms, Edelstein and Gallagher, Advances in atomic and molecular physics, vol 14 (1978)

Ref 3, page 49 and Ref 4.15 (+http://prl.aps.org/pdf/PRL/v42/i13/p835_1)

Ref 4, For example Fig 7.2, page 250 and Chapter 6.6.4

Project A2

Figure 3.1, page 13 in Ref 1 is an example of equipment for exercising control of atoms at the quantum level. The overall set-up is quite complicated. The atoms are laser cooled (Ref 3, Section 9.8) in a Magneto-Optical Trap (MOT) (Ref 3, Fig 9.73, page 383) inside a high vacuum system using gradient magnetic fields and pairs of counter-propagating laser beams. One set of lasers is used for cooling the ground state atoms in the MOT before transferring them to the Far Off Resonance Trap (FORT) created by another laser. Still another set of lasers is used to prepare atoms that have reached the FORT in their Rydberg states. The FORT can contain two atoms (or ensembles of atoms) separated by just a few micrometers in space, such that their interactions can be investigated at micro-meter scale separations. This makes it possible to implement and study gate operations between individual atoms. Laser cooling and trapping including the principles of magneto-optical traps are essential parts in the course in light-matter interaction (FAFN05/FYST21) and we will not cover these topics in detail in the present course.

In this second subproject the task is to discuss some aspects of the lasers used to excite the Rb atoms to their Rydberg states.

Describe how the excitation to the Rydberg states is done in the experiment!

The 480 nm radiation is produced by frequency doubling the output from a Toptica TA-100 system (Ref 1, page 115). Look at the Toptica TA-SHG pro system. What is the purpose of the optical isolators?

What is the advantage of separating the laser oscillator from the amplifier?

What is the purpose of the mode matching optics?

What is the purpose of the doubling cavity and why does it need to be resonant?

What equipment is typically needed to obtain an operating diode laser system in addition to the actual diode laser chip?

In general what equipment could be useful to characterize the performance of a laser?

What are the properties of diode lasers that make them suitable for the tasks to be carried out in this (and many other) experiment?

Both 960 and 780 nm systems are locked to an ultra-stable external cavity (Ref 1, Fig C.11, page 114). The Rydberg level line width is about 2 kHz (Ref 1, page 110) and the stabilized laser system has more than an order of magnitude more narrow line width (Ref 1, Fig C.10). For the cavity in Fig C.11, what is the largest cavity length change allowed if the cavity resonance frequency, ν, should keep within 2 kHz? [2]

Could you in general think about what actions/precautions that one could take in order to make the passive stability as good as possible?

Some potentially relevant links

http://www.toptica.com/products/research_grade_diode_lasers/frequency_converted_diode_lasers/ta_shg_pro_frequency_doubled_high_power_tunable_laser.html

Diode laser operation 101, http://www.laserfocusworld.com/articles/print/volume-50/issue-03/features/laser-diodes-laser-diode-operation-101-a-user-s-guide.html

For additional information Googling also often works quite well of course.

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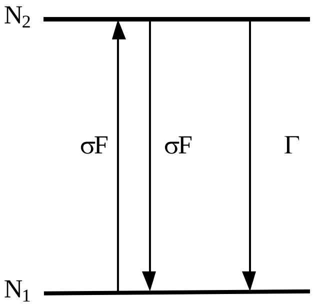
[2] With all the precautions made this stability is still only obtained because the Brownian motion of the cavity mirror atoms is averaged across the laser beam cross section area. A state of the art cavity of this kind costs ~10 k€. On the other hand the Toptica TA-SHG pro system is of the order of 100 k€.

Project A3

This subproject aims at analyzing some aspects on atom excitation and predicting the fraction of excited atoms in an ensemble under excitation and project C3 will then look at the possibility to detect an excited atoms. Ref 5 might be useful in parts of the present project. An additional task in this project is to briefly discuss how a FORT (Far Off Resonance Trap) works.

For parts of this subproject it may be useful to consider a two-level system as shown below and also assumed it is closed two-level system, *i.e.* $N_1 + N_2 = N$, where N is a constant number.



N_k = number of atoms/volume in level k, $[N_k] = 1/m^3$
σ = absorption cross section for transition 1↔2, $[\sigma] = m^2$
F = photons/(area and second), $[F] = 1/m^2s$
$T = 1/\Gamma$ = upper state lifetime, $[\Gamma] = 1/s$

a) Page 13 in the thesis contains an equation describing the fraction of excited atoms for given input intensity. (There is a misprint in that equation, the correct equation is $f_{exc} = \frac{I/2I_s}{1+I/I_s+(\frac{2\Delta}{\Gamma})^2}$ and the same error occurs in the Eq. on page 23.) Equation 9.1, page 287 in Ref 3 is basically the on resonance version of the above equation. Motivate why we get half the atoms in the upper state as the excitation intensity goes to infinity!

Assume we are tuned exactly into resonance. When the light intensity, *I*, is equal to the saturation intensity, I_s, how many photons per transition cross section area and lifetime does this correspond to?

What is the relation between the transition cross section and the absorption coefficient?

For the two-level system above the upper-lower state population difference is N at zero intensity. Use rate equations to derive the upper-lower state population difference at $I=I_s$!

What power is needed in a 100 μm radius beam to saturate the 5s $^2S_{1/2}$ (F=2) - 5p $^2P_{3/2}$ (F=3) ^{87}Rb transition? A top hat intensity can be assumed.

b) The FORT trap is of the so called dipole trap type. Dipole traps have been used extensively as so called optical tweezers to, for example, capture small biological object and move and manipulate these in space. How does the dipole trap work and how can it be used to also capture atoms?

Project B: Combustion diagnostics

Coherent anti-Stokes Raman spectroscopy (CARS) is a commonly used laser-based technique for combustion diagnostics. It is based on the interaction of normally three photons in a non-linear optical process. The three photons are provided by three focused laser beams that intersect in a point in which the CARS process is taking place, which also defines the measurement volume. The frequency difference between two of the photons, often termed pump and Stokes photons, is in resonance with vibrations and/or rotations in the molecules under investigation. The coherently excited molecules are then probed by a third photon, often termed probe photon, which generates a CARS signal photon, whose frequency is shifted relative to the probe photon by the vibrational or rotational Raman frequency of the molecule. The CARS signal is propagating in a well-defined direction as a laser-like beam. By spectrally dispersing the CARS signal and analysing the shape of the resulting spectrum the temperature in the measurement point can be determined.

Project B1

Thermometry is to be carried out using vibrational CARS in nitrogen (N_2). A green laser beam at 532 nm is used to deliver both pump and probe photons, while a red laser beam is the source of the Stokes photons.

a) Sketch a general energy level diagram for the vibrational CARS process. Indicate pump, Stokes, probe, and CARS transitions.

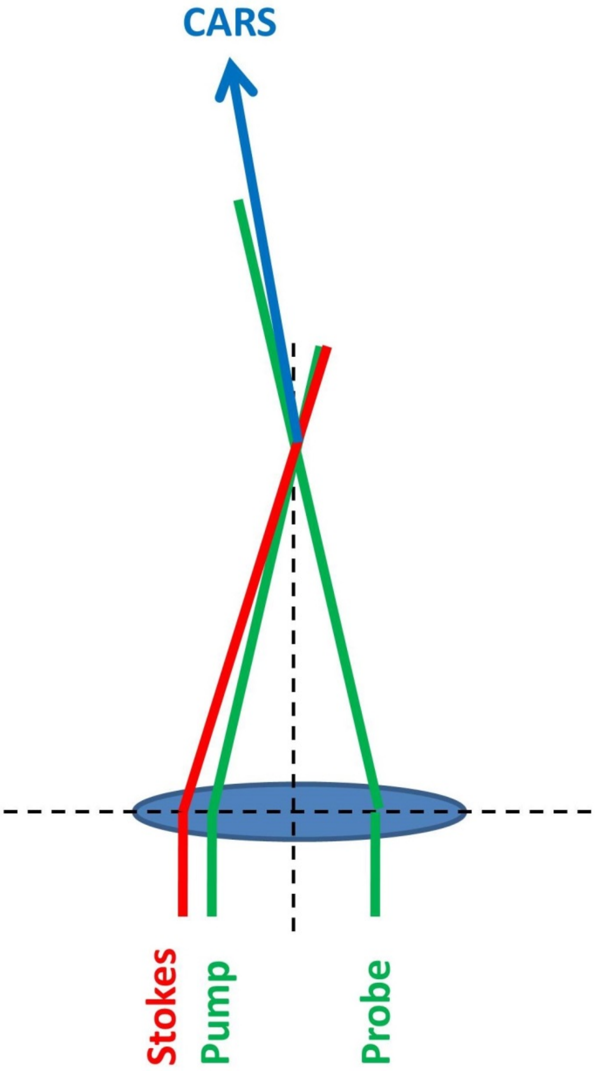
b) Using molecular constants of N_2 (available in the Appendix), calculate the vibrational Raman frequency, i.e. the wavenumber corresponding to the energy difference between v = 1 and v = 0 in the electronic ground state (X $^1\Sigma_g^+$). If we neglect molecular rotation, we now have the information needed to determine the wavelength of the laser used for the Stokes transition as well as the wavelength of the generated CARS signal. Calculate thus these two wavelengths.

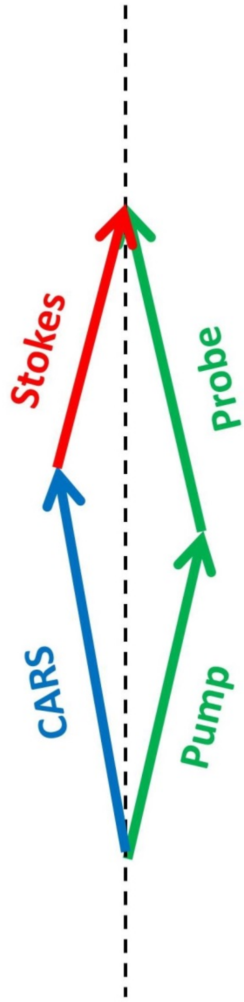
c) Now, also take the rotational structure into account and calculate the two wavelengths corresponding to the Q(10) transition, i.e. the Q-branch transition originating in rotational state J = 10. Note that it is not a pure rotational transition but rather a rovibrational transition, i.e. a transition between a particular rotational state (J = 10) in v = 0 and a particular rotational state in v = 1.

d) So far only the fundamental band has been considered. However, at elevated temperatures “hot bands” are also observable. The first “hot” band corresponds to transition between v = 1 and v = 2. Calculate the Raman frequency corresponding to this band, i.e. calculate the wavenumber corresponding to the energy difference between v = 2 and v = 1 (still in the electronic ground state (X $^1\Sigma_g^+$)). Calculate the wavelengths of the Stokes transition as well as the CARS signal corresponding to this “hot” band (neglect the rotational structure).

e) At what temperature do you expect to observe the first “hot” band in the CARS spectrum? [Hint: Assume that the first “hot” band is observable when the relative population in v = 1 is larger than 5%]

f) When performing a CARS-measurement both energy and momentum (phase-matching) conservation must be fulfilled. Thus $\bar{k}_{CARS} = \bar{k}_{pump} + \bar{k}_{probe} - \bar{k}_{Stokes}$ where $k=2\pi n/\lambda$. The focal length of the focussing lens is 30 cm, and the distance between the pump and probe beams is 15 mm (see figure below). Both pump and Stokes are on the same distance from the center of the focusing lens. Calculate the distance between the pump and Stokes beams on the focusing lens to maximize the CARS signal. [Hint: Projection of wave vectors on both the x-axis and the y-axis will lead to two equations with two unknown parameters]





Project B2
Assume that you have recently joined a company as a new expert in applied laser spectroscopy. Your first job is to buy and put together a complete setup for CARS measurements of temperatures in a large-scale furnace with limited optical access (only two optical windows opposite to each other are available). Make a list of equipment/optics you would buy, and make a schematic drawing showing how you would arrange the equipment/optics to achieve the goal. Remember that when you start you come to a completely empty lab.

Project B3
In order to obtain reliable data from laser-diagnostic techniques, they must be applied with care, considering the specific measurement situation and potential interferences.

a) Since the laser radiation polarizes the molecules by moving the electric field at the frequency of the incident radiation, one can imagine that there is an upper limit to the laser intensity before electrons are removed from the molecules and ions are formed. When creating such a plasma, the medium has been significantly altered and a diagnostic measurement gives no signal that is possible to interpret. In flames the intensity for which breakdown occurs is around 10^{12} W/cm^2. Assume that the laser pulses used in the CARS experiment have 5 ns duration and estimate the highest pulse energy (Joule) that can be used without the risk of causing breakdown. Assume that the laser beams are focused with a spherical lens of 500-mm focal length.

b) For high enough laser intensities the molecular energy levels may be perturbed, a phenomenon called Stark effect, resulting in splitting or shifts of spectral lines. Assume that the laser radiation must provide an electrical field that is one thousandth (0.001) of the internal electric field in the nitrogen molecule to generate observable Stark effect. Make the approximation that the internal electrical field in the nitrogen molecule is roughly the same as the electrical field in a hydrogen atom and then calculate the laser intensity that is needed to induce observable Stark effect in nitrogen. For the same lens and laser pulse duration as in a) calculate the laser pulse energy corresponding to this intensity.

c) The optical windows for optical access to the furnace are critical components. Discuss which factors that should be considered when selecting the windows.

d) If vibrational CARS is applied in sooty flames, C_2 fragments may be created by the intense laser beams. Study the absorption spectrum of C_2 and discuss how C_2 fragments may disturb CARS measurements in nitrogen using the setup outlined in B2? Is it possible to circumvent the problems caused by C_2? If yes, how can it be done?

Molecular constants for N_2

(From: Huber and Herzberg, *Constants of Diatomic Molecules*, Van Nostrand Reinhold, New York, 1979)

The unit is cm^{-1} for all constants except for r_e which is given in Ångström (Å).

State	**T_e**	**ω_e**	**$\omega_e x_e$**	**B_e**	**α_e**	**D_e ($\times 10^6$)**	**r_e (Å)**
B’ $^3\Sigma_u^-$	66272.47	1516.88	12.181	1.4733	0.01666	(5.56)	1.2784
W $^3\Delta_u$	59808	1501.4	11.6				
B $^3\Pi_g$	59619.35	1733.39	14.122	1.63745	0.01791	[5.9]	1.21260
A $^3\Sigma_u^+$	50203.63	1460.64	13.872	1.45460	0.0180	[6.15]	1.2866
X $^1\Sigma_g^+$	0	2358.57	14.324	1.998241	0.017318	[5.76]	1.097685

[ ]: Data refer to v = 0 or lowest observed level. T_e values in square brackets give the energy of this level relative to the minimum of the ground-state potential energy curve. Vibrational frequencies in square brackets correspond to $\Delta G(1/2)$ or the lowest observed signal.
( ): Uncertain data

Project C

Projects A and C both analyze aspects related to an experiment on Rydberg atoms and quantum information carried out at University of Wisconsin-Madison [1]. However, the techniques, methods and equipment are in general common in laser-based measurement and in particular for many experiments in modern laser-based atomic physics research, making this experiment a suitable basis for projects in the Atomic & molecular spectroscopy course.

Atoms where an electron is excited to a high principal quantum numbers, *n*, so called “Rydberg atoms”, have been of interest over a very large number of years due their unique properties. For example Rydberg atoms were used for demonstrating interaction between single atoms and single photons in the Nobel Prize winning work in the group of Serge Haroche [2].

Rydberg atoms have among other things recently been used to demonstrate logical gates between single pairs of atoms, such that the quantum state of one atom controls in which quantum state a nearby atom ends up in when it is subjected to light pulses. Gate operations such as those mentioned above are of interest in investigations towards the possibility to carry out computations based on quantum mechanical systems, which can provide improved performance for certain tasks since they are not limited by the laws of classical physics[1]. The project will address properties of Rydberg atoms and examples of equipment and experimental methods used to carry out the investigations of interacting Rydberg atoms.

Incidentally there is also a historical connection to Lund since the designation Rydberg atoms was chosen after Janne Rydberg, who was a professor in Lund at the beginning of the 20th century.

Some references are given below: Additional references and links are also given in connection with each subproject.

References

[1] “*Rabi oscillations and excitation blockade between ground and Rydberg states of single optically trapped Rubidium atoms*”, Todd Johnsson, Phd Thesis http://hexagon.physics.wisc.edu/papers%20and%20pubs/theses/TAJthesis.pdf

[2] http://www.nobelprize.org/nobel_prizes/physics/laureates/2012/popular-physicsprize2012.pdf

[3] S. Svanberg, Atomic and Molecular Spectroscopy – Basic Aspects and Practical Applications

[4] Atoms molecules and photons, W Demtröder, Springer

[5] “*Rubidium 87 D line data*”, Daniel Steck, http://steck.us/alkalidata/rubidium87numbers.pdf

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[1] The areas quantum information and quantum computing are covered more extensively in the course FYST30, “Quantum information”.

Project C1

Nonlinear interactions (where the value of one quantity depends on the state of another quantity) are needed to create hardware able to carry out computational tasks. In a computer the key nonlinear element is the transistor (the drain current is not only determined by the source current but also by the gate voltage). Nonlinear interactions between atoms may for example occur when optical pulses are directed onto an atom and the resulting state of this atom is determined not only by these input pulses but also by the state of another (nearby) atom. An example how this could be carried out using two Rydberg atoms is described on pages 84-85 in Advances in Atomic Molecular and Optical Physics, volume **61** (2012). The energy shift, ΔE, due to interaction between two dipoles with dipole moment μ, separated a distance r is approximately given by $\Delta E = h\,\Delta\nu = \mu^2/(4\pi\varepsilon_0 r^3)$, where h is Planck's constant and ε_0 is the permittivity of vacuum. For Rydberg atoms with a principal quantum number n, the effective dipole moment is approximately $\mu = n^2 e a_0$ (where e is the electron charge and a_0 is the Bohr radius).

Consider the FORT trap in Fig 5.4, page 52 in Ref 1 (this figure is a smaller part of the more complete experimental set up in Fig 3.1 on page 13). In your report please describe how an atom in one of the two FORT sites can control the state of an atom in the other FORT site.

Assuming the frequency width of the transition from the ground state to the Rydberg state is limited by the upper state lifetime, which can be estimated from Chapter 4.1 in Ref 1, you can compare this width to the dipole-dipole interaction shift. What would be the maximum distance between two Rydberg atoms in the experiment for the dipole-dipole interaction to still be larger than one transition linewidth?

Why might Rydberg atoms be a good choice for gate operations based on atom-atom interactions?

Project C2

a) The experimental set up in Fig 3.1, page 13, Ref 1, contains a large number of acousto-optic modulators (AOMs). What is the principle of operation of an AOM? What are typical diffraction efficiencies, tuning bandwidths and rise times?

There are three AOMs in the beams from the Rydberg excitation lasers. Each AOM is then typically driven from a radio-frequency generator & a radio-frequency amplifier. What is the AOM based noise eater used for and how does it work?

What is the AOM based positioner used for?

In fact, beam diffraction angle and frequency shift for an AOM are not independent. What is the problem with this and how is this problem solved in the present experiment?

Which directions are the sound waves propagating in the AOMs in Fig. 5.4, page 52 in Ref. 1?

The tuning AOM is operated in double-pass mode. How does this work and what might be the reason it is operated in this configuration?

b) Optical single-mode fibres are often used to efficiently transport laser light between different spatial locations such as between different rooms, different optical tables or different platforms. Single-mode fibres have the added advantage that they also work as laser spatial mode cleaners. If the spatial input laser mode is strongly non gaussian the coupling efficiency into the fibre will be poor, but in any case the output (unless the fibre is very short) will be gaussian which is highly useful in many experiments, not least because a known profile is useful for comparing with theoretical calculations. The price for single-mode fibres depends on wave length, but it may be about 5€/m at 800 nm. If the fibre should preserve the polarization the cost would be about 20-30€/m. In this experiment polarization preserving fibres are used (Ref 1, Fig. 3, page 13).

What do you think is the reason for using polarization preserving fibres in this experiment?

How does a polarization preserving fibre work?

What equipment is needed/used to couple light into single mode fibres?

How many degrees of freedom for the adjustment might be needed?

What might be a reasonable coupling efficiency (assuming the input laser has a spatial mode of good quality)?

Some potentially useful references/links

Fundamentals of photonics, Saleh & Teich, Wiley, 2nd edition, Chapters 19.1 and 19.2
http://massey.dur.ac.uk/resources/slcornish/AOMGuide.pdf
http://web.stanford.edu/~langrock/coursework/EE234_Lab_4.pdf

Project C3

In this subproject the aim is to think about some aspects on the detection of single atoms or molecules. Single atom/molecule detection is used in many areas in physics, chemistry and biology/medicine.

Various data for ^{87}Rb can be found in reference 5. If What would be the highest photon rate emission we could expect by repeatedly exciting a Rb atom on its 5s-sp transition?

Subsection 3.3 pages 16-17 in Ref 1 describes how fluorescence photons are collected. The collection efficiency is ~2% which may seem low. Assume you have two lenses as shown in Fig. 3.1 page 13. What would the focal lengths of these lenses be to be consistent with the numbers given in in 3.3?

Let us think some more about the collection efficiency. In Ref. 1 it appears (looking at other materials published from the same group) the author here used the equation $\Omega = (1-\cos\theta)/2$ to define the solid angle, Ω. However the generally accepted definition is $\Omega = 2\pi(1-\cos\theta)$ (see *e.g.* Wikipedia for a definition of quantities). This means that if we collect light from all directions from an object the collection solid angle will be 4π, which is very reasonable. Using the conventional definition the collection solid angle would be roughly 0.45 (instead of 0.036 as given on line 2 on page 17 in Ref 1). It is written that the collection solid angle is limited by the vacuum chamber port window. What would be the port window diameter if it is at distance of 10 cm from the FORT trap?

Using the conventional definition the collection solid angle also means that the equation on 17 for the photon collection efficiency now instead must read

$$\eta = \frac{\Omega \eta_{opt} \eta_{pe}}{4\pi} = 0.023$$

Neglecting transmission and camera efficiency losses a photon collection efficiency of 3.6% is obtained. Clearly it can be complicated to have really high photon collection efficiency. Suppose you would wish to have much higher collection photon collection efficiency. In this experiment there are many practical limitations due to the need for laser cooling and trapping etcetera, so instead we plainly assume that you have an emitting point source and you would like to collect a higher fraction of the photons, for example >10% and >50% respectively. How would you propose to do it? Be specific suggest lenses, mirrors or whatever components you need and construct an actual set-up with collection efficiencies as given above.

Let's now assume that this emitter sits in a piece of transparent glass or crystal instead of just being in air. Would you need to change any of your previous solutions to get the same efficiency? If so how could you change/complement your previous set-up?

Project D: Remote sensing of atmospheric pollutions

Light detection and ranging (LIDAR) is a method commonly used for remote sensing of the atmosphere. Most LIDAR experiments are based on a pulsed laser and through time-resolved detection of backscattered radiation it is possible to obtain range-resolved information about atmospheric properties. Just like laser spectroscopic studies in general, a LIDAR measurement may be based on different types of laser-matter interactions, e.g. elastic scattering, inelastic scattering, absorption, fluorescence, etc. This project consists of three parts. The purpose of the first part is to get familiar with some basic features of the LIDAR concept and to obtain an understanding of the principles of differential absorption LIDAR (DIAL). You will also make some calculations in order to additionally strengthen the conceptual understanding. In the second part your task is to design a DIAL setup for a particular measurement task. Finally, the third part deals with identification and discussion of various error sources.

Project D1

a) Assuming an infinitely fast electronic response of the detection system, derive an expression for the range resolution of a LIDAR system based on a laser generating pulses of duration τ_p. What is the ultimate range resolution for 100-ps, 1-ns, and 10-ns pulses, respectively?

b) Assume a LIDAR setup based on 1064-nm pulses provided by an Nd:YAG laser (Quantel Brilliant-b). The laser beam transmitted towards the region of interest is the beam directly delivered by the laser (i.e. no converging or diverging optics are used). Estimate the laser spot size at 100 m, 1 km, and 10 km distance. It is possible to reduce the divergence of a laser beam using a beam expander. Assume that the beam is expanded to a diameter of 10 cm, and estimate the laser spot size at the same distances (assume a diffraction-limited beam). Are there other benefits (besides improving the spatial resolution) that a low divergence may bring to a LIDAR measurement?

c) In order to make species-specific concentration measurements of gaseous pollutants in the atmosphere with LIDAR, resonance absorption can be used. Typically a tunable laser, alternately tuned on (λ_{on}) and off (λ_{off}) an absorption line of the species of interest, is used. This differential absorption technique, called DIAL (Differential absorption lidar), hence results in pairs of LIDAR curves, $P(\lambda_{on}, R)$ and $P(\lambda_{off}, R)$, recorded on and off the molecular resonance, respectively. An expression for the ratio between two such curves is given by

$$\frac{P(\lambda_{on},R)}{P(\lambda_{off},R)} = exp\left\{-2\left[\sigma(\lambda_{on}) - \sigma\left(\lambda_{off}\right)\right]\int_0^R N(r)dr\right\} \qquad (1)$$

The quantity of interest in this equation is of course N(r), i.e. the number density of the investigated species versus distance. Derive an expression for N(r).

d) The result of a DIAL measurement of SO_2 is shown in Fig. 1. Use the ratio-plot displayed in the middle panel, the DIAL expression for N(r) derived previously, and the absorption spectrum shown in Fig. 2, to make a rough estimate of the peak number density of SO_2 (in molecules/m^3). Convert your result into concentration in mg/m^3 and compare your estimate with the result shown in the lower panel of Fig. 1. Estimate the signal-to-noise ratio of the result shown in the lower panel of Fig. 1 and then estimate the SO_2 detection limit (in mg/m^3). The result presented in Fig 1 was obtained with a range resolution of 70 m. What detection limit is to be expected for a range resolution of 1 m?

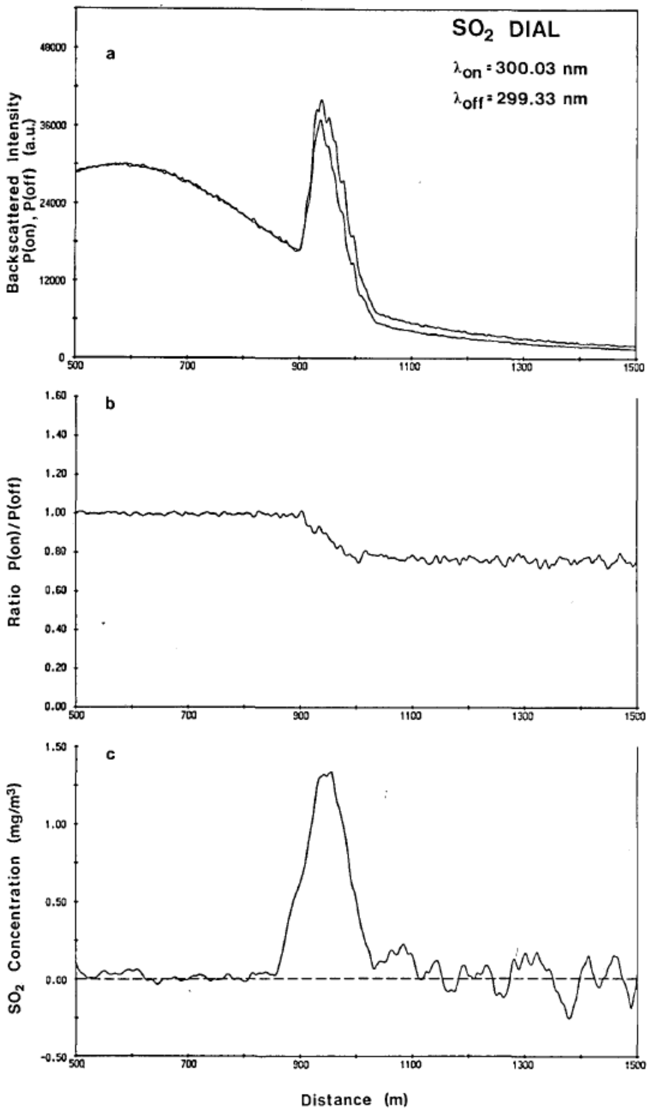

Fig. 1 *SO_2 DIAL measurement (from Edner et al., Appl. Opt.* ***26****, 4330 (1987)).*

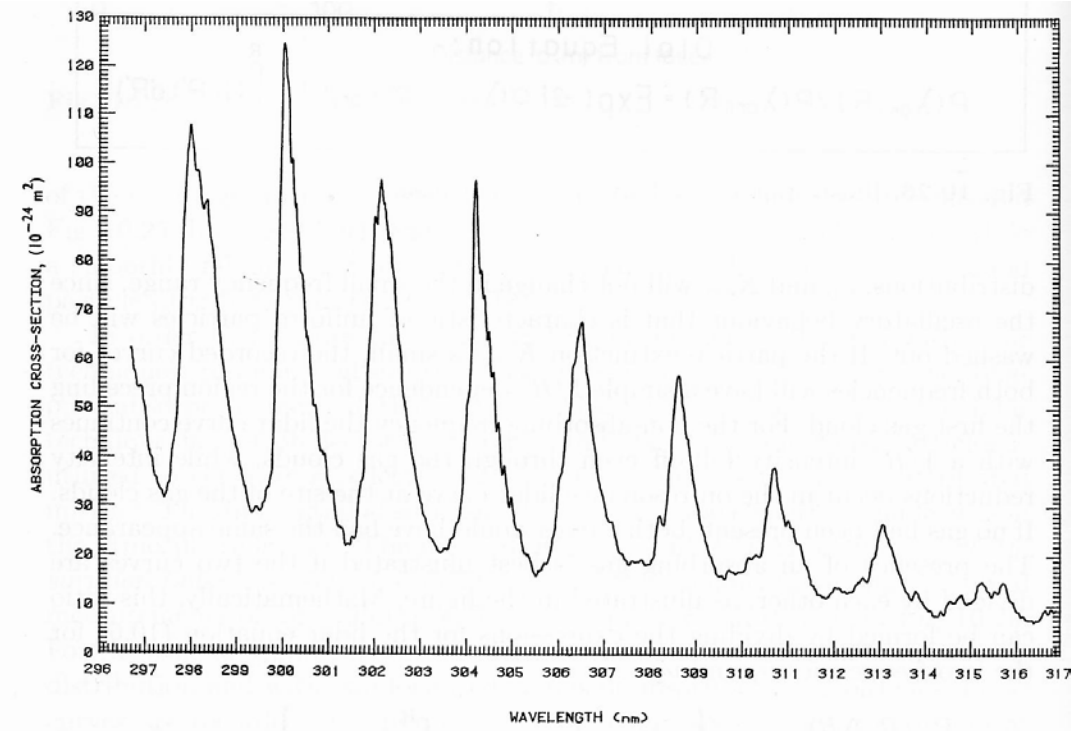

Fig. 2 *SO_2 absorption spectrum (from Brassington, Appl. Opt.* ***20****, 3774 (1981)).*

e) Study the absorption spectrum of ozone (O_3) in the UV-vis region and discuss the potential for DIAL measurement of this species. What on- and off-wavelengths do you select?

Project D2

Assume that a field measurement campaign, aiming at extracting concentration profiles of SO_2 and O_3 in an urban area, is to be performed. Your task is to design and construct an experimental setup for this purpose. You should aim for a system that is as compact and rugged as possible. A tip is to start thinking about the task without so much concern about compactness and ruggedness, just focusing on a system that in principle would work, and then think about if it is possible to modify the system in order to make it more compact.

a) Propose suitable laser wavelengths for DIAL measurements of the two species. What are the differential absorption cross sections for SO_2 and O_3, respectively, based on your selected laser wavelengths?

b) Suggest suitable lasers for generation of the desired wavelengths.

c) Propose a suitable receiver system, i.e. make a schematic outline of telescope, signal separation optics, and detectors.

d) Sketch a schematic experimental setup.

e) Discuss the possibilities to also measure water vapor concentration with the setup.

Project D3

The complete DIAL equation can be written

$$N(R) = \frac{1}{2\Delta\sigma}\frac{d}{dR}\left[\ln\frac{P(R,\lambda_{off}}{P(R,\lambda_{on})}\right] - \frac{1}{2\Delta\sigma}\frac{d}{dR}\left[\ln\frac{\beta(R,\lambda_{off}}{\beta(R,\lambda_{on})}\right] - \frac{\alpha\left(R,\lambda_{off}\right) - \alpha(R,\lambda_{on})}{\Delta\sigma}$$

Term 1 Term 2 Term 3

where $\Delta\sigma = \sigma(\lambda_{on})-\sigma(\lambda_{off})$, β is the atmospheric backscattering coefficient, and α is the atmospheric extinction coefficient (excluding the extinction due to the absorption of the species of interest). For many molecular species the wavelength separation between on and off resonance wavelengths can be very small (< 1 cm^{-1}), and then the differences in scattering properties of the atmosphere (Term 2) and the differential extinction due to aerosol and interfering gases (Term 3) are small enough to be safely neglected. In such cases the DIAL equation is greatly simplified as it then only contains Term 1. For ozone however, a rather large wavelength separation is needed in order to obtain a large enough differential absorption cross section (which you probably found out in B2 e).

a) Assume that you make an ozone concentration measurement with the system you designed in B2 and evaluate your data using the simplified DIAL equation (i.e. only including Term 1). Assume a situation where the atmosphere is free of aerosols and particles, i.e. it only consists of gaseous molecules. Are you expecting any systematic errors due to the fact that Term 2 is neglected? Motivate your answer.

b) Obviously an atmosphere free of aerosol is a highly idealized case, which is quite unrealistic. If aerosol and larger particles, i.e. particles giving rise to Mie scattering, are present during the measurements, significant systematic errors may arise. Explain using your own words why Term 2 may contribute significantly in atmospheric DIAL measurements based on a large difference between λ_{on} and λ_{off}.

c) Term 3 can often be neglected if no molecules have interfering absorption lines at the applied wavelengths. Assume that you are making a DIAL measurement of O_3 with the system designed in B2. Sulfur dioxide is expected to be present in the atmosphere. Estimate the error due to interfering SO_2 absorption, i.e. calculate Term 3, for a point where the SO_2 concentration is as high as the peak value shown in the lower panel of Fig. 1 (use your SO_2 number density calculated in B1 d). Estimate the relative error due to the SO_2 interference if the O_3 concentration is 100 ppb?