Optical Pumping

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March 17, 2017

1 Results and Analysis

The key atomic interactions of Rubidium are spin-orbit coupling, electron-nuclear couping, and, when in the presence of an external magnetic field, the Zeeman effect. Rubidium is Hydrogen-like with a closed $n = 4$ shell and a single $n = 5$ valence electron, so Rubidium's first two electronic transitions, as determined by the selection rules (enforcing conservation of angular momentum), are ${}^2P_{3/2} \leftrightarrow {}^2S_{1/2}$, which emits/requires a photon of wavelength 780 nm, and ${}^2P_{1/2} \leftrightarrow {}^2S_{1/2}$, which emits/requires a photon of 794.8 nm. Note that the $5P$ Hydrogenic energy level loses degeneracy due to electron-spin orbit coupling, as it requires more energy for $\vec{L}$ and $\vec{S}$ to be aligned, correspondingly when $J = L + S = 3/2$, than for when the two are anti-aligned in the $J = 1/2$ state, where $\vec{L}$ is the electron's orbital angular momentum and $\vec{S}$ is the electron's intrinsic angular momentum. In our experiment, we consider only electrons occupying the ${}^2P_{1/2}$ or ${}^2S_{1/2}$ state. The electron's total angular momentum, listed above as J, and the nuclear angular momentum I couple to form the total atomic angular momentum F, which we write as the quantum mechanical vector sum

$$F = |J - I|, |J - I| + 1, ..., |J + I| - 1, |J + I|. \tag{1}$$

We used a Rubidium sample containing approximately 70% ${}^{85}Rb$, which carries $I = 5/2$, and 30% ${}^{87}Rb$, which carries $I = 3/2$. Thus, for the $J = 1/2$ states of ${}^{85}Rb$, there is possibility for $F = 3$ or $F = 2$, where, as before, $F = 3$ is the aligned state and is at higher energy than the $F = 2$ state. Similarly, in ${}^{87}Rb$, all $J = 1/2$ states can have either $J = 2$ or $J = 1$. Then, in the presence of an external magnetic field, electronic energy levels are distinguished according to their magnetic quantum number m_F and electrons can transition between any of these states, so long as they satisfy $\Delta m_F = \pm 1$ or 0, by absorption or emission of a photon of energy

$$\Delta E_{Zeeman} = g_F \mu_B B \tag{2}$$

where $\mu_B = 9.27401 \times 10^{-24}$ JT^{-1} is the Bohr magneton, and g_F is the lande g-factor, which is a measure of the atom's net magnetic moment and is calculated as

$$g_F = g_J \frac{F(F+1) + J(J+1) - I(I+1)}{2F(F+1)}, \tag{3}$$

where

$$g_J = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}. \tag{4}$$

Our apparatus subjects the Rubidium sample to an optically focused beam of only right circularly polarized photons σ^+, which, when absorbed by Rubidium's valence electron, always induce a $\Delta m_F = 1$ transition from $^2S_{1/2}$ to $^2P_{1/2}$, to leverage the fact that since m_F is bound from above by a finite value F, there exists a terminal state for which a $\Delta m_F = 1$ transition is not allowed. Each time a σ^+ induced transition occurs, the subsequent decay can be of $\Delta m_F = \pm 1$ or 0, which ensures a net upward transfer of atoms to states with higher m_F, since the whole process will never result in a decrease of m_F. When all atoms, of both isotopes, are pumped into their maximum m_F states, σ^+ travels through the sample without being absorbed. Therefore, we can use a measurement of the intensity of exiting photons along the beam path as an indicator for when the entire atomic population is trapped in the highest excited m_F state. Note that when σ^+ is absorbed, the following decay emits a photon in a random direction, which does not interfere with our measurement.

In the case of zero applied magnetic field, there is no Zeeman splitting, thus all m_F states are energetically equivalent. Therefore, atoms exist in states composed of a linear combination of m_F states, with probabilities distributed in an approximately even manner, such that an incident photon always finds an atom capable of the $\Delta m_F = +1$ transition necessary for absorption. Equipped with Helmholtz coils to cancel the natural magnetic field present at our location, we found the magnetic dip angle, shown in degrees

$$\theta_D = \arctan \frac{B_V}{B_H} = 66.34 \pm 0.14 \tag{5}$$

where $B_V = 22.63 \pm 0.06$ μT is the downwards component of earth's magnetic field (as we are in the northern hemisphere), and $B_H = 9.91 \pm 0.06$ μT is the horizontal component. These measurements are on the same order of magnitude as those listed by NASA, being $B_V = 23.4$ μT and $B_V = 23.9$ μT, where any discrepancy between the two is largely explained by the magnetic influence of our building structure. Through use of a magnetic dip meter, We found the dip angle increased from 72.5 degrees in our laboratory to 83 degrees in the lobby, approximately 10 meters apart. Precise measurements of the local magnetic field were determined by varying the laboratory applied vertical and horizontal field until our detector measured a sharp dip in intensity, which appears in Figure 1, as the leftmost, deepest, dip, where the oscilloscope is set in persistence mode as we sweep the horizontal magnetic field amplitude periodically.

The pair of peaks on the right of Figure 1 appear when we subject the sample to an additional electromagnetic field, to create RF photons, which, when at the resonant frequency f such that the photon energy hf is equivalent to that of an allowed Zeeman transition, shake atoms into downward m_F transitions, which we detect as a greater amount of photon absorption. When the RF photon frequency is increased (decreased) the peak pair, as seen on the oscilloscope, shift in proportional response to the right (left) as a group, and grow further apart (closer together). This suggests that the energy of both isotope's Zeeman transitions increase linearly with external magnetic field, and, since dip spacing diverges with increasing magnetic field strength, the isotopes do not share the same value for g_F.

Multiple measurements of the resonant frequency of RF photons and external magnetic field allowed us to perform a linear least squares fit to Equation 2 and experimentally determine g_F. For ^{87}Rb, seen in Figure 2, we found $g_F = 0.5273 \pm 0.0018$, and for ^{85}Rb, seen in Figure 3, we found $g_F = 0.3474 \pm 0.008$. Both measurements

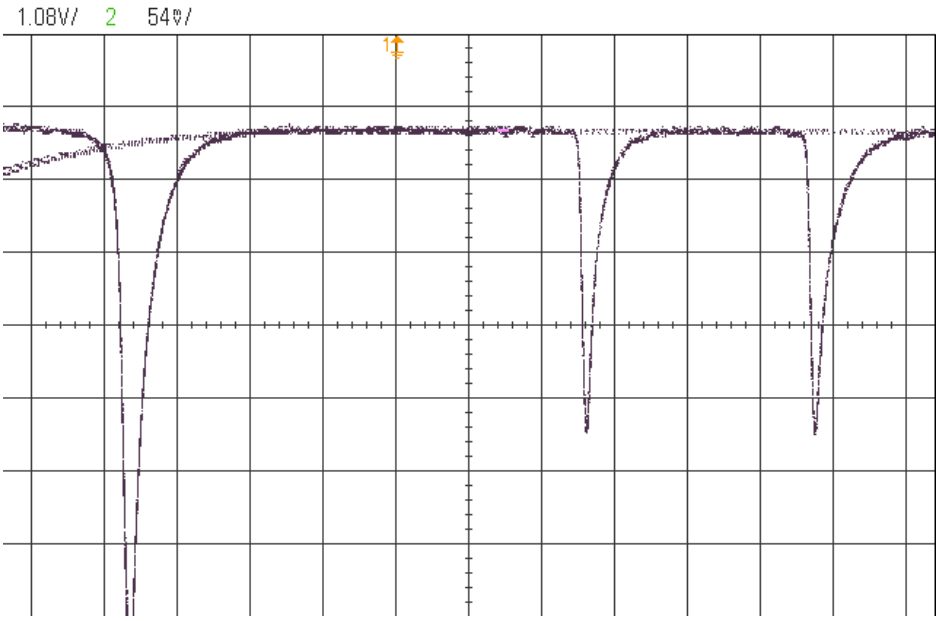

Figure 1: Oscilloscope display of the photodetector measured intensity, on the vertical axis, vs. the magnetic field generating voltage (which are related proportionally), on the horizontal axis. The leftmost dip occurs when the sample's internal magnetic field is zero, and the other two dips correspond to the RF depumping of each isotope.

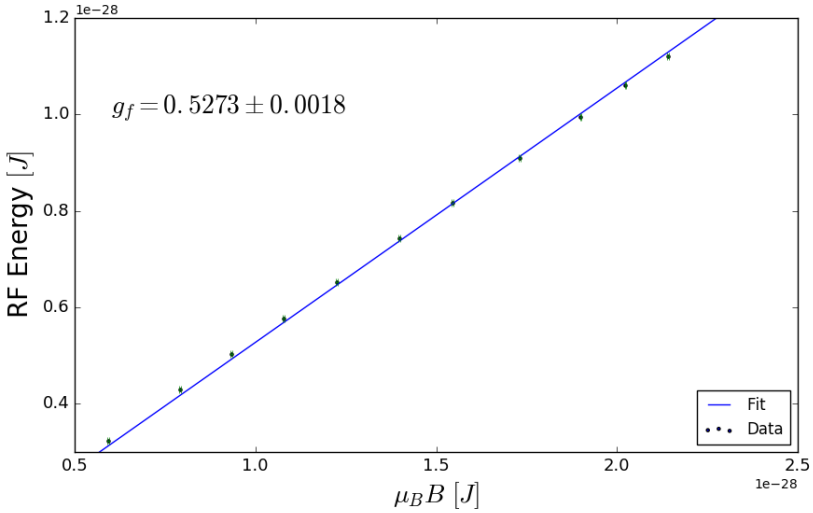

Figure 2: ^{87}Rb: Linear least square fit for to the relation of Equation 2 between the Zeeman transition energy, as measured by RF photons, and the external magnetic field to determine the proportionality constant g_F.

are of similar magnitude to the theoretically predicted values of $g_F = 1/2$ for ^{87}Rb, and $g_F = 1/3$ for ^{85}Rb, although, to our precision, there is a discrepancy between the two, which suggests that treating L and S as accurate state labels is an imperfect prescription, but serves as a fair approximation. Although the $L-S$ coupling is weak, each magnetic moment still experiences a torque due to the other, which causes L and S to not be separately conserved in such a way that the mean value for g_J, across the entire sample, is increased, effecting an increase in g_F. Since the nuclear mass reduces

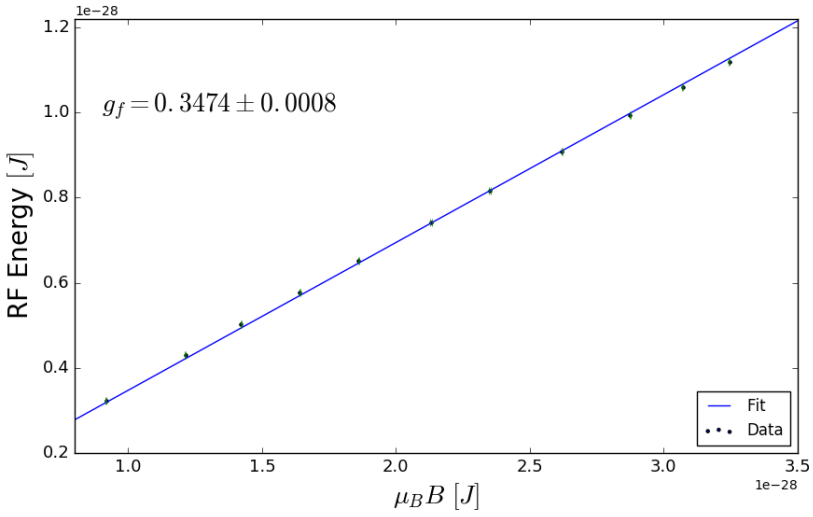

Figure 3: ^{85}Rb: Linear least square fit for to the relation of Equation 2 between the Zeeman transition energy, as measured by RF photons, and the external magnetic field to determine the proportionality constant g_F.

its magnetic moment considerably, there is negligible $I - J$ coupling, and J, I, F are good quantum numbers. Thus, the available explanation is that the numerator of Equation 4 must increase. So, in coupling, Rubidium atoms are, on average, reducing their valence electron's orbital angular momenta in favor of an increase in intrinsic electronic angular momenta.

If the Rubidium sample is allowed to reach thermal equilibrium, the process of pumping the entire sample into a uniform, and maximal, state requires a finite amount of time, in analogy with charging a capacitor. This is the optical pumping time, which we determine by measuring the photodetector reported intensity during the time window immediately following a pause in application of RF photons. When the RF signal is on, the sample appears opaque to the pumping photons, but the instant RF photons are no longer being applied, there is an exponential rise in the intensity of exiting σ^+ as the sample transitions into states that can no longer accept σ^+ photons. In Figure 4, we show this behavior, and our curve fit to the exponential

$$V = V_o(1 - e^{-t/\tau}) \tag{6}$$

where V is the photodetector voltage with maximal value V_o, and t is time, which we used to determine the time constant $\tau = 116.4 \pm 0.3$ μs, during a time window in which we triggered a cessation of the RF signal. This gives a measure of the elapsed time before the majority of atoms have fallen to the m_F states that are out of range for an RF induced electric dipole transition to m_{FMax}.

We also observed an underdamped transient effect following reapplication of the RF field, seen in Figure 4, which is due to RF driven transitions between the m_{FMax} and $m_{FMax} - 1$ state, which cause an oscillation of intensity. Reason suggests that a stronger RF field should be more effective than a weak RF field at inducing transitions, thus the inverse oscillation period (frequency) of this transient effect varies linearly with the amplitude of RF magnetic field B_{RF}, and the slope of such a line will be proportional to g_F, since the g-factor describes the atomic-magnetic field interaction

strength.

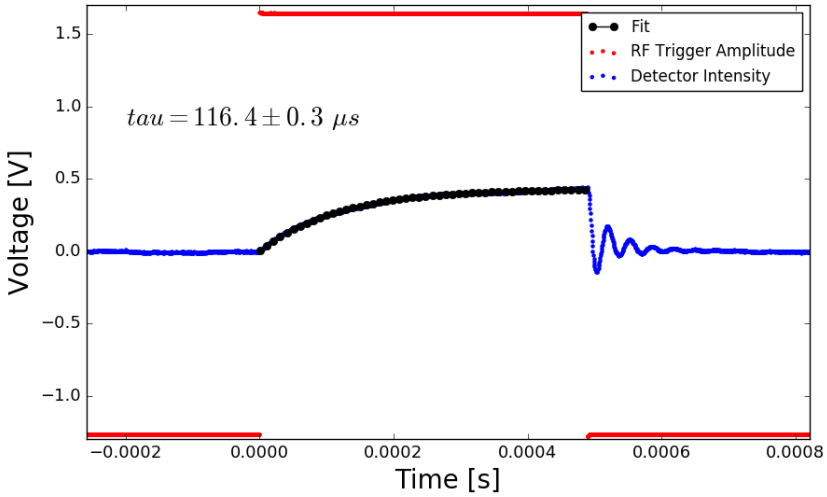

Figure 4: Exponential growth of exiting photon intensity with time when there is a brief absence of applied RF radiation. A curve fit with of the growth region provides the time constant. Note a transient oscillation in intensity occurs as the RF signal returns due atoms transitioning between the m_{FMax} and $m_{FMax} - 1$ state, altering the sample transparency.

In Figure 4, we show the oscillation frequency $1/T$ vs the magnitude of applied RF field for both Rubidium isotopes, and perform a linear least squares fit to determine the slope of each line. Then, the ratio of these slopes, found to be 1.48 ± 0.03, is equivalent to the ratio of g-factors of the isotopes. This ratio is within two standard deviations our previous measurement of $g_{F^{87}Rb}/g_{F^{85}Rb} = 0.5273/0.3474 = 1.517 \pm 0.006$, and is near the theoretical (approximate) value of 1.667.

2 Conclusion

We have demonstrated a process for optically pumping a gas of Rubidium atoms into a non-equilibrium state, and trapping them there by using right circularly polarized photons to induce $\Delta m_F = 1$ transitions from $^2S_{1/2}$ to $^2P_{1/2}$ until the entire sample is locked in the terminal m_F state. Then we use RF photons tuned to the resonant frequency for Zeeman transitions, to induce $\Delta m_F = -1$, effectively depumping the sample, which is indicated by an increase in intensity of exiting photons. By measuring the necessary RF energy to induce such transitions, at various applied magnetic field strengths, we performed a linear fit to determine $g_{F^{87}Rb}/ = 0.5273 \pm 0.0018$ and $g_{F^{85}Rb} = 0.3474 \pm 0.0008$, which are near the theoretically predicted values of $g_F = 1/2$ and $g_F = 1/3$, respectively, which suggests that $L - S$ coupling is present, but weak compared to the other atomic interactions.

Then we determined the optical pumping time to be on the order of 100 μs by measuring the photodetector intensity as a function of time after releasing the sample from depumping and allowing it to ladder up to the trapped state. Here we noticed a transient effect that appeared immediately after the RF signal was applied, which

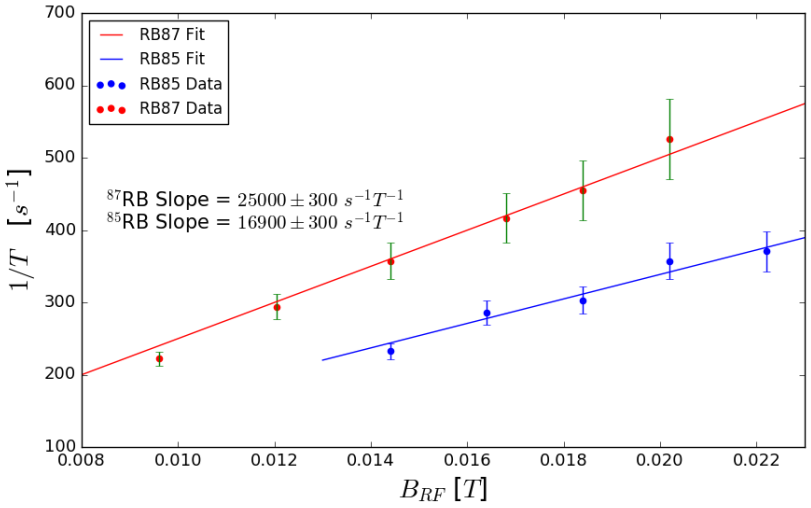

Figure 5: Inverse period of the transient oscillation vs RF magnetic field strength, and linear least square fitting to determine the slopes for each isotope. Here, uncertainty is estimated as 0.2 ms in measurements of the period, which is due to oscilloscope precision.

occurs because the RF photons are capable of causing any $\Delta m_F = \pm 1$ or 0 transitions, and found that the oscillation frequency is linearly related to the applied RF field strength, which allowed us to perform a measure of the g-factor ratio between isotopes, where we found $g_{F^{87}Rb}/g_{F^{85}Rb} = 1.48 \pm 0.03$. Additionally, the optical pumping apparatus has the capability to precisely measure the local magnetic field which we found to be: $B_V = 22.63 \pm 0.06\ \mu$T as the downwards component of earth's magnetic field, and $B_H = 9.91 \pm 0.06\ \mu$T as the horizontal component, in agreement with the values listed on the NASA website.