Data Analysis Exercise: Atomic Magnetometry

Physics 106 Winter 2025

Before jumping into taking and analyzing your own data, you will spend the first lab session preparing graphs with experimental data that have already been taken for you. Use this opportunity to familiarize yourself with data analysis tools in Python, which you will use througout the course. Also, practice formatting the graphs for ease of interpretation and visual appeal.

Atomic spectroscopy is a valuable tool for sensitive magnetometry [1, 2], with applications ranging from precision tests of fundamental physics to medical imaging. The spatial resolution of atomic magnetometers can be significantly enhanced by employing dense samples of ultracold atoms [3, 4]. Yet in the very process of preparing ultracold atoms, the magnetic-field sensitivity of atomic energy levels can pose a challenge. Certain methods of laser cooling are only effective at zero magnetic field [5, 6], requiring any ambient magnetic field to be precisely calibrated and compensated.

To calibrate the magnetic field in our laser-cooling laboratory, we use the atoms themselves as sensors. A simple technique for atomic magnetometry is microwave spectroscopy, wherein a microwave field of variable frequency is used to transfer atoms between two internal atomic states. If these states have different magnetic moments $\mu_1 \neq \mu_2$, then the resonant frequency depends linearly on the magnitude of the applied magnetic field $\mathbf{B}$ (the Zeeman effect):

$$\nu_{1\to2} = \nu_0 + \frac{\mu_1 - \mu_2}{h}|\mathbf{B}|, \tag{1}$$

where h is Planck's constant.

To ascertain the reference frequency ν_0, we first perform spectroscopy on a transition between two states of zero magnetic moment (blue lines in Fig. 1). The resulting spectrum is saved as `rabispectrum.txt`, where you will find two columns of data, labeled `frequency` and `fraction`. These data were obtained by initially preparing all atoms in state $|b\rangle$, applying a microwave pulse of the specified `frequency` (in Hz) for a fixed time ($t = 60\ \mu$s), and recording what `fraction` of the atoms were subsequently found in state $|f\rangle$.

- Plot the data set `rabispectrum.txt`. (Do you notice any systematic errors?) Fit the data to determine the frequency ν_0, and annotate your plot with the fit parameters and their uncertainties.
  Note: To obtain the best possible fit, it helps to know some quantum mechanics [7]. For an atom initially in state $|b\rangle$ and driven by radiation with detuning δ from the $|b\rangle \to |f\rangle$ transition (i.e., frequency $\nu_0 + \delta$), the probability P_f of finding the atom in state $|f\rangle$ after a time t oscillates as

$$P_f = \frac{\mathcal{F}^2}{\mathcal{F}^2 + \delta^2}\sin^2\left(\pi\sqrt{\mathcal{F}^2+\delta^2}\,t\right), \tag{2}$$

  where the *Rabi frequency* $\mathcal{F}$ is set by the strength of the microwave field.

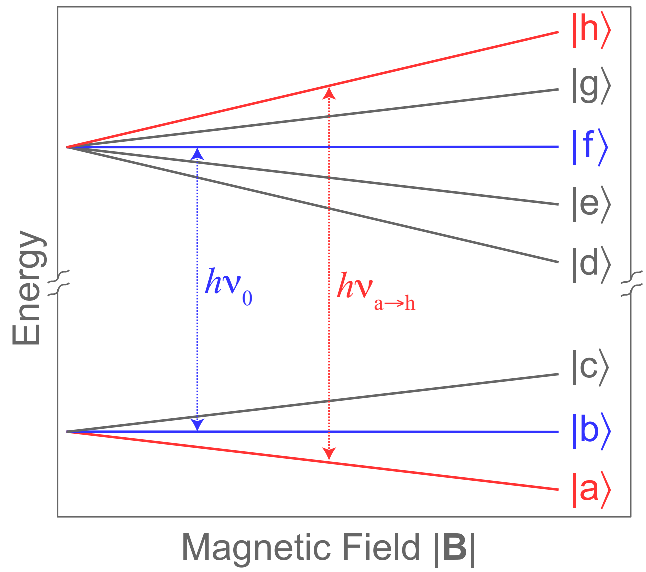

FIG. 1: **Hyperfine states of rubidium-87:** schematic of energies *vs.* magnetic field $|\mathbf{B}|$ in the weak-field regime of linear Zeeman splitting. The frequency of the magnetic-field-insensitive transition $|b\rangle \to |f\rangle$ (blue) is $\nu_0 \approx 6.83$ GHz. In this work, we perform magnetometry using the $|a\rangle \to |h\rangle$ transition (red), with Zeeman shift $d\nu_{a\to h}/d|\mathbf{B}| = 2.1$ MHz/G.

We proceed to calibrate the magnetic field in the laboratory by performing spectroscopy on the magnetic-field-sensitive transition between states $|a\rangle$ and $|h\rangle$ (red lines in Fig. 1). Our objective will be to zero the magnetic field using three orthogonal pairs of Hemholtz coils (Fig. 2) that generate a compensating field of the form

$$\mathbf{B}_{\text{comp}} = \beta_x I_x \hat{\mathbf{x}} + \beta_y I_y \hat{\mathbf{y}} + \beta_z I_z \hat{\mathbf{z}}, \tag{3}$$

where (I_x, I_y, I_z) are the currents in the three coil pairs. To determine the set of currents required to cancel the ambient magnetic field ($\mathbf{B}_{\text{comp}} = -\mathbf{B}_{\text{amb}}$), we measure the transition frequency $\nu_{a\to h}$ as a function of each of the three currents, in each case keeping the other two currents fixed. The resulting data set (`Bcompensation.txt`) provides us with a full calibration of the ambient magnetic field vector $\mathbf{B}_{\text{amb}}$ in our lab and of the magnetic field β_i produced by each pair of Helmholtz coils per ampere of current.

- Plot and fit the data in `Bcompensation.txt` to de-

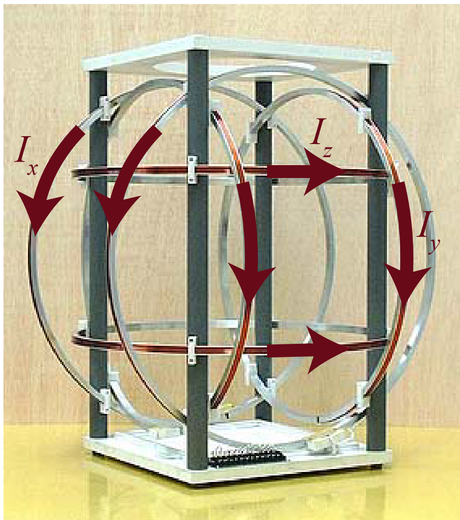

FIG. 2: **Three-axis Helmholtz coils**. A similar set of coils surrounds the vacuum chamber containing our atoms, allowing us to control the magnetic field via the currents I_x, I_y, I_z. Figure adapted from Ref. [8].

termine the magnetic field produced by each coil pair (in G/A). To what values should you set the currents I_x, I_y, I_z in order to zero the magnetic field in the lab? Record these values and their uncertainties in your lab book.

Important notes: The frequencies `fx`,`fy`,`fz` are in units of MHz, and the currents `Ix`,`Iy`,`Iz` are in units of amperes. The states $|a\rangle, |h\rangle$ have magnetic moments $\mu_a/h = -0.7$ MHz/G, $\mu_h/h = 1.4$ MHz/G. When not being varied, the currents were set to the values $(I_x, I_y, I_z) = (0, 0, 5.5)$ A.

- With the coils set to the compensation currents you found above, within what tolerance (in G) do you expect the field to be zeroed?

- What is the ambient field $\mathbf{B}_{\mathrm{amb}}$ in the absence of any compensation ($I_x = I_y = I_z = 0$)?

- In taking these data (`Bcompensation.txt`), we did not record their uncertainties. Assuming that the statistical uncertainty of each recorded frequency was the same, estimate this uncertainty from the data themselves by calculting the r.m.s. residual from the fit. Should you add error bars to your plot?

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