Assessment
Atomic physics

UNIVERSITY of TASMANIA

Assignment 3: Atomic physics applications

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Exercise 1 *Stern-Gerlach: measurement edition* (8 points)

Consider an ensemble of silver atoms incident on an inhomogeneous magnetic field (i.e. the OG Stern-Gerlach experiment with spin-1/2 particles).

1. (5 marks) Suppose we have measured $\langle S_x \rangle$, $\langle S_y \rangle$ and $\langle S_z \rangle$ but we do not know the initial state of the system. Is it possible to know the density matrix of the system, ρ?
2. (3 marks) Now suppose that we know that the system is pure. Is it possible to determine ρ with fewer measurements?

Exercise 2 *Laser cooling* (20 points)

We are going to perform some calculations based on the simplest laser-cooling system, namely a laser beam incident on a source of thermal atoms.

1. Find the distance required to stop a room-temperature rubidium atom with the resonant scattering force
2. Show that rubidium atoms with velocity $v = 350$ m/s are resonant with a counter-propagating laser with a frequency detuning of 450 MHz
3. In class, we looked at using a magnetic field to deal with the changing Doppler shift of the light as seen by the atom. An alternative method is to change the laser frequency, known as *chirping* the frequency. What is the maximum rate at which one could chirp the laser frequency to cool rubidium atoms? Assuming a Doppler width of 1 GHz, how long would it take to slow the atoms?
4. In laser cooling experiments, it turns out to be necessary to have (at least) two laser beams to actually cool atoms; in the case of rubidium, only two are required. Suggest what is the reason that multiple lasers are required, and describe what properties (e.g. intensity, frequency, polarisation) that these laser beams should have, and why?

The Magneto-Optical Trap (MOT) is the workhorse of atomic physics, having revolutionised how ensembles of atoms can be prepared and interrogated.

1. Explain what a MOT is, and how it works
2. Imagine that you have a MOT: it is completely standard except you altered the beams which propagate along the vertical axis to have a frequency difference between them; normally, all six beams have the same detuning $\Delta \approx -\Gamma/2$, but here the beams in the horizontal plane have the detuning Δ, but the vertical beams each have a detuning $\Delta \pm \delta$. What will happen?
3. Atoms trapped in a MOT are typically imaged using absorption imaging, that is, illuminating the atom cloud with an on-resonant laser beam, and then imaging the profile of the laser beam, which will have a "shadow" where the atoms were. What effect will this imaging have on the atoms?
4. Assuming that the system can be described in the steady state, what would be the effect of imaging with an slightly detuned laser?

Exercise 3 *What even is happening?* (17 points)

We have looked extensively at the two-level atom, that is, a ground state $|1\rangle$ and an excited state $|2\rangle$ which have an energy difference $\hbar\omega_0$, and we expose the system to radiation of frequency ω. In our description of this system, states $|1\rangle$ and $|2\rangle$ are energy eigenstates of some Hamiltonian H_0 (e.g. the hydrogen atom) and we have treated the dipole interaction as a perturbation, H', to this Hamiltonian.

1. (1 mark) Are the states $|1\rangle$ and $|2\rangle$ eigenstates of the full Hamiltonian $H = H_0 + H'$

2. (5 marks) Using the pure state

$$|\psi\rangle = c_1|1\rangle + c_2|2\rangle,$$

the Schrödinger equation, and the rotating wave equation, show that

$$\frac{d}{dt}\begin{pmatrix}\bar{c}_2 \\ c_1\end{pmatrix} = -i\begin{pmatrix}-\Delta & \Omega/2 \\ \Omega/2 & 0\end{pmatrix}\begin{pmatrix}\bar{c}_2 \\ c_1\end{pmatrix}$$

where $\bar{c}_2$ is the slowly-varying variable in the rotating wave approximation.

3. (4 marks) Using the above result, or otherwise, show that the eigenvalues $\lambda_\pm$ and the associated eigenvectors $|\pm\rangle$ of this system are

$$\lambda_\pm = -\frac{\hbar\Delta}{2} \pm \frac{\hbar\Omega'}{2}$$

and

$$|+\rangle = \sin(\theta)|1\rangle + \cos(\theta)|2\rangle$$
$$|-\rangle = \cos(\theta)|1\rangle - \sin(\theta)|2\rangle$$

where $\tan(2\theta) = -\Omega/\Delta$.

Hint: computing the ratio of the coefficients c_1 and $\bar{c}_2$ might prove useful.

4. (6 marks) The time has come: interpret the above mathematical results physically. Given this is hard, you should make a plot of the eigenvalues as a function of Δ, first for the case $\Omega = 0$, and then make additional plots for $\Omega \neq 0$ and comment on what happens. What is happening in our system, and why?

Hint: Think hard about what eigenvalues and eigenvectors mean physically

5. (1 mark, golden) Perhaps the most surprising result of this work is how this system will respond to a frequency chirp (i.e. changing Δ). Let us imagine we start in the ground state, and we sweep our coupling field frequency, beginning such that $\Delta \ll \Omega$ and ending with $\Delta \gg \Omega$, and we do this sufficiently slowly such that no funny business will occur (effects that we have not considered). Explain physically what will have transpired, and why it happens.

Note: This is an "advanced" problem, insomuch as it knocks on the door of the kind of quantum effects which start to crop up everywhere once you start looking, but are not routinely covered in undergraduate courses because it is hard to interpret classically. As such, this question is only worth one point, but a golden point, meaning there is an additional bonus (which will not alter your mark) for providing a correct answer.

Exercise 4 *Ramsey interferometry* (24 points)

In this question, we are going to explore Ramsey interferometry in a two-level atom.

1. (5 marks) Explain how Ramsey interferometry allows for a precise determination of the resonance frequency in a two-level system

As seen in class, the excited-state population for a general detuning Δ for Ramsey interferometry can be calculated via

$$\rho_{22} = 4\left(\frac{\Omega}{\Omega'}\right)^2 \sin^2\left(\frac{\Omega'\tau}{2}\right)\left[\cos\left(\frac{\Delta T}{2}\right)\cos\left(\frac{\Omega'\tau}{2}\right) - \frac{\Delta}{\Omega'}\sin\left(\frac{\Delta T}{2}\right)\sin\left(\frac{\Omega'\tau}{2}\right)\right]^2.$$

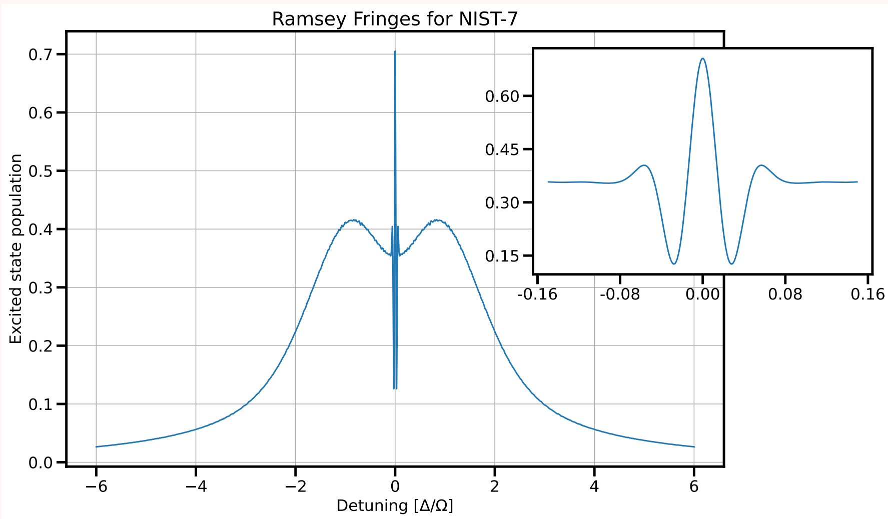
1. (4 marks) The NIST-7 (also discussed in class) has experimental parameters $(v, l, L, \tau, \frac{\Omega}{2\pi}) = (230\,\mathrm{m/s}, 23\,\mathrm{mm}, 1.53\,\mathrm{m}, 100\,\mu\mathrm{s}, 2.5\,\mathrm{kHz})$ for the beam velocity, interaction region width, propagation distance, interaction time, and Rabi frequency. Explain why these values are chosen to obtain an accurate measurement of the transition, with specific reference the the effect(s) of changing the parameters.

`\begin{Computational content}`

Our goal is to understand the experimental signal that is measured when the clock is operational.

1. (3 marks) Using the experimental parameters given above, plot the expected signal - that is, excited state state population as a function of the detuning from atomic resonance, Δ

2. (12 marks) Shown below is a (simulated) plot of the measured signal from the apparatus



This should look distinctly different to the plot you produced in the previous question. Your goal is to reproduce the above plot, which will require you to identify why the signal does not look like the signal predicted by the equation above, and then you will have to simulate what is actually measured, and hopefully it will look like the above plot (which is indeed what is actually measured)

Hint: The Maxwell-Boltzmann distribution may or may not be useful, along with the information that the temperature of the caesium beam oven was about 55 degrees C.

Exercise 5 *Atomic physics and eternal glory* (20 points)

Your final (assignment) question for atomic physics may see your name live on in the *annals of atomic physics as taught by Andy*, which is a measure of eternal glory, albeit a quantity of ϵ glory units.

Your task is to find a "recent" atomic physics experiment, and write a summary and discussion piece about the experiment, with particular emphasis on highlighting the relevance of content that we have learned through the semester.

Trawling through research journals can be tedious, so you are likely better off looking through pop-science articles which discuss recent experiments, for example nature has a *news and views* section, and Physics Today exists to promote the dissemination of physics research. In most cases, the actual experiment/research will be published in one of a few places:

- Physical Review A: the primary journal for "everyday" atomic and quantum physics (read: pretty dense and technical)
- Science, nature/nature physics, or Physical Review Letters: these high-profile, multidisciplinary journals are where the "bigger" results will end up (read: splashy headlines, sexy images, and more fluff, all in order to appeal to a general audience)

You will be assessed on

- How relevant is the experiment to the content we have learned in the unit
- How well you communicate the performed experiment, including why the experiment was performed in the way it was, why the parameters where chosen to be the values they were, etc.
- Your discussion of the pertinent physics - can you understand/explain/interpret the results of the experiment
- Most importantly: your communication and understanding of the physics as it relates to the content of this unit. Depending on the experiments you look at, you may see some *very* complex atomic physics in the wild. Firstly, if it looks crazy, just move on and find something else. In all cases, once you have selected an experiment, please do not get lost in the weeds, rather, focus on stripping back the complexity, boiling it down to the basics and, for example, provide some back-of-the-envelope calculations or a simple simulation to illustrate you understand what is happening and why it is happening.

There is no rigid structure to the submission, so use your judgement. If reproducing a figure will tell a good story, do it. If a simple doodle will tell it better, do it. This includes selecting a "recent" experiment: by recent, I simply mean something that has a distinctly modern flavour to it, so let's say the experiment must have been performed during your lifetime. I am not going to set a word/page limit, but if you have more text than couple of pages, I would reassess. If you are covering a cool paper but there is too much to talk about, only cover half of it, or just one of many presented results. Use your judgement and discretion. Ultimately, the goal of this exercise is to demonstrate your command over the content we have learned by applying it in a new context.

Beyond the mark awarded for this question, the best submission (as judged by me, so obviously subjective), will be awarded glory, a very special prize, and have their name enshrined forevermore on the KYA323 website - once it gets properly up and running - and with permission, the work will also be reproduced on the site.

Hint: If you cannot access research articles, ensure that you are connected to the university's network, where you will have *institutional access* to many journals.