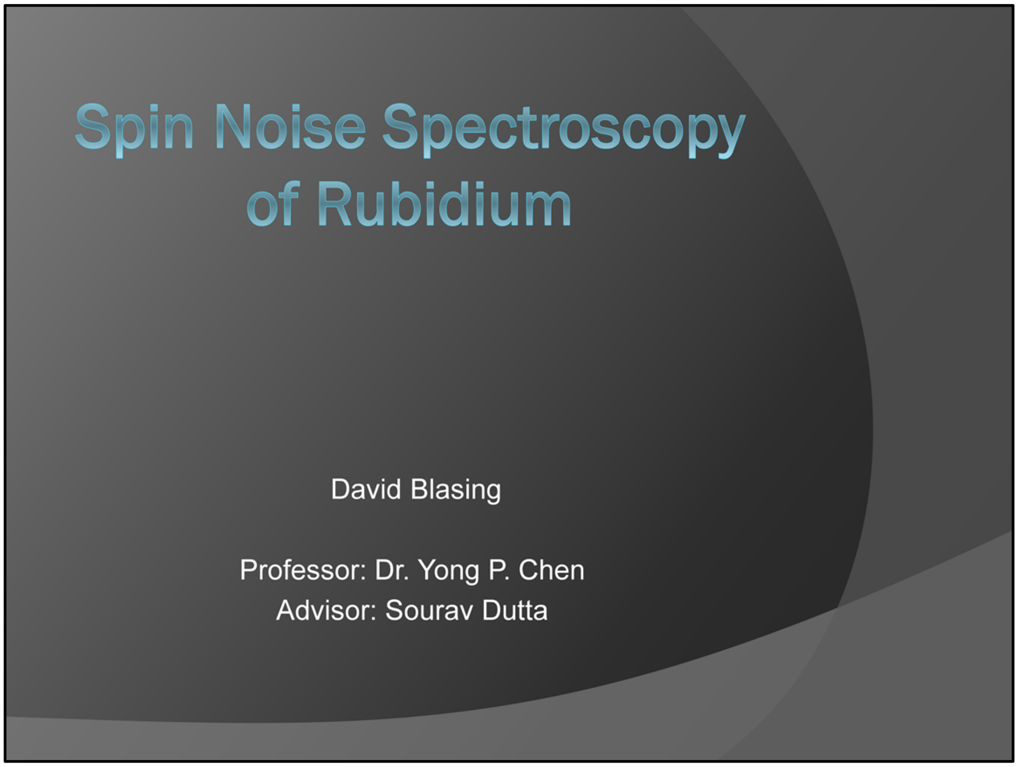


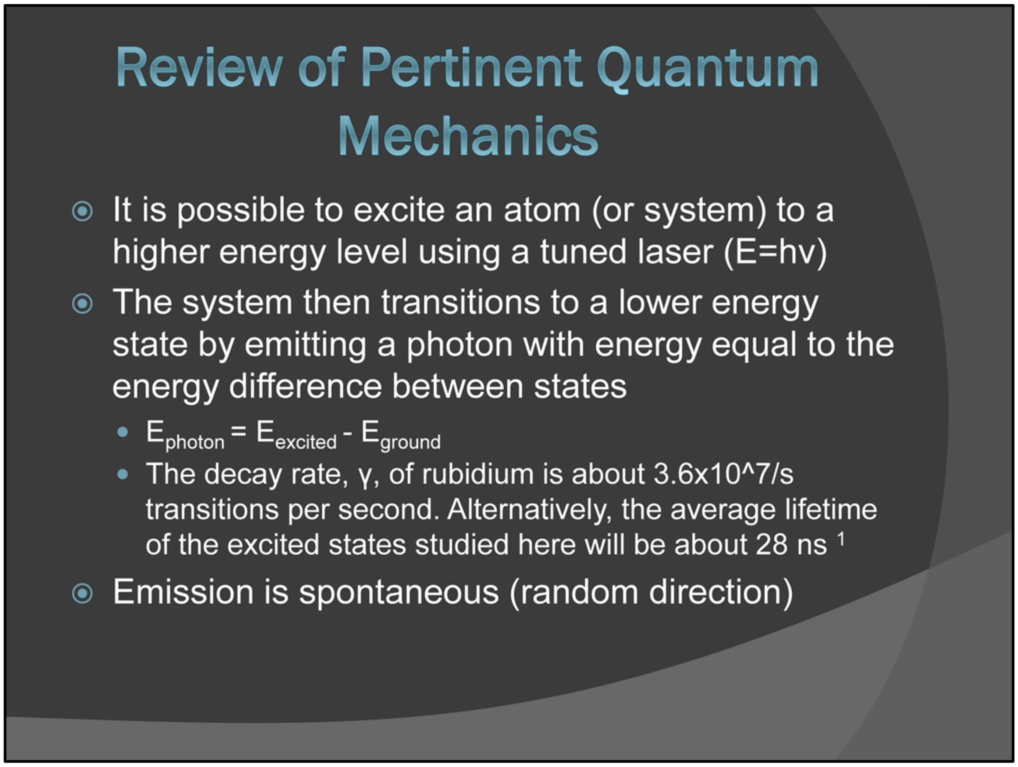
Spin Noise Spectroscopy of Rubidium

David Blasing

Professor: Dr. Yong P. Chen
Advisor: Sourav Dutta

Presentation Outline

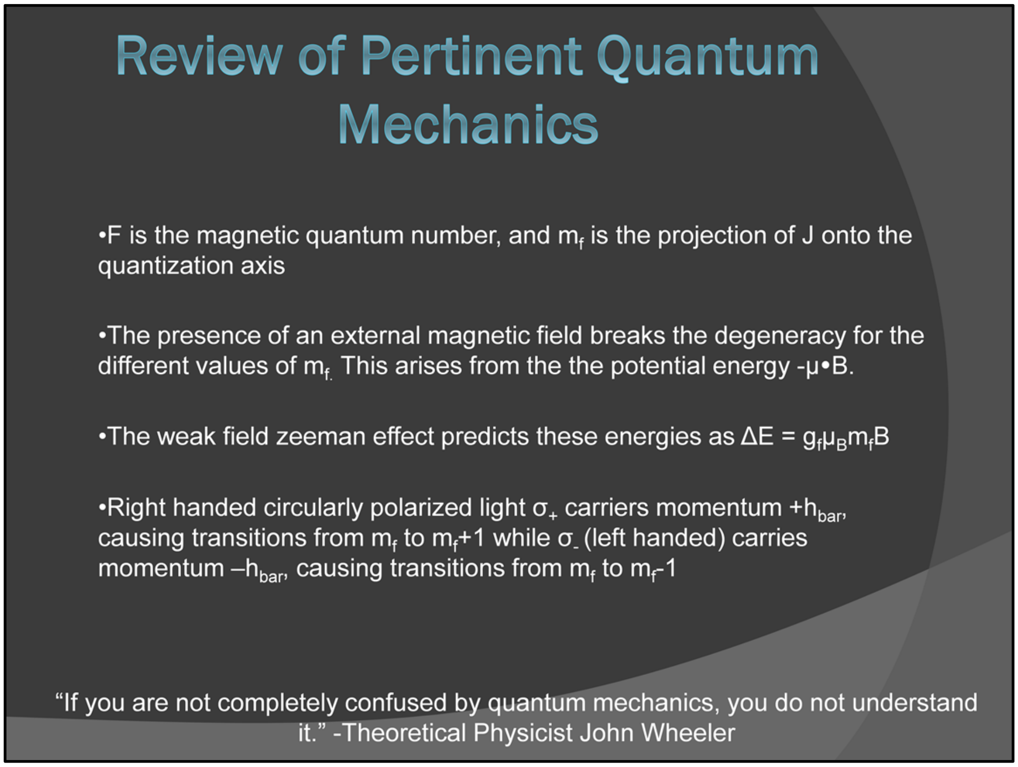
- Review of Pertinent Quantum Mechanics
- Hyperfine Structure of Rubidium 85
- Faraday Rotation
- Spin Noise
- Future Goals



Review of Pertinent Quantum Mechanics

- It is possible to excite an atom (or system) to a higher energy level using a tuned laser (E=hv)
- The system then transitions to a lower energy state by emitting a photon with energy equal to the energy difference between states
  - $E_{photon} = E_{excited} - E_{ground}$
  - The decay rate, γ, of rubidium is about 3.6x10^7/s transitions per second. Alternatively, the average lifetime of the excited states studied here will be about 28 ns [1]
- Emission is spontaneous (random direction)

Transition rate is a ballpark for the rubidium levels reached by the 780nm laser

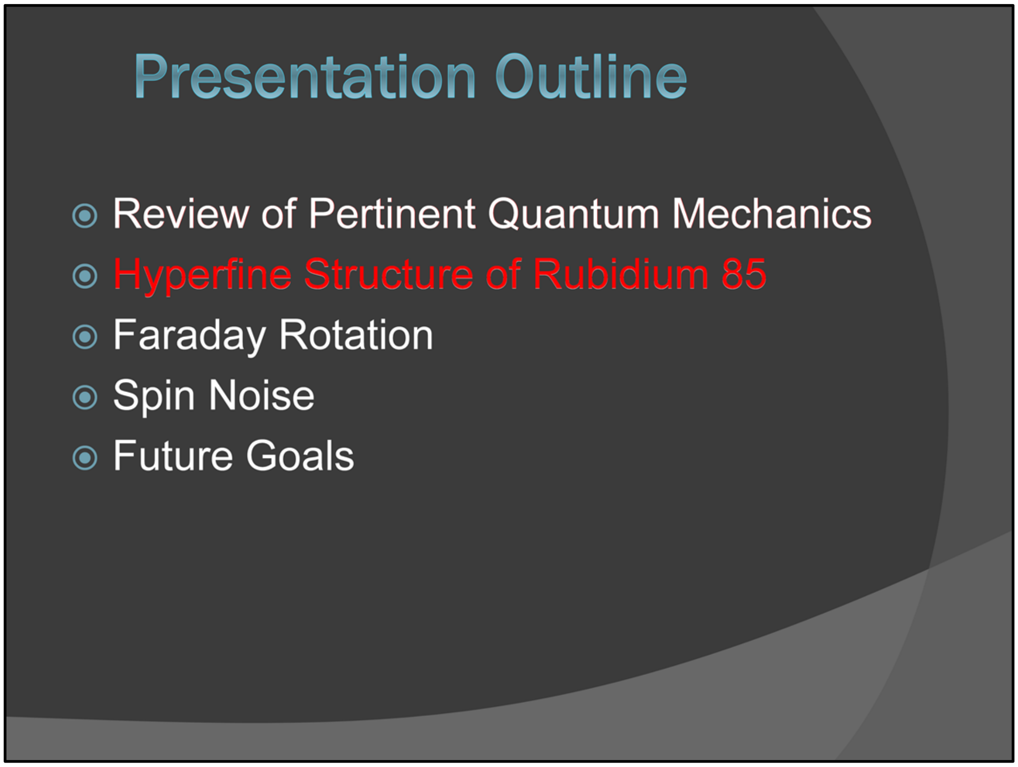


Review of Pertinent Quantum Mechanics

- F is the magnetic quantum number, and m_f is the projection of J onto the quantization axis
- The presence of an external magnetic field breaks the degeneracy for the different values of $m_{f.}$ This arises from the the potential energy $-\mu \bullet B$.
- The weak field zeeman effect predicts these energies as $\Delta E = g_f \mu_B m_f B$
- Right handed circularly polarized light σ_+ carriers momentum $+h_{bar,}$ causing transitions from m_f to m_f+1 while σ_- (left handed) carries momentum $-h_{bar,}$ causing transitions from m_f to m_f-1

"If you are not completely confused by quantum mechanics, you do not understand it." -Theoretical Physicist John Wheeler

G_j is the lande G factor, μ_B is the bohr magneton, m_j is the z-component of the total angular momentum, and B is the applied magnetic field. The magnetic field associated with the fine structure correction is ~3000 Gauss.



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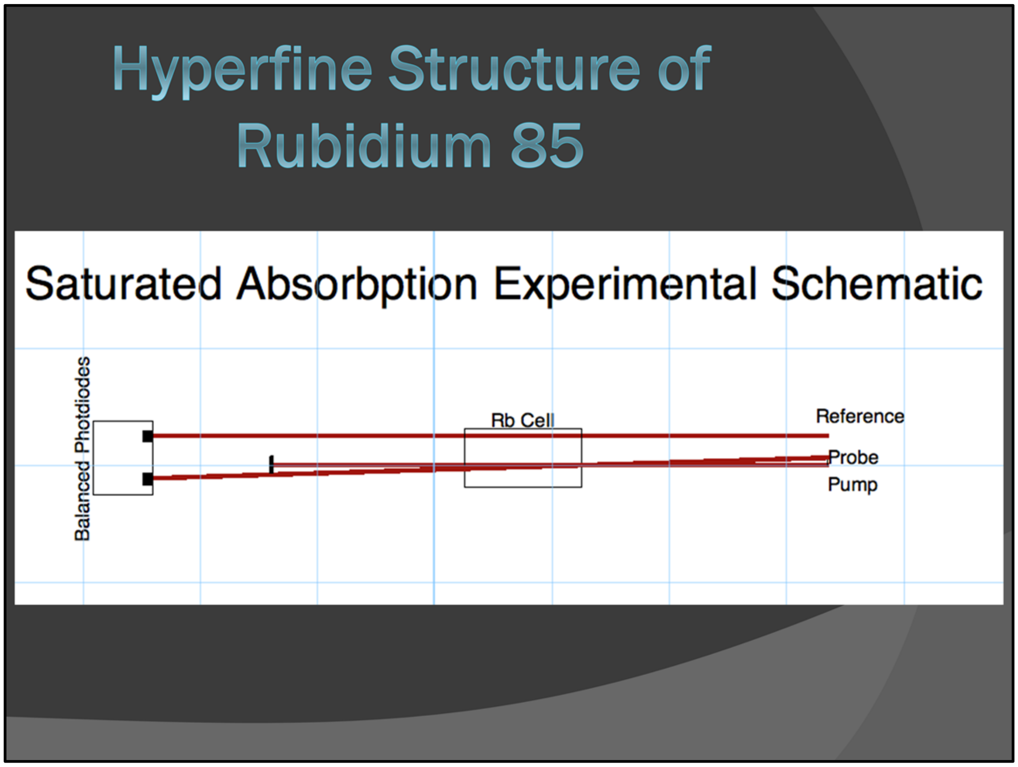


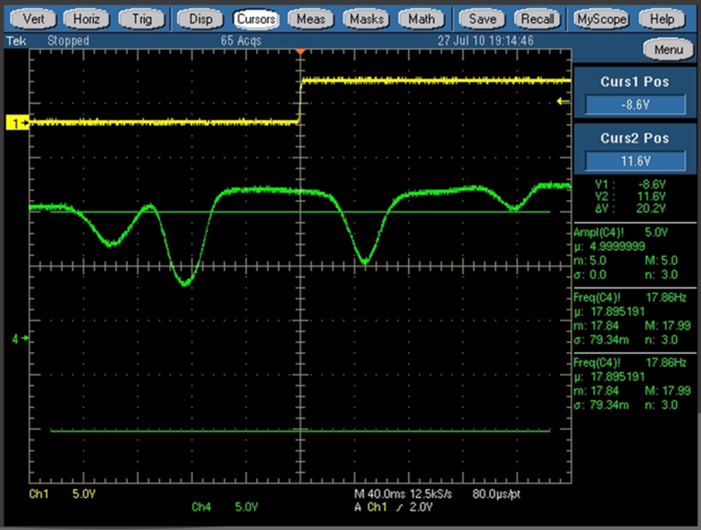
Hyperfine Structure of Rubidium 85

Saturated Absorbption Experimental Schematic

Fine structure results from spin-orbit coupling of the electron, while hyperfine structure results from spin of the nucleus interacting with the spin of the electron.

Hyperfine Structure of Rubidium 85

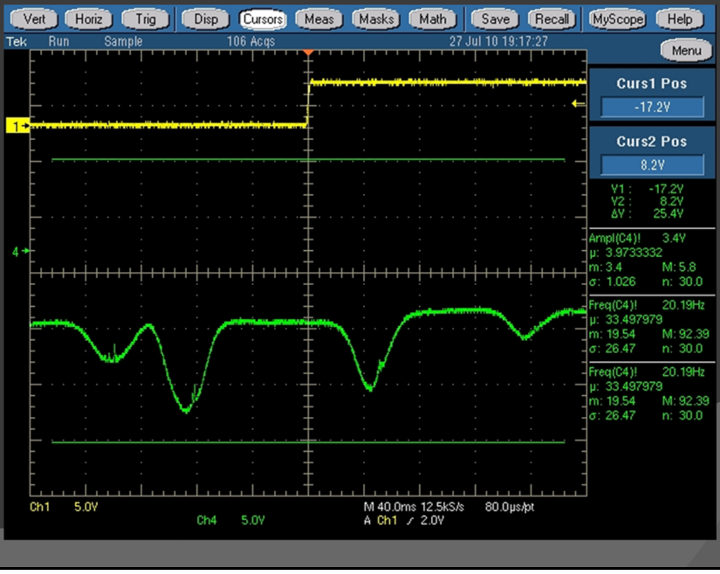
Reference Beam



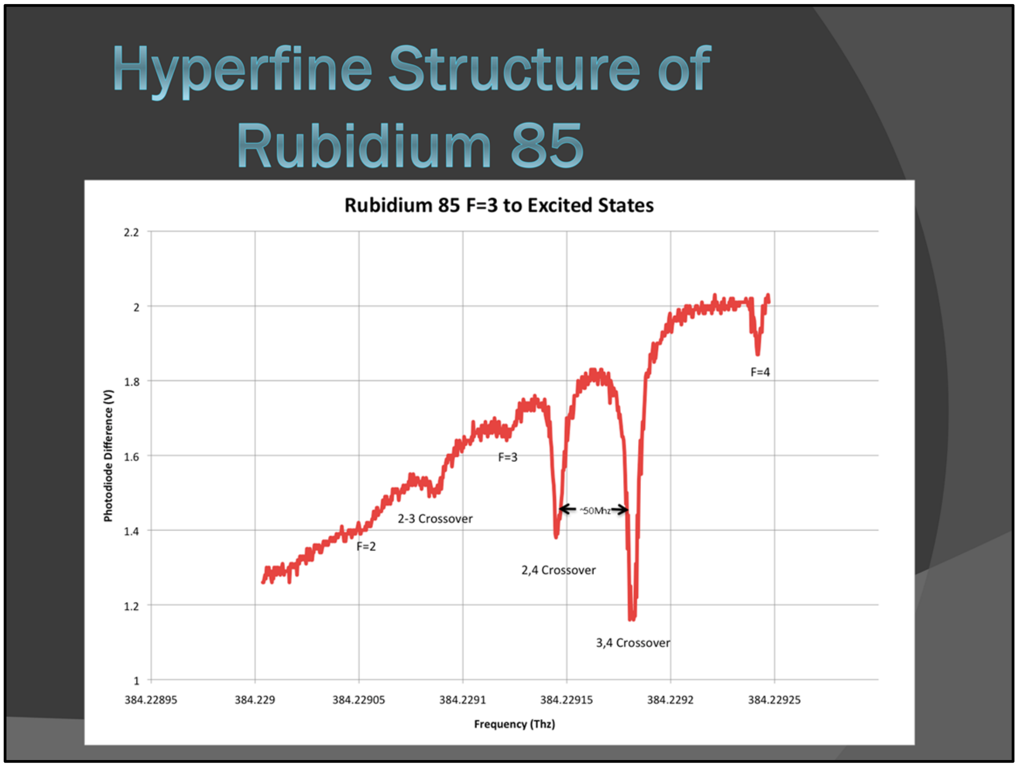
```
Tek    Stopped          65 Acqs              27 Jul 10 19:14:46

Curs1 Pos
-8.6V
Curs2 Pos
11.6V
  V1 :    -8.6V
  V2 :    11.6V
  ΔV :    20.2V
Ampl(C4)!      5.0V
μ: 4.9999999
m: 5.0         M: 5.0
σ: 0.0         n:  3.0
Freq(C4)!      17.86Hz
μ:  17.895191
m: 17.84       M: 17.99
σ: 79.34m      n:  3.0
Freq(C4)!      17.86Hz
μ:  17.895191
m: 17.84       M: 17.99
σ: 79.34m      n:  3.0

Ch1    5.0V                          M 40.0ms 12.5kS/s    80.0μs/pt
              Ch4    5.0V            A  Ch1  ⁄  2.0V
```

Hyperfine Structure of Rubidium 85

Probe Beam

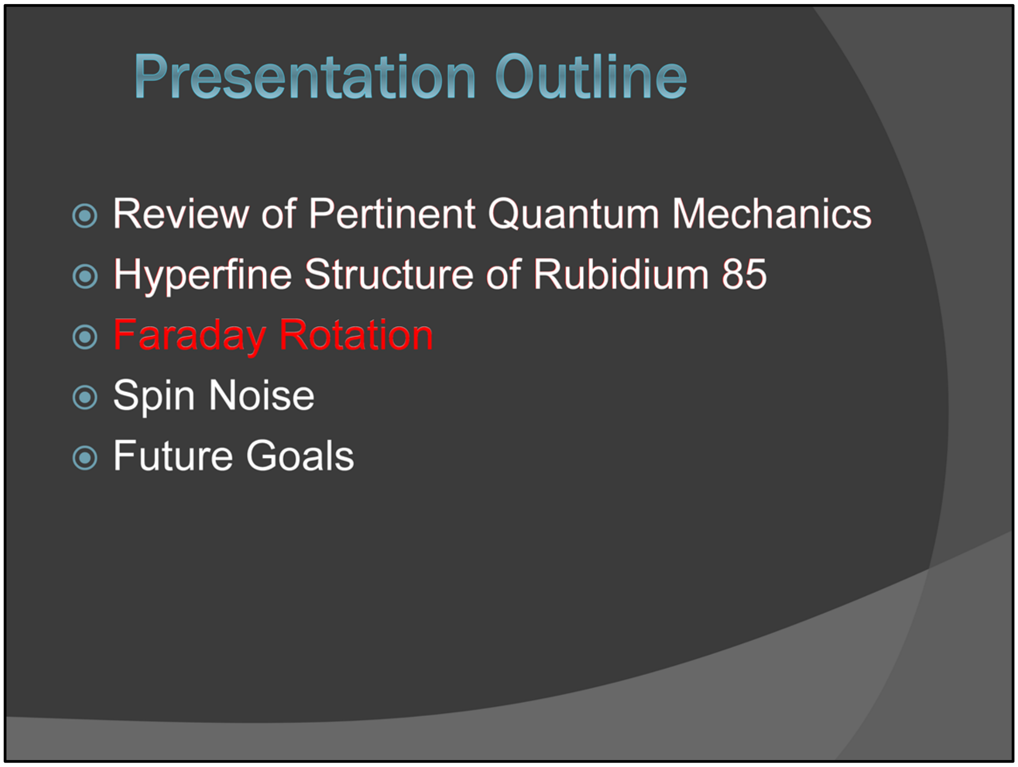


```
Tek    Run    Sample    106 Acqs    27 Jul 10 19:17:27

Curs1 Pos
-17.2V
Curs2 Pos
8.2V
V1 :   -17.2V
V2 :     8.2V
ΔV :    25.4V
Ampl(C4)!     3.4V
μ: 3.9733332
m: 3.4        M: 5.8
σ: 1.026      n: 30.0
Freq(C4)!     20.19Hz
μ: 33.497979
m: 19.54      M: 92.39
σ: 26.47      n: 30.0
Freq(C4)!     20.19Hz
μ: 33.497979
m: 19.54      M: 92.39
σ: 26.47      n: 30.0

M 40.0ms 12.5kS/s    80.0μs/pt
A Ch1 ⁄ 2.0V
```



Hyperfine Structure of Rubidium 85

Fine structure results from spin-orbit coupling of the electron, while hyperfine structure results from spin of the nucleus interacting with the spin of the electron.



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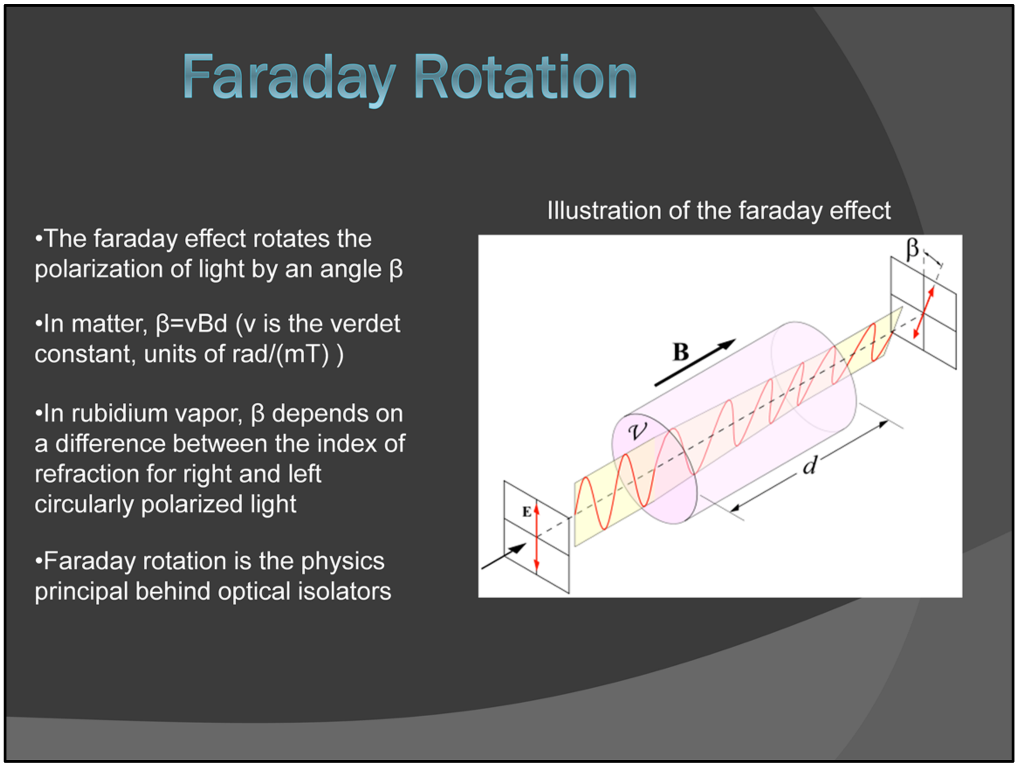
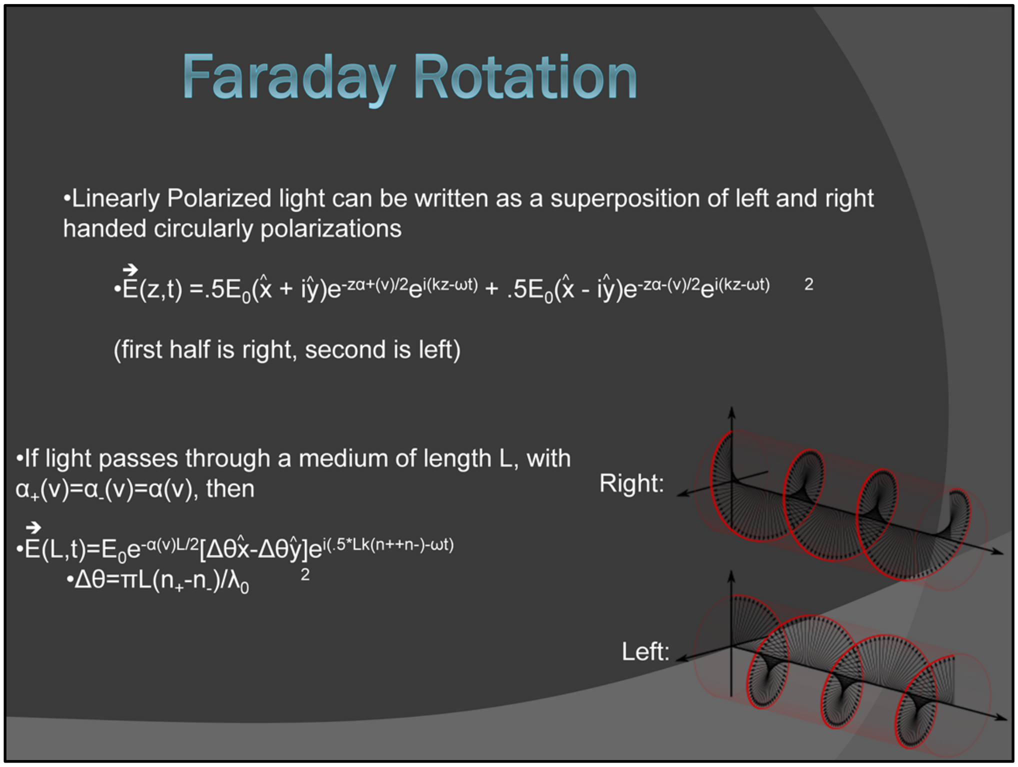


Faraday Rotation

- The faraday effect rotates the polarization of light by an angle β
- In matter, β=vBd (v is the verdet constant, units of rad/(mT))
- In rubidium vapor, β depends on a difference between the index of refraction for right and left circularly polarized light
- Faraday rotation is the physics principal behind optical isolators

Illustration of the faraday effect

Positive faraday constant means counter clockwise rotation when then direction of the magnetic field and laser are parallel, and clockwise when they are anti parallel.



Faraday Rotation

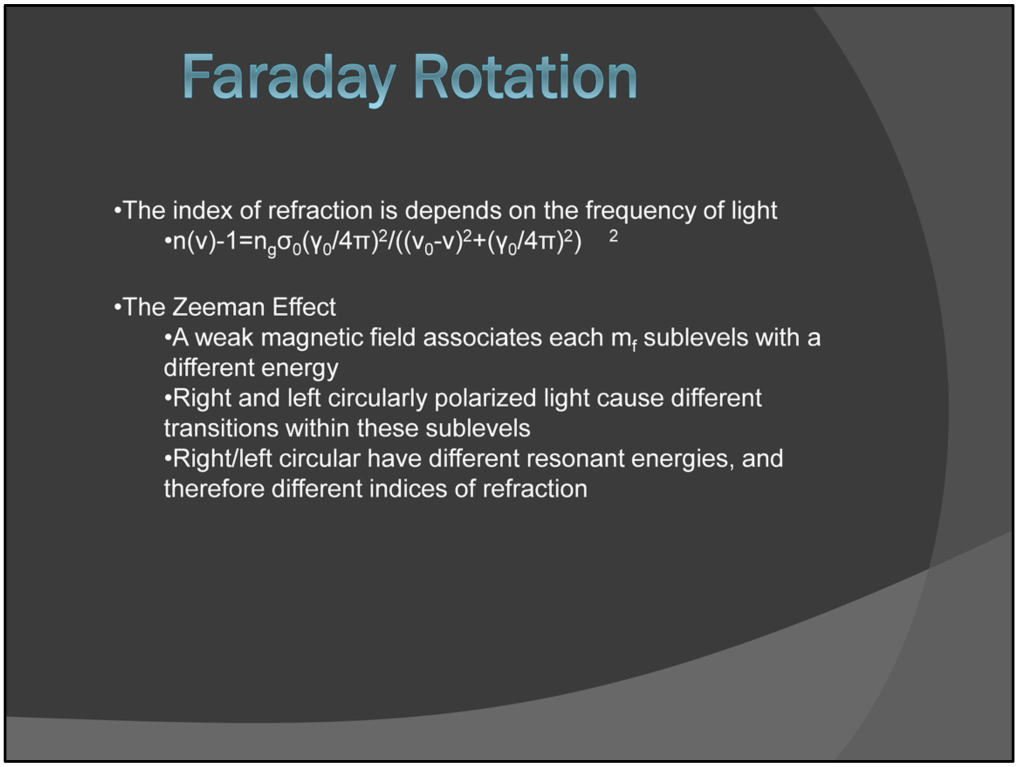
- Linearly Polarized light can be written as a superposition of left and right handed circularly polarizations
  - $\vec{E}(z,t) = .5E_0(\hat{x} + i\hat{y})e^{-z\alpha+(v)/2}e^{i(kz-\omega t)} + .5E_0(\hat{x} - i\hat{y})e^{-z\alpha-(v)/2}e^{i(kz-\omega t)}$ [2]

  (first half is right, second is left)

- If light passes through a medium of length L, with $\alpha_+(v)=\alpha_-(v)=\alpha(v)$, then
- $\vec{E}(L,t)=E_0e^{-\alpha(v)L/2}[\Delta\theta\hat{x}-\Delta\theta\hat{y}]e^{i(.5*Lk(n++n-)-\omega t)}$
  - $\Delta\theta=\pi L(n_+-n_-)/\lambda_0$ [2]

Positive faraday constant means counter clockwise rotation when then direction of the magnetic field and laser are parallel, and clockwise when they are anti parallel.

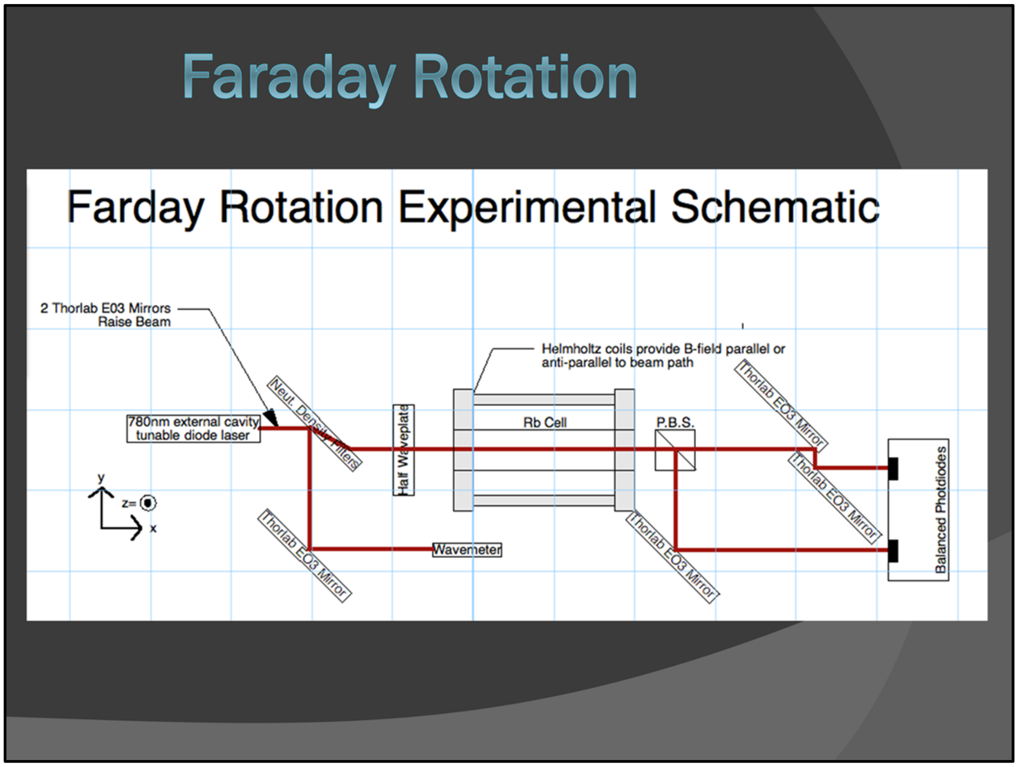
In the linearly polarized light equation, the k's are different because λ is frequency dependent



Faraday Rotation

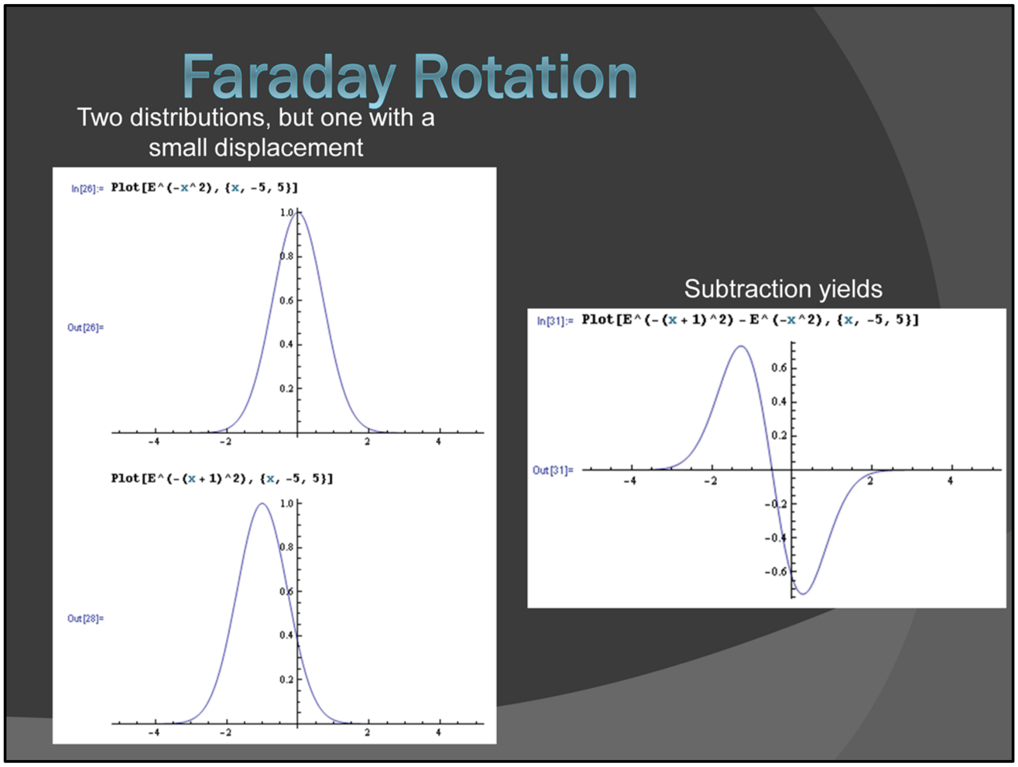
- The index of refraction is depends on the frequency of light
  - $n(\nu)-1=n_g\sigma_0(\gamma_0/4\pi)^2/((\nu_0-\nu)^2+(\gamma_0/4\pi)^2)$ [2]
- The Zeeman Effect
  - A weak magnetic field associates each m_f sublevels with a different energy
  - Right and left circularly polarized light cause different transitions within these sublevels
  - Right/left circular have different resonant energies, and therefore different indices of refraction

n_g is the number density of atoms
σ_0 is the integrated cross section of interaction
$\gamma_0/2\pi$ is the natural line width of the transition
ν_0 is the resonant frequency



Faraday Rotation

Farday Rotation Experimental Schematic



Faraday Rotation

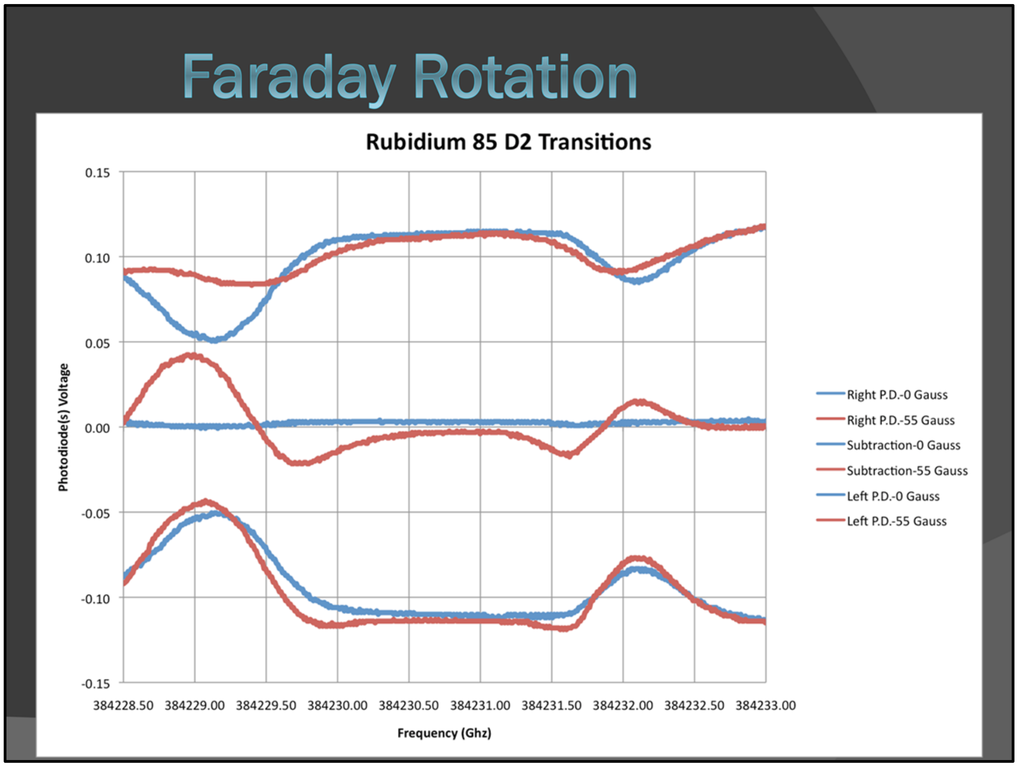
Two distributions, but one with a small displacement

```
In[26]:= Plot[E^(-x^2), {x, -5, 5}]
Out[26]=
```

```
Plot[E^(-(x+1)^2), {x, -5, 5}]
Out[28]=
```

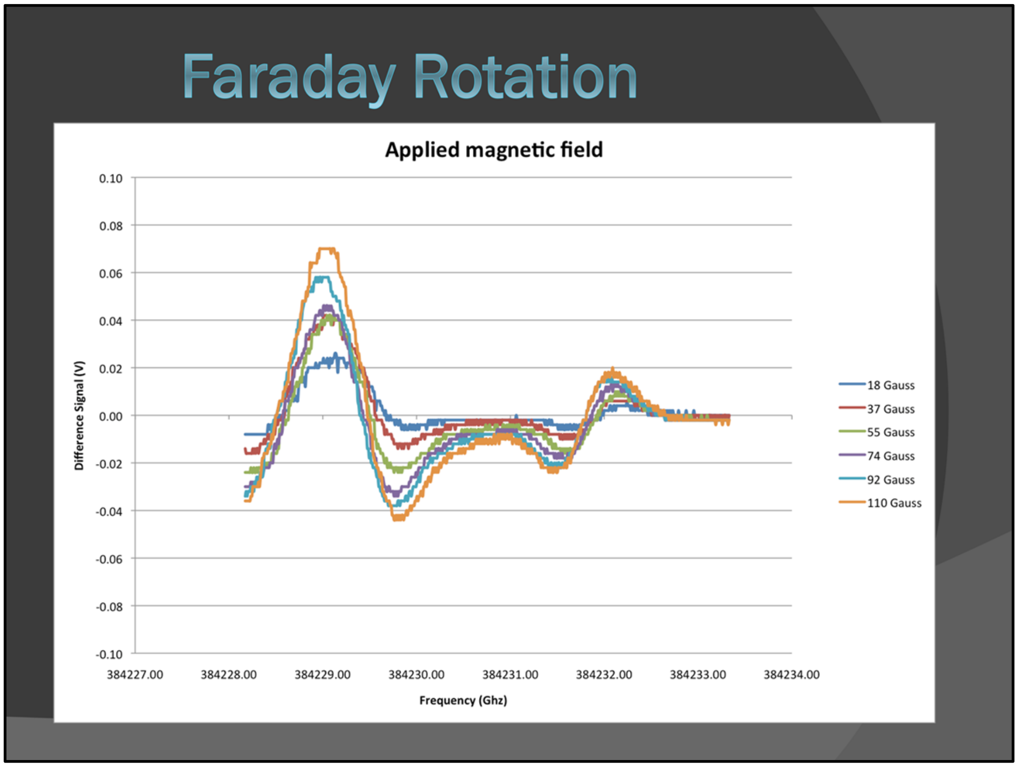
Subtraction yields

```
In[31]:= Plot[E^(-(x+1)^2) - E^(-x^2), {x, -5, 5}]
Out[31]=
```



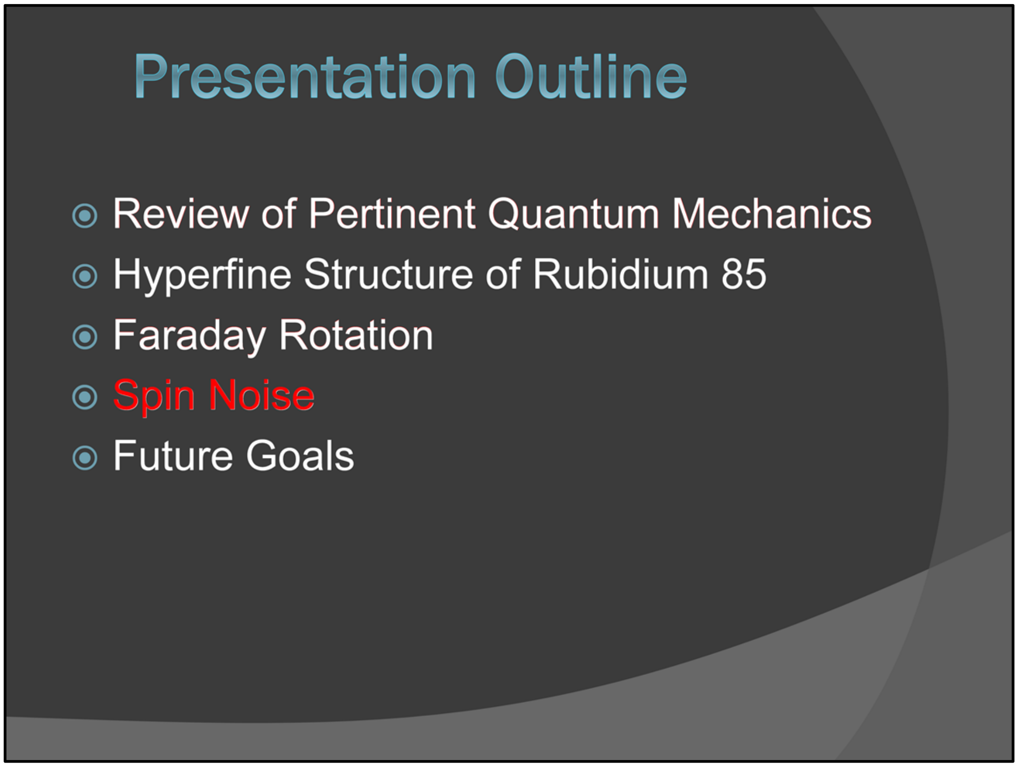
Faraday Rotation

The peaks are both from Rb 85, f=2,3 to excited states



Faraday Rotation

Larger Peak is Rb 85 while the smaller peak is Rb 87



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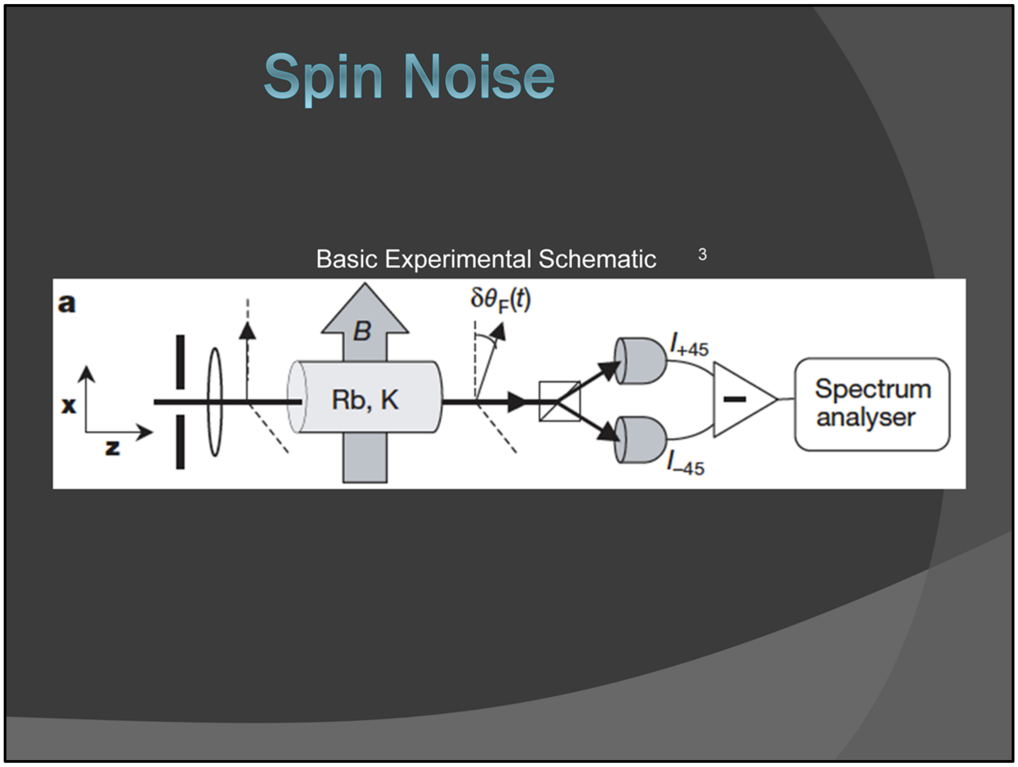


Spin Noise

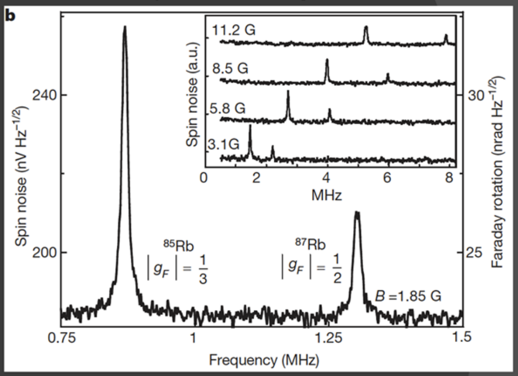
Basic Experimental Schematic [3]

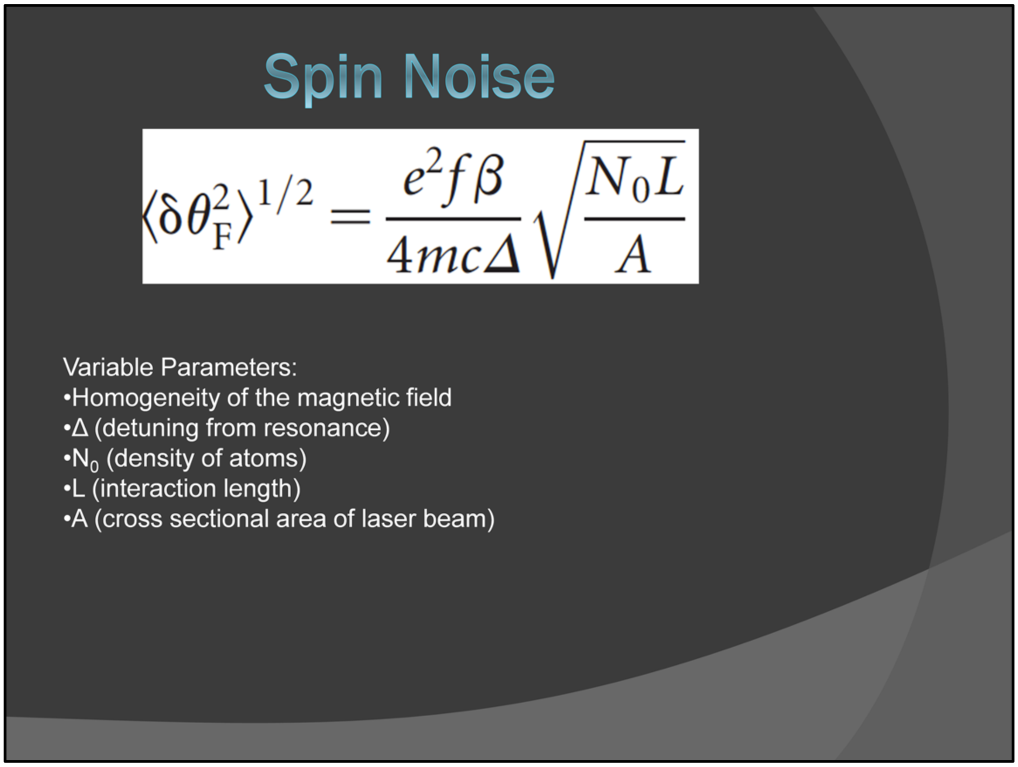
Spin Noise

Predicted Faraday Rotation [3]

$$\langle \delta\theta_F^2 \rangle^{1/2} = \frac{e^2 f \beta}{4mc\Delta}\sqrt{\frac{N_0 L}{A}}$$

Example-Previously Published [3]

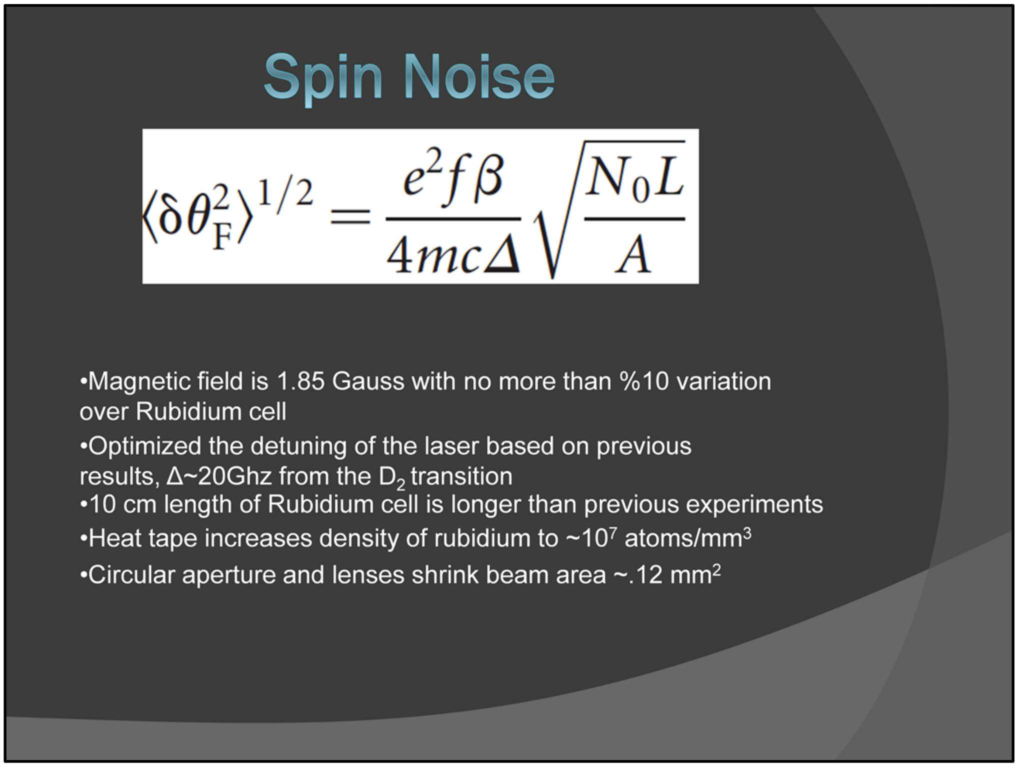




Spin Noise

$$\langle \delta\theta_{\mathrm{F}}^{2} \rangle^{1/2} = \frac{e^{2} f \beta}{4 m c \Delta} \sqrt{\frac{N_{0} L}{A}}$$

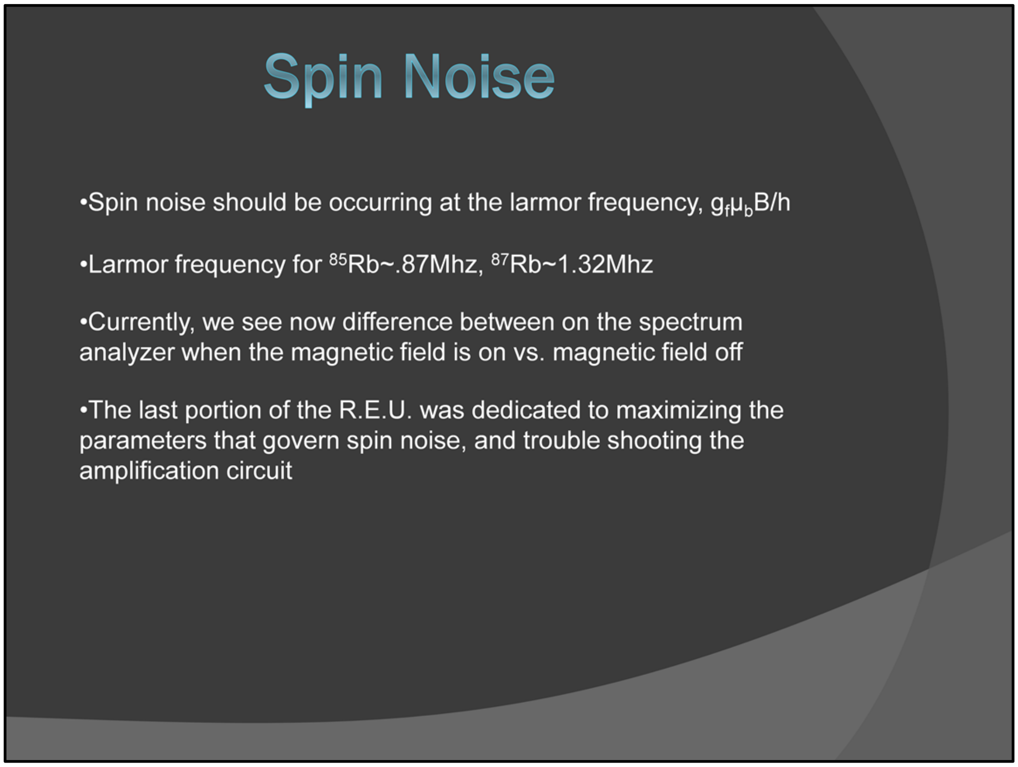
Variable Parameters:
- Homogeneity of the magnetic field
- Δ (detuning from resonance)
- N_0 (density of atoms)
- L (interaction length)
- A (cross sectional area of laser beam)



Spin Noise

$$\langle \delta\theta_F^2 \rangle^{1/2} = \frac{e^2 f \beta}{4mc\Delta}\sqrt{\frac{N_0 L}{A}}$$

- Magnetic field is 1.85 Gauss with no more than %10 variation over Rubidium cell
- Optimized the detuning of the laser based on previous results, Δ~20Ghz from the D_2 transition
- 10 cm length of Rubidium cell is longer than previous experiments
- Heat tape increases density of rubidium to ~10^7 atoms/mm^3
- Circular aperture and lenses shrink beam area ~.12 mm^2



Spin Noise

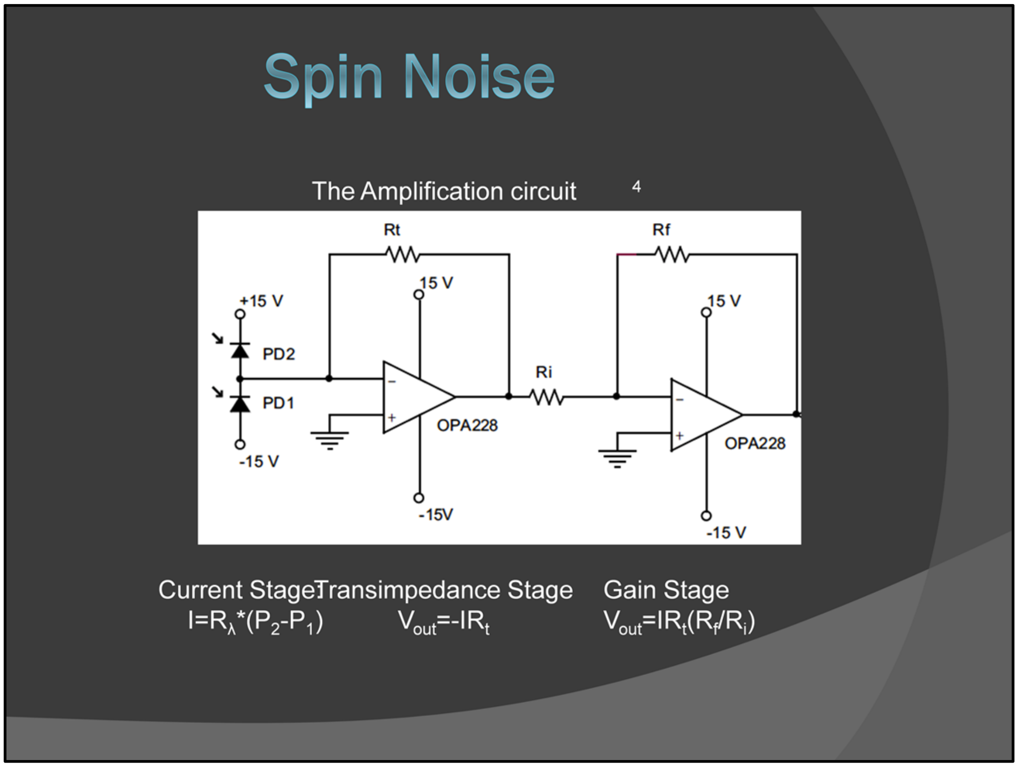
•Spin noise should be occurring at the larmor frequency, $g_f\mu_b B/h$

•Larmor frequency for ^{85}Rb~.87Mhz, ^{87}Rb~1.32Mhz

•Currently, we see now difference between on the spectrum analyzer when the magnetic field is on vs. magnetic field off

•The last portion of the R.E.U. was dedicated to maximizing the parameters that govern spin noise, and trouble shooting the amplification circuit

H=planks constant, μ_b=planks constant, B is magnetic field, g_f=ground state g-factor.

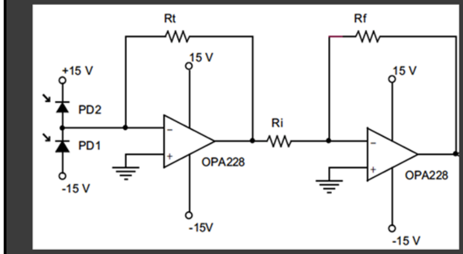


Spin Noise

The Amplification circuit [4]

Current Stage	Transimpedance Stage	Gain Stage
$I=R_{\lambda}*(P_2-P_1)$	$V_{out}=-IR_t$	$V_{out}=IR_t(R_f/R_i)$

Spin Noise

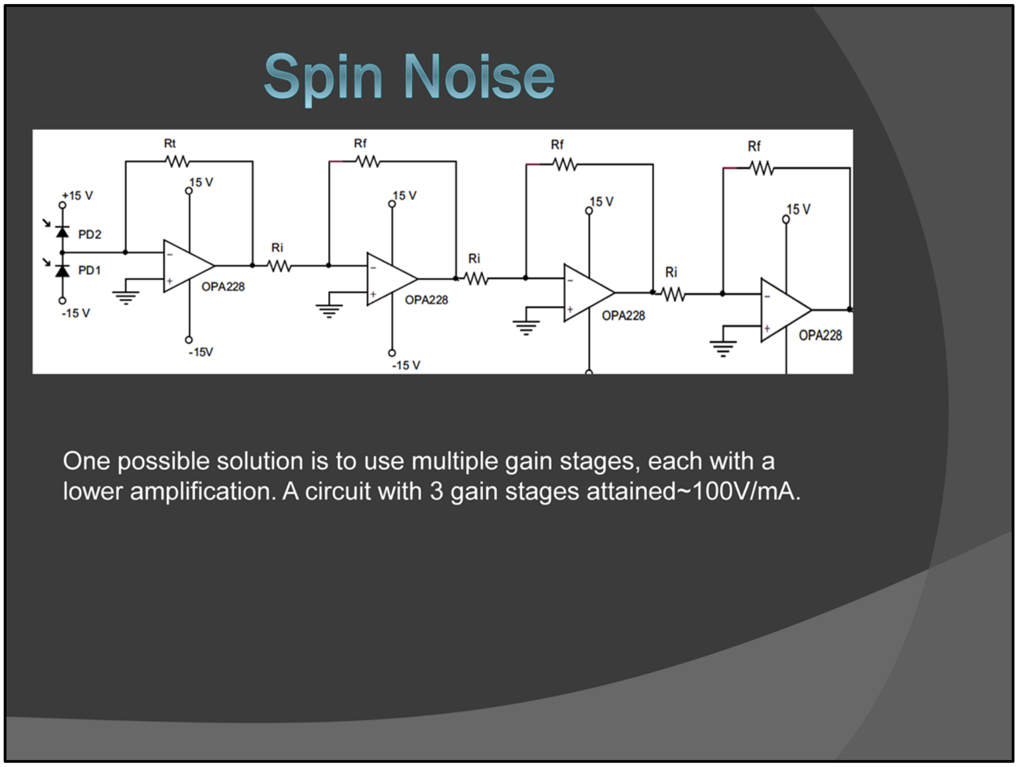


R_t determines the bandwidth and risetime of the photodiodes. R_t=1kΩ~4Mhz.

The gain, R_f/R_i, determines the bandwidth of the gain stage. For OPA228, R_f/R_i=3 means bandwidth~2.6 Mhz.

Total transimpedance gain ~ 3V/mA.

Previous groups had transimpedance gains of ~40V/mA



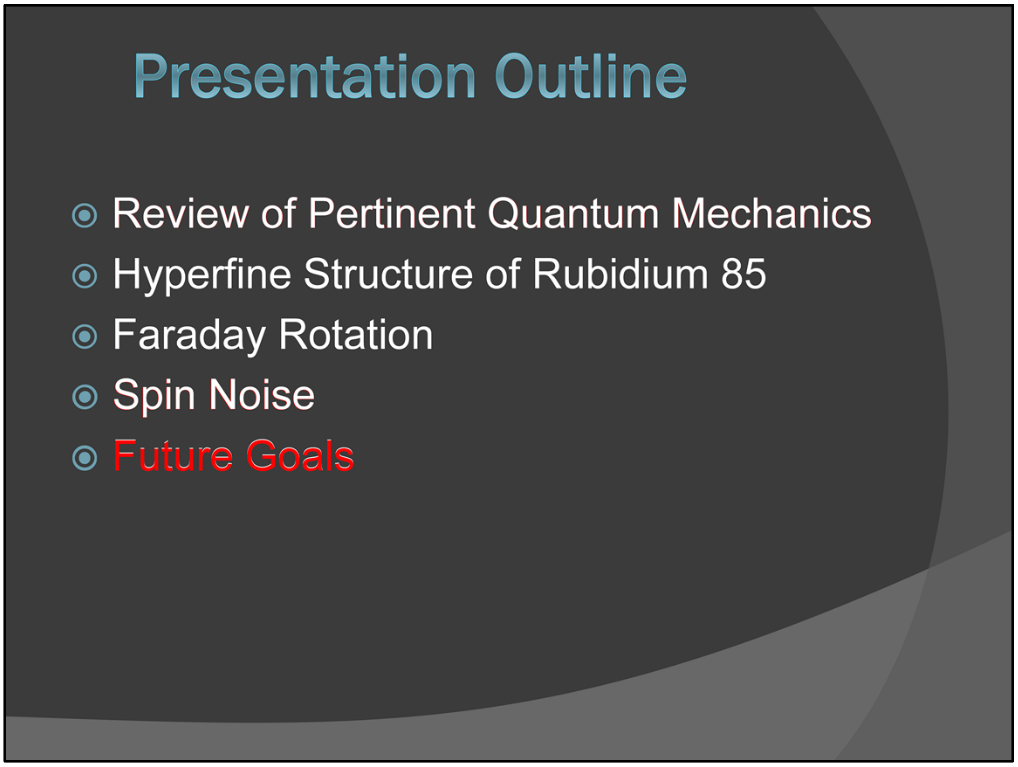
Spin Noise

One possible solution is to use multiple gain stages, each with a lower amplification. A circuit with 3 gain stages attained~100V/mA.

Spin Noise

With the 3 gain stage circuit, we attempted to find spin noise one last time

In the spectrum analyzer around 1Mhz
- Noise floor was ~500μV with fluctuations of 250μV.
- Two peaks of 3.1mV and 7.7mV with fluctuations of 1.5mV and 2.5mV
- Spin noise will be in the nanovolt region



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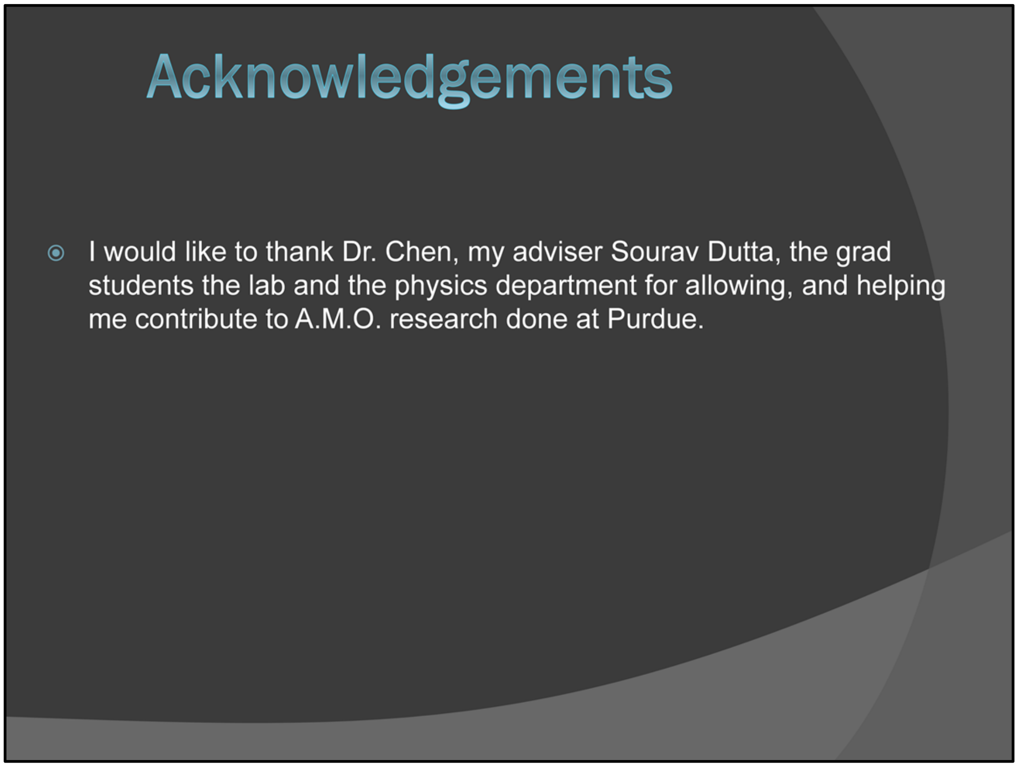
Future Goals

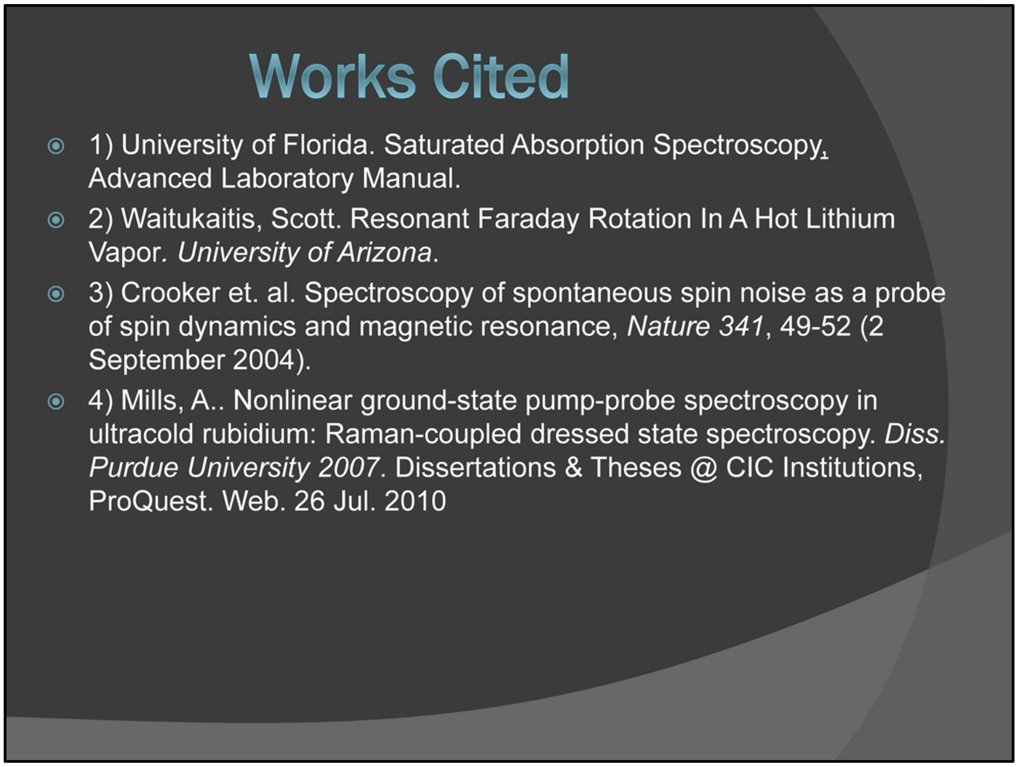
Two main areas for future work

1. Refining the controllable parameters for spin noise
    - Creating a more static magnetic field, or using a smaller rubidium cell
    - More elaborate set of optics to shrink the beam area even further
    - Cell oven to increase max temperature
2. Engineering a low noise, high bandwidth, high gain circuit
    - Current is on the scale of picoamps or lower, and is oscillating around 1mhz
    - Commercially balanced, low noise detectors are available, but are pricey
    - Examining each circuit element in the spectrum analyzer to see its noise contribution, and selecting lower noise alternatives if neccesary



Acknowledgements

- I would like to thank Dr. Chen, my adviser Sourav Dutta, the grad students the lab and the physics department for allowing, and helping me contribute to A.M.O. research done at Purdue.



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- 1) University of Florida. Saturated Absorption Spectroscopy, Advanced Laboratory Manual.
- 2) Waitukaitis, Scott. Resonant Faraday Rotation In A Hot Lithium Vapor. *University of Arizona*.
- 3) Crooker et. al. Spectroscopy of spontaneous spin noise as a probe of spin dynamics and magnetic resonance, *Nature 341*, 49-52 (2 September 2004).
- 4) Mills, A.. Nonlinear ground-state pump-probe spectroscopy in ultracold rubidium: Raman-coupled dressed state spectroscopy. *Diss. Purdue University 2007*. Dissertations & Theses @ CIC Institutions, ProQuest. Web. 26 Jul. 2010