MOT-based Lifetime Measurements of Potassium-39 $5p_{1/2}$ and $5p_{3/2}$ states

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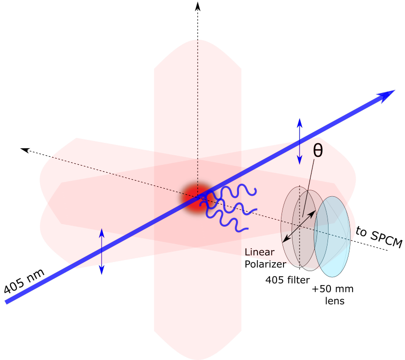
Why lifetime measurements?

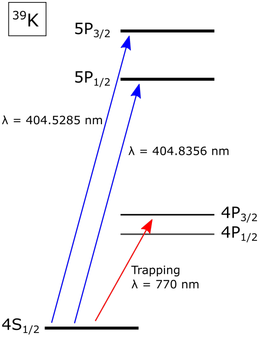
$$\frac{1}{\tau_{fi}} = \frac{4\alpha\omega_0^3}{3c^2} \left| \langle f | \, e\mathbf{r} \, | i \rangle \right|^2$$

- Provide empirical data/constants
- Confidence in matrix element calculations for understanding fundamental physics (e.g. parity violation)

Idea

Excite the **MOT** by a (short) 405 nm pulse, and observe fluorescence.

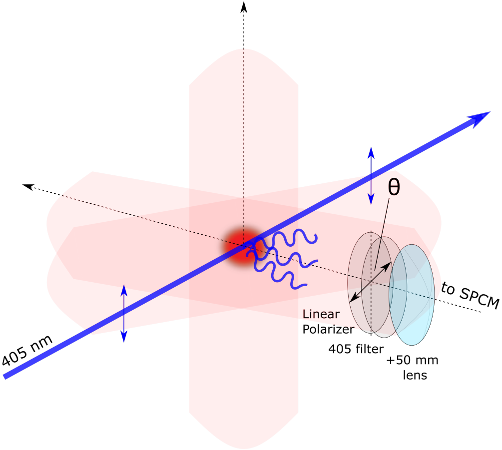


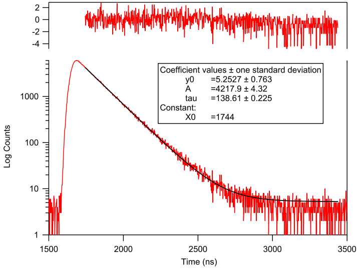


Cloud diameter $\sim$ 1 mm. T $\sim$ 1 mK. Density $\sim 10^9$ atoms/cm^3.

Idea

Fluorescence should be an exponential decay.

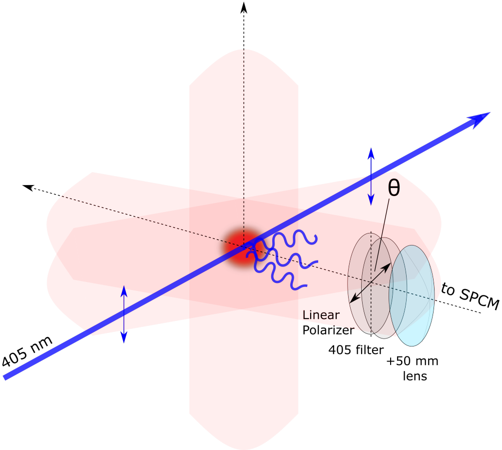


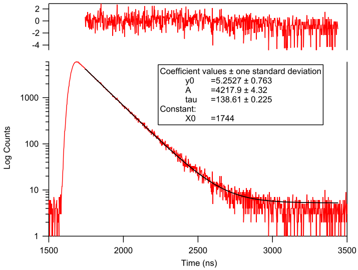


Data fitted with $N = Bkg + A\exp[-(t - t_0)/\tau]$. Residual is normalized.

Idea

Fluorescence should be an exponential decay. **Or should it?**





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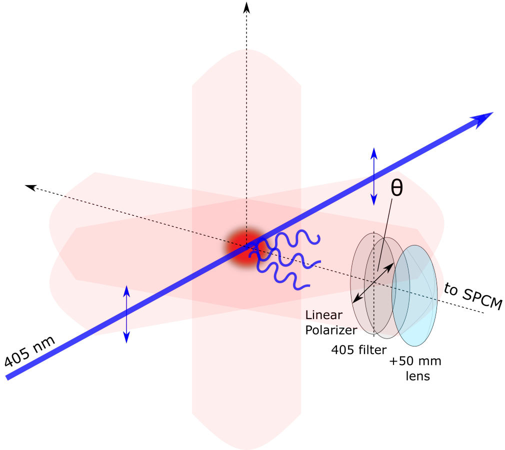

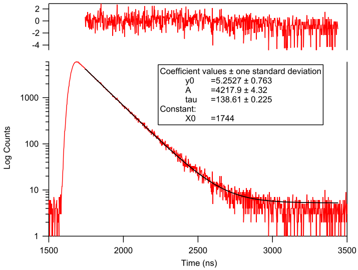

$\Longrightarrow$ **Need some understanding of the fluorescence from 5p in K-39**

Theory: Hyperfine Structure

- Fine structure $\sim$ Special relativity $+$ $\mathbf{S}, \mathbf{L}$ coupling ($+$ Darwin)

$$\Longrightarrow \quad \text{New quantum number: } \mathbf{J} = \mathbf{S} + \mathbf{L}$$

Theory: Hyperfine Structure

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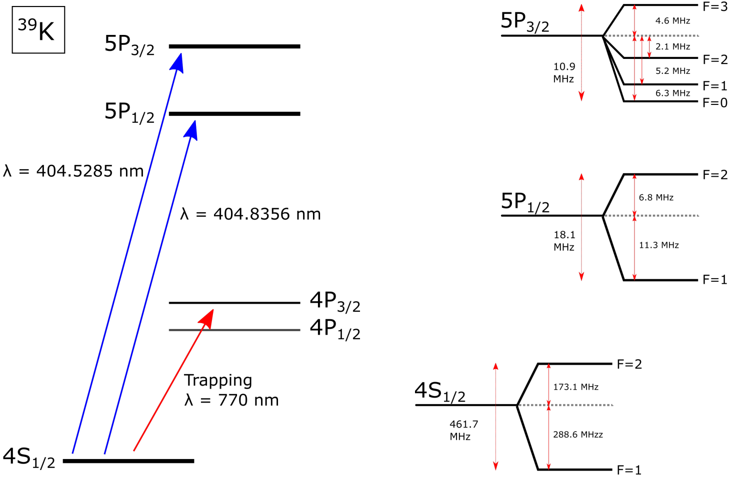
- Hyperfine structure $\sim$ Fine structure $+$ Nuclear spin

$$\implies \quad \text{New quantum number: } \mathbf{F} = \mathbf{J} + \mathbf{I}$$

Theory: Hyperfine Structure



Theory: Hyperfine Structure

In general,

$$\frac{1}{\tau_{fi}} = \frac{4\alpha\omega_0^3}{3c^2} |\langle f|\, e\mathbf{r}\, |i\rangle|^2$$

For fine-structure levels,

$$\frac{1}{\tau_{JJ'}} = \frac{\omega_0^3}{3\pi\epsilon_0\hbar c^3} \frac{|\langle nJ|\,|e\mathbf{r}|\,|n'J'\rangle|^2}{2J+1} = A_{JJ'}$$

For hyperfine-structure levels,

$$A_{FF'} = (2F'+1)(2J+1) \begin{Bmatrix} J & F & I \\ F' & J' & 1 \end{Bmatrix}^2 A_{JJ'}.$$

$\Longrightarrow$ **Knowing $\tau_{JJ'}$ is enough to deduce $\tau_{FF'}$**

Theory: Zeeman effect

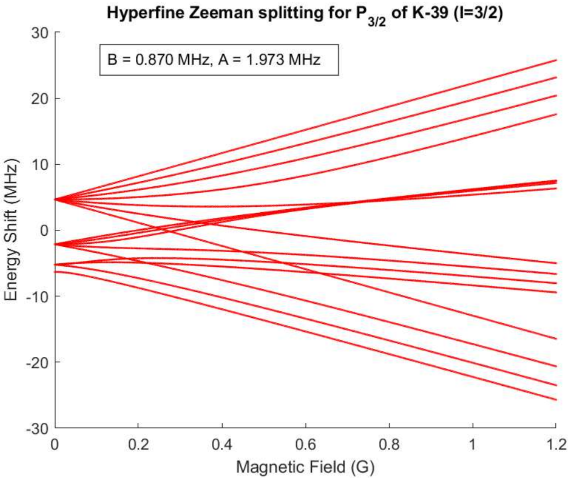
External magnetic fields make hyperfine sublevels nondegenerate.

$$H_B = \frac{\mu_B g_J}{\hbar}(\mathbf{J} + \mathbf{I}) \cdot \mathbf{B},$$

In the electric quadrupole approximation,

$$H_{\text{hfs}} = A_{\text{hfs}} \mathbf{I} \cdot \mathbf{J} + B_{\text{hfs}} \frac{3(\mathbf{I} \cdot \mathbf{J})^2 + \frac{3}{2}\mathbf{I} \cdot \mathbf{J} - \mathbf{I}^2 \cdot \mathbf{J}^2}{2I(2I-1)J(J-1)} + \frac{\mu_B}{\hbar}(g_J m_J + g_I m_I)B$$

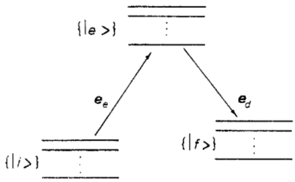
Theory: Zeeman effect

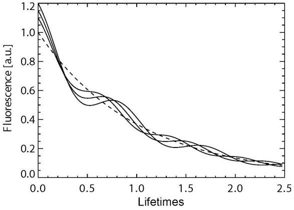


Theory: Quantum beats

"Interference" due to hyperfine sublevels.

$$|\psi(t)\rangle = c_i\,|i\rangle\,e^{-i\omega_i t} + c_f\,|f\rangle\,e^{-i\omega_f t} + c_e\,|e\rangle\,e^{-i\omega_e t}$$





The detector sees

$$|E|^2 = A + B\exp\left[i(\omega_e - \omega_f)t\right] + c.c.$$

$\Longrightarrow$ **Difficult to extract lifetimes when quantum beats are present**

Theory: Quantum beats

Quantum beats don't always occur.

From angular momentum algebra:

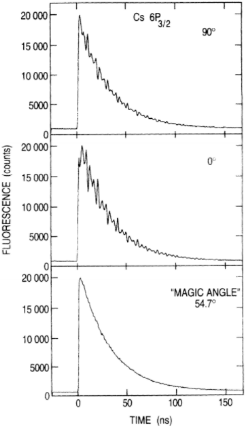
- Quantum beats in the $P_{1/2}$ decay: **NO**
  $\implies$ $\tau_{5p_{1/2}}$ is easier to measure

- Quantum beats in the $P_{3/2}$ decay: **YES**
  $\implies$ $\tau_{5p_{3/2}}$ is difficult to measure

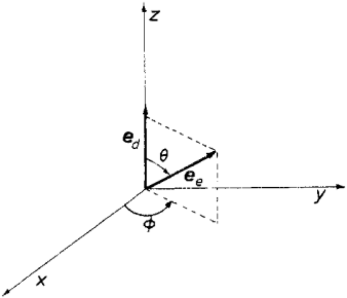
Theory: Quantum beats

In some cases, quantum beats can be eliminated.

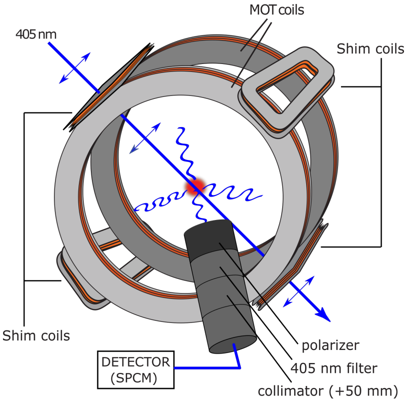
$\implies$ The **magic angle** solution: $\theta_m = \arccos\left(1/\sqrt{3}\right) \approx 54.7^\circ$

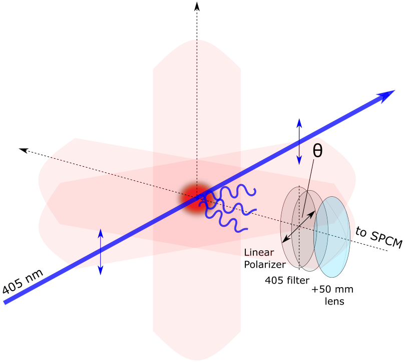


(a) Young et al. PRA 1994



Experiment

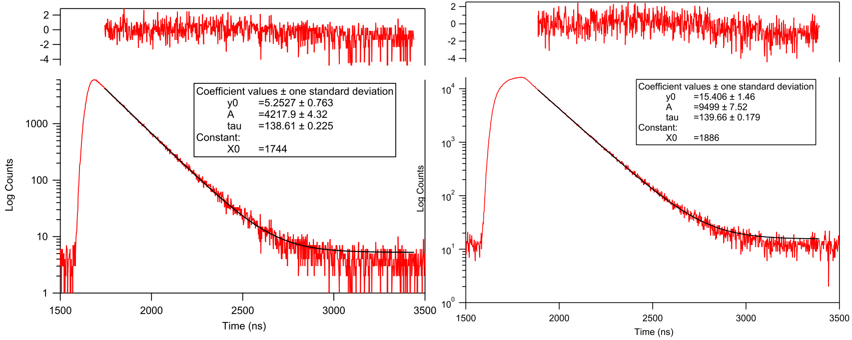




The cloud is imaged onto an optical fiber tip.
The SPCM (Hamamatsu) as QE $\sim 30\%$ at 405 nm.

Data: $5P_{1/2}$

Nice, beatless, exponential decay since $J = 1/2$

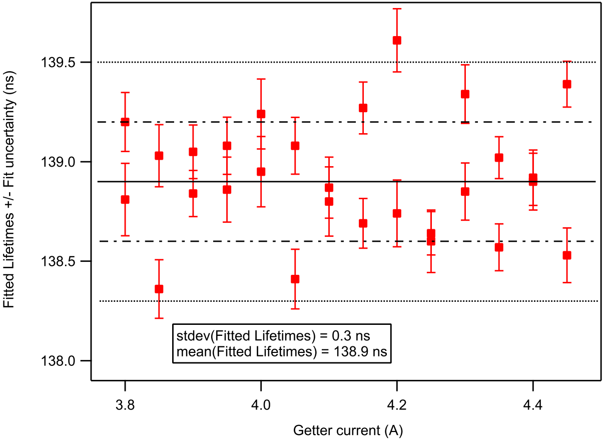


Data: $5P_{1/2}$: Error budget

Source of error	Value (ns)
Timing uncertainty & Nonlinearity	$\pm$ 0.1%
Truncation uncertainty + pulse pile-up	$\pm$ 0.4%
Radiation trapping/rescattering	$\pm$ 0.2%
Other statistical errors	$\pm$ 0.2%
Result	**138.9 $\pm$ 1.6**
Prioir result (Mills et al. (2005))	**137.6 $\pm$ 1.3**

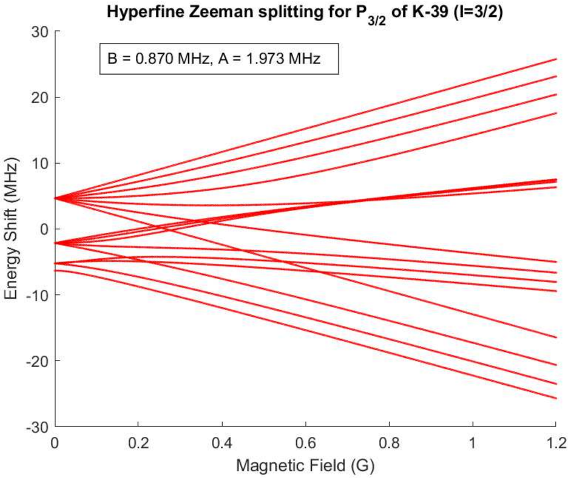
Data: $5P_{1/2}$: Radiation trapping test

Changing the getter current changes the density of the MOT.



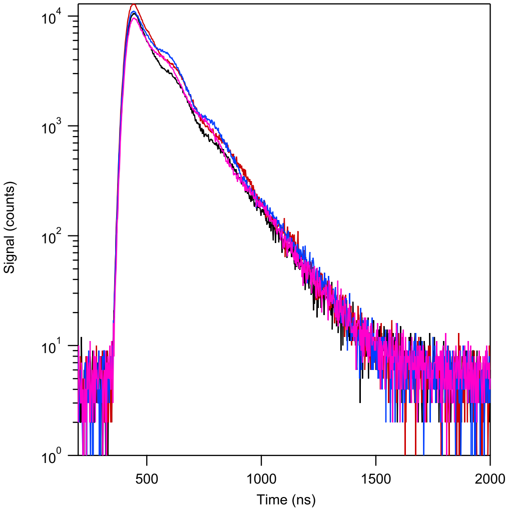
Data: $5P_{3/2}$

The MOT requires a magnetic field gradient ($dB/dr \approx 1$ G/mm) $\implies$ Zeeman effects present.



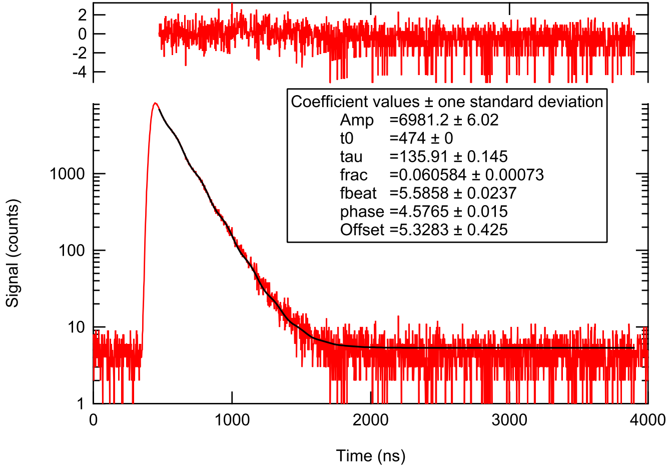
Data: $5P_{3/2}$

Quantum beats observed.



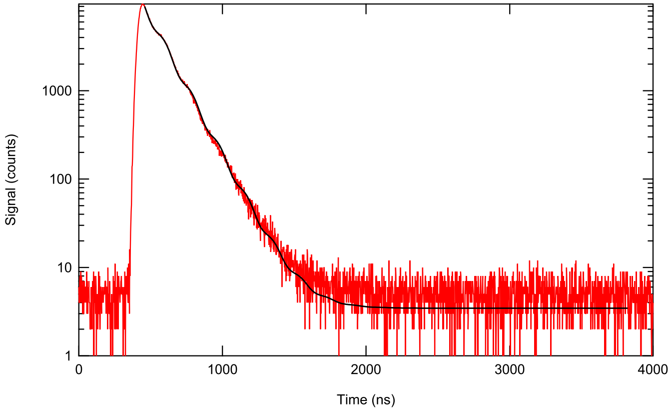
Data: $5P_{3/2}$

The **magic angle** trick does not eliminate beats due to Zeeman effects
$\Longrightarrow$ must null magnetic fields. This is easier said than done!



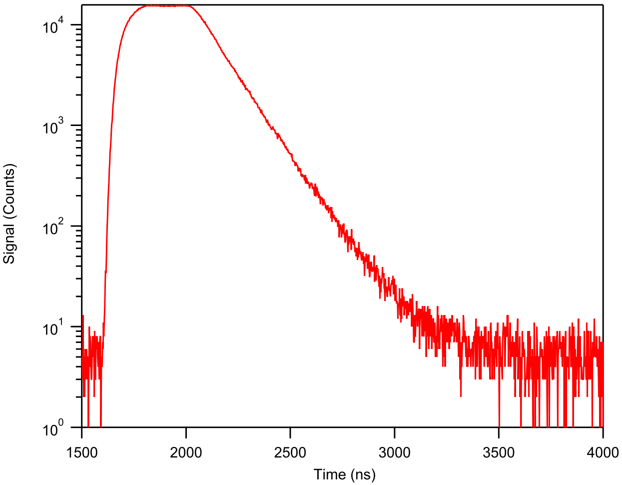
Data: $5P_{3/2}$

Exciting different parts of the MOT cloud gives different beat amplitudes.



$5P_{3/2}$: Alternative approaches

Using a long pulse $\implies$ removes coherence.



$5P_{3/2}$: Alternative approaches

- Hanle effect (fairly involved)
- Level-crossing (sweeping the magnetic field)
- Work with a vapor cell (many pros and cons)
  - Pros: no B gradient & nulling B is possible
  - Cons: large Doppler width, atomic motion, large radiation trapping