Ultracold quantum gases
Problem set 2

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2.1 Laser Spectroscopy

We want to analyze an atom gas sample contained in a transparent glass cell by shining a laser beam through it. We then scan the laser beam frequency slowly and observe at which wavelength light is absorbed by the gas. Scanning lasers over absorption lines to determine the position and shape of absoprtion lines is called „laser spectroscopy“. After the development of the laser it became one of the major fields of atomic (and molecular) physics

The gas in the cell is Rubidium (^{87}Rb), and the laser operates around the D2 line at 780.24 nm. The decay rate of the excited state for this transition is is $\Gamma = 6$ MHz, and for now we assume a simple line with no substructure (two-level scheme). The pressure inside the cell for now is 10^{-9} mbar and the cell length is 50 mm.

2.1.1

In the limit of very low light intensity $I_0 \ll I_{sat}$, how much of the light do you expect will be absorbed when the light is in resonance with the transition (assuming there is no Doppler Effect)? (For example by considering the amount of light scattered inside a given volume of due to the excitations from the beam).

2.1.2

When increasing the light intensity to be comparable or larger than the saturation intensity $I_{sat} = \pi hc\Gamma/(3\lambda^3)$: How does the shape of the line change, and how does the absorption on resonance change? Please plot for $I_0 = 2I_{sat}$ and for $I_0 = 30I_{sat}$ (For calculating the local absorption, neglect the fact that the intensity is not quite constant along the path of the beam due to the absorption, and also still neglect the Doppler effect).

2.1.3

Laser spectroscopy was (and is) such a success because it allowed much higher frequency resolution than could easily be achieved before, when tunable „monochromatic“ light was mostly generated using light bulbs with color filters as well as glass prisms and gratings.

So, let's consider a more realistic scenario: At a pressure of 3×10^{-7} mbar, and at room temperature. Because of the Doppler effect, the speed of the atoms affects the absorption: How strong is the absorption of the light on the resonance now? How does the absorption coefficient change now, when scanning the laser frequency ω_L over the resonance? What is the spectral resolution (The smallest possible shape of a feature in the spectrum)?

2.1.4

To increase the spectral resolution even further (meaning: to get narrower and sharper absorption features), the high spectral power densities possible with lasers can be exploited, too, by using nonlinear effects during the spectroscopy:

We try this by sending a second laser beam through the glass cell, but with a very high intensity $I_0 \approx 30 I_{sat}$, and along the *opposite* direction. Both beams still fill the entire cell. The frequency of this beam is fixed, and it is 100 MHz higher than the atomic resonance ω_R. How will this affect the absorption of the weak spectroscopy beam (what is the shape of the absorption line now)? Consider that the absorption is not only given by the density of atoms, but by the density of atoms ready to absorb a photon of a given frequency. The shape of the resulting absorption spectrum needs only be schematic but should be reasonably labeled.

2.1.5

What factors are now limiting the spectral resolution of the method, when using the non-linearity?