Hyperfine Spectrum of Rubidium: optical pumping experiments

Physics 480W
(Dated: Spring 2011)

I. PERSPECTIVE AND OBJECTIVE

This experiment explores the hyperfine structure of the Rubidium atom and permits an experimental determination of the quantum number most directly related to nuclear magnetism, the nuclear spin angular momentum, \( I \). Nuclear magnetism gives rise to what is called hyperfine structure in spectral lines which generally are smaller splittings than so called ‘fine structure’. Hyperfine structure stems from the perturbation energy of the nuclear spin \( I \), the quantum number we seek to determine, and its magnetism. The perturbing Hamiltonian may be written,

\[
H_{hf} = AI \cdot J,
\]

where the subscript identifies the hyperfine interaction of importance here, which arises from energy of the magnetic moment of the unperturbed energy state (the unperturbed spectroscopic term, for which the total angular momentum is given by \( J \) is the total angular momentum of the unperturbed state) within the magnetic field created by the nuclear spin. This perturbation leads to the coupling (addition) of the nuclear spin angular momentum with the total angular momentum of the unperturbed state,

\[
F = J + I.
\]

The hyperfine spectrum of a spectral line then provides a way of determining the magnetic moment and angular momentum of a nucleus. Like the spin-orbit effect, the hyperfine Hamiltonian creates a set of degenerate manifolds of states, the kets \( |F M_F\rangle \)'s, within which the degeneracy may be lifted by subjecting the atom to an external magnetic field, through the Zeeman effect. Transitions between the \( M_F \) states may be effected by energies of order \( 10^{-9} \text{eV} \), whereas the transition creating the optical spectra line (said to possess hyperfine structure) itself has a term energy difference of about \( 1.5 \text{eV} \), so this clearly this is a very high resolution atomic spectroscopy experiment.

A. References

1. TeachSpin Optical Pumping Laboratory Manual.

We will do the experiments described in sections 4-B and 4-C. A copy of the manual will always be in our lab room. Read this before the first lab meeting. A nice overview of this particular experiment can be found on-line at TeachSpin’s website, http://www.teachspin.com, and follow the links to the optical pumping apparatus, and particularly take note of ‘the conceptual tour’. Review this as well.

2. Ch6. in our text. Our experiment relates directly to the discussion of saturation absorption spectroscopy of Rubidium, however, the entire chapter lays the necessary physics background for the experiment.

B. Procedure

We will be doing experiments 4B and 4C described in the manual.

C. Questions to ponder

1. What is ‘optical pumping’? This is one aspect of a more general question, the answer to which you will need to understand deeply, “how does the experiment work?”

2. What do the linear polarizer and the quarter wave plates do? Why are they needed? Why are they placed in their particular order? This question is one aspect of a general one which you will need to understand thoroughly for yourself: “can you sketch, and explain, the principal parts of the experimental apparatus, including ancillary electrical instruments?”

3. Is it necessary to align the optical axis of the detection system with the local magnetic field? If so, why? There are two sets of Helmholtz coils. What do they do? Why are there not 3? How is the magnetic field in this experiment varied?

4. What does the RF energy do?

5. The light coming from the Rb lamp is spread in wavelength. How much do you ‘spose, and does its line width matter, and if so, how? What Doppler shift do we expect in the line coming from the oven?

6. Can you account for all the basic features of figure 1 shown below? How does this figure demonstrate optical pumping? How can it be used to determine \( g_f \) and in turn, \( I \)?
FIG. 1. This plot of detector signal vs. magnetic field demonstrates optical pumping for zero and very low magnetic fields. Both the Rb\textsuperscript{85} and Rb\textsuperscript{87} isotopes produce only unresolved single lines in these low fields.

7. Try to plot for yourself Figure 2B-3 in the manual using the Breit-Rabi formula for the interaction energy. It takes some sorting out. Annotate the figure to describe the experimental results. What resonances are exploited to observe the dips that we see in the two experiments?

8. What is an isotope shift?

[3] Questions like these will be posed during the final oral exam, and during each tutorial session. Being prepared will require reading the references and thinking carefully about what one has read.