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Visit of the Magnetometry Laboratory Report

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1 The cesium magnetometer.

In order to make dipole measurements of the neutron possible a high resolution magnetic field sensor is necessary to fulfill the magnetic field stability requirement. The Cesium magnetometer used is based on the concept of optically detected magnetic resonance (ODMR) spectroscopy. Cesium is an alkali metal, which means there is one valence electron in an s-orbital. More specific the electronic configuration of cesium can be described as $[Xe]6s^1$.Therefore the interaction of Cesium with an external magnetic field is governed by the magnetic moment of its unpaired electron, aligned with the electron spin. Since the absorption of resonant polarized light also depends on the electron spin it is possible to link magnetic interactions via light dependent properties.

The cesium hyperfine and Zeeman structure The first step in understanding ODMR is a better understanding of the hyperfine and Zeeman structure in cesium. The only stable isotope of cesium is ${}^{133}_{55}\mathrm{Cs}$, which is used in all applications. It has a nuclear spin of $\frac{7}{2}$. The interaction of this nuclear spin with the $J = \frac{1}{2}$ angular momentum provided by the valence electron results in a splitting of the ground state $6S_{\frac{1}{2}}$ into two hyperfine states $F = |I \pm J| = 3, 4$. These two hyperfine states are separated by an energy difference corresponding to a frequency of $9.2GHz$. An energy scheme of Cs is shown in figure 1a. The transition D_1 to the first excited state lies in the near-infrared (894.6 nm). The hyperfine interaction also splits this first excited state $6P_{\frac{1}{2}}$ into two hyperfine states corresponding with $f = 3, 4$ separated by an energy difference corresponding to $1.2GHz$. The zeeman splitting observed when an magnetic field is applied causes a further splitting of the hyperfine states into $2F + 1$ degenerate sublevels, as shown in figure 1b. More formal we say state $|F\rangle$ splits into $|F, m_f\rangle$ with $m_f = -F, -F + 1, ..., F - 1, F$. The energy difference between those degenerate sublevels can be quantified with the Breit-Rabi1 formula. Where μ_b is the Bohr magneton and g_f is the Landé g-factor for the hyperfine level.

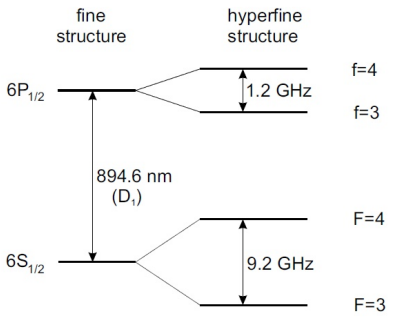
$$\Delta E\left(M_F\right) = g_f \mu_b B_0 M_f \tag{1}$$

From equation 1 it's easy to calculate the energy difference between two consecutive states and therefore the corresponding frequency, the Larmor frequency ω_L. From equation 2 we get an expression for ω_L, where γ is the gyromagnetic ratio $\gamma = \frac{g_f \mu_b}{\hbar}$. Equation 2 is our first equation which relates a frequency to the applied magnetic field resulting in Zeeman splitting. From a very accurate knowledge of the gyromagnetic ratio, information concerning the magnetic field can be obtained resulting from frequency measurements. Which in physics is a very desired tool because frequency is the quantity which can be most precisely measured. In the cesium ground state $\gamma = 2\pi \cdot 3.5Hz/nT$, a magnetic field in the order of μT results in a (Larmor) frequency of some kHz, which can be measured very precisely.

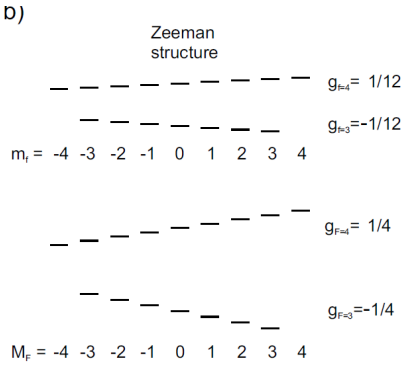
$$\omega_L = \frac{1}{\hbar}\left[\Delta E(M_{F+1} - \Delta E(M_F))\right] = \gamma B_0 \tag{2}$$

The general idea from which we want to determine the magnetic field is based on equation 2 and an exact knowledge of γ for a certain transition. The component missing is an exact measurement of the energy difference and thereby the frequency between two neighboring Zeeman states. This magnetic resonance frequency will be determined using the optical properties linked with the spin state. To be able to use these optical properties it requires a preparation of our cesium gas done with the technique of optical pumping, which is discussed next.

Optical pumping The energy difference between the two ground state hyperfine levels is around $38\mu eV$, which is smaller than the thermal energy at room temperature. The twp hyperfine states $F = 4$ and $F = 3$ are therefore equally populated. In order to observe magnetic resonance between Zeeman



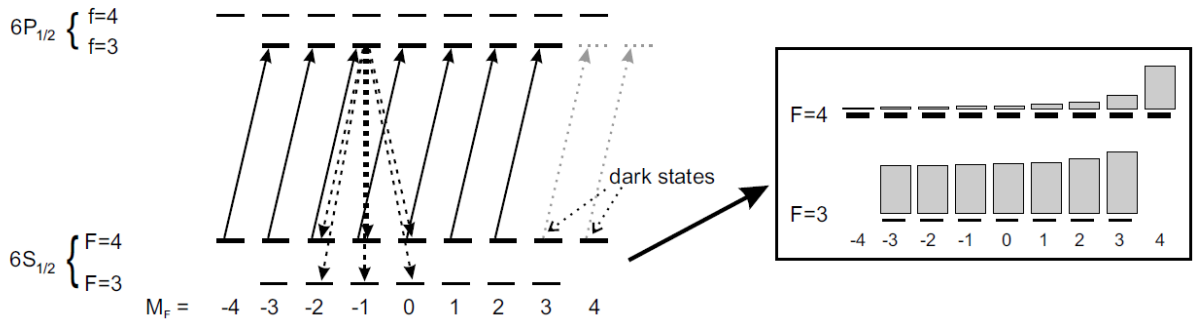
(a) Energy scheme of ^{133}Cs. D_1 transition with hyperfine structure.



(b) Linear Zeeman effect in a small magnetic field (not to scale). The Zeeman levels presented are sublevels of the hyperfine levels presented in 1a

states a population imbalance is necessary. This imbalance is generated using optical pumping, which basically means you illuminate your sample which causes the transition to higher energy states. this can be done using a Cs discharge lamp with the disadvantage that their emission spectrum is very broad. As a consequence multiple possible transition are excited all at once. To avoid this we make us of a tunable laser which makes it possible to focus on the excitation of just one hyperfine transition. Moreover the laser has the advantage of providing a higher light intensity. In the literature consulted the laser is focused on the D_1 hyperfine transition: $6S_{\frac{1}{2}}, F = 4 \rightarrow 6P_{\frac{1}{2}}, f = 3$, as shown in figure 1a. We consider a laser producing right circularly polarized light (σ^+), this beam produced consist of photon carrying one unit of angular momentum. When absorbed by the atom the angular momentum of the atom increases by one. Mathematically speaking the laser excites transition from $|4, M\rangle$ states to $|3, M + 1\rangle$ states. The atom is in an excited stated which spontaneously decays back into the ground state level, following the selection rules $\Delta F = \pm 1, 0$ and $\Delta M = \pm 1, 0$. The photon emitted during this decay can, because of the selection rules, posses an angular momentum of 0 (linearly polarized) or ± 1 (circularly polarized). The possible transitions induced by circularly polarized light and possible decay channels are shown on the left hand side of figure 2.

During the absorption-emission pumping cycle an atom originally in a $|4, M\rangle$ state gets excited to an $|3, M + 1\rangle$ state by absorption of a σ^+ photon. After decay following the selection rules the original $|4, M\rangle$ state can end up in a $|4, M\rangle$, $|4, M + 1\rangle$ or $|4, M + 2\rangle$ state. Depending on the angular momentum of the emitted photon. This means that a state cannot lose angular momentum during an absorption-emission single, but it can only earn angular momentum. When σ^+ light is applied to the sample the $F = 4$ Zeeman level population is driven towards the $M = 3, 4$ states. This result in the increase of population of those states as shown on the right hand side of figure 2. These specific states cannot absorb σ^+ photons anymore and are called dark states. At this configuration out sample is completely polarized and the sample is completely transparent for σ^+ light. A major problem is the depolarization because of spin-exchange collisions and collisions whit the walls of the container.This depolarization because of collisions with the walls can be strongly reduced by coating the inner walls of the cell with paraffin.



Figuur 2: Transitions induced by right circularly polarized light are shown by the solid lines. The decay channels of the level $6P_{\frac{1}{2}}|f=3, m=-1\rangle$ are indicated by the dashed lines.