Direct probe of spin polarization in potassium for β-decay

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Introduction

TRIUMF's **N**eutral **A**tom **T**rap (TRINAT) investigates β decay asymmetries in highly spin polarized potassium isotopes. At the moment we are using the fluorescence of the trapped atoms to accurately measure their spin polarization [B. Fenker et al. Phys Rev Lett 120 062502 (2018) Supp Mat]. While sufficient this technique is indirect and relies on a complicated model to produce results. We are currently developing an alternative technique that directly probes the groundstate sublevel populations of the $4s_{1/2} \to 5p_{1/2}$ transitions.

Theory of Operation

Our probe exploits the Zeeman splitting of hyperfine energy levels in the presence of an external magnetic field (B_{ext}). Assuming a weak field ($B_{\text{ext}} < 10$ G) the splitting for a π-light excited hyperfine transition from $F \to F'$ is given by [H. Metcalf et al. Springer 1999]:

$$\Delta E^{F\to F'}_{\text{Zeeman}} = (g_{F'} - g_F) m_F \mu_B B_{\text{ext}} \tag{1}$$

The $4s_{1/2} \to 5p_{1/2}$ transition is advantageous since its linewidth of 1.1 MHz means that individual hyperfine transitions can be resolved when applying a small field of approximately 2 G. By sweeping the laser across the $F = 1$ and $F = 2$ groundstates and counting the number of photoions produced we can determine the normalized groundstate populations (p_{F,m_F}) and hence determine the nuclear polarization:

$$P = \frac{1}{I}\left[\frac{5}{4}\sum_{m_F=-1}^{1} m_F p_{1,m_F} + \frac{3}{4}\sum_{m_F=-2}^{2} m_F p_{2,m_F}\right] \tag{2}$$

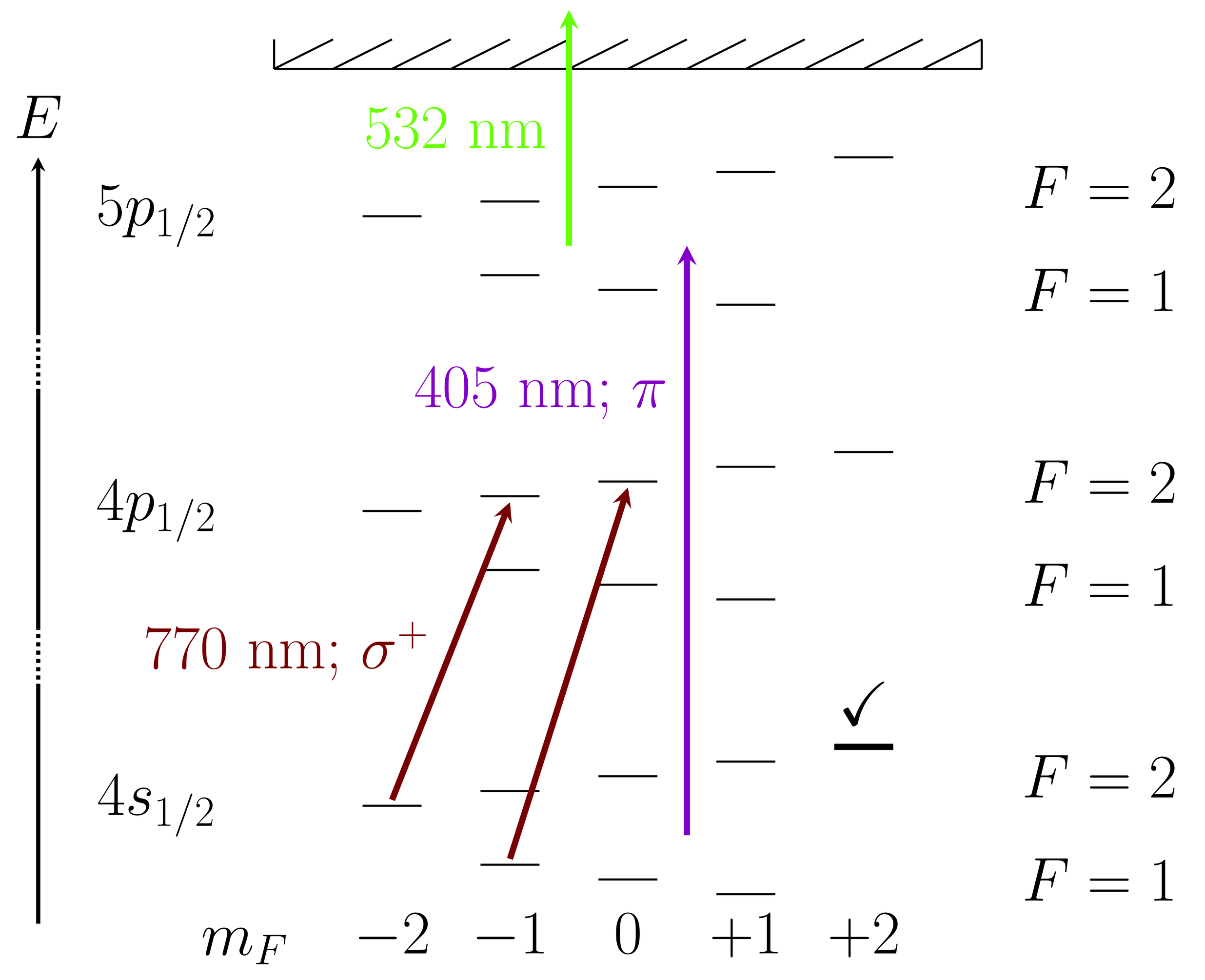

Fig. 1: Optical pumping light (770 nm) is σ^+ ($\Delta m_F = +1$) polarized meaning that excited atoms will shift one hyperfine level to the right. Excited atoms randomly decay into either $F = 1$ or $F = 2$ with random $\Delta m_F = 0, \pm 1$. Over time the OP light will 'push' atoms into the right most hyperfine state $m_F = +2$. Note that for the opposite polarization σ^- ($\Delta m_F = -1$) the atoms will 'move' to $m_F = -2$. Atoms excited by the probe laser (405 nm) decay with the same mechanism, changing hyperfine populations and unfortunately perturbing the nuclear polarization. The 532 nm laser is used to test for the presence of atoms in $5p_{1/2}$.

Experimental Setup

At TRINAT atoms are first collected from the ISAC-1 beamline using a DC-MOT and then pushed over into a RAC-MOT (**R**ectified **AC**). The main feature of the RAC-MOT is that we can quickly switch from an oscillating field to a static field to allow for optical pumping of the atoms. The atoms are optically pumped along the $F = 1 \to 2'$ and $F = 2 \to 2'$ $4s_{1/2} \to 4p_{1/2}$ using the sidebands of a 770 nm laser with either σ^+ ($\Delta m_F = +1$) or σ^- ($\Delta m_F = -1$) polarization. To produce these sidebands we have been applying an RF signal on the laser diode. While functional, this method of generating the sidebands produces a more complicated locking signal which makes it harder to (a) lock the laser and (b) decreases the stability of the lock. We have recently switched to using a fiber coupled EOM (**E**lectro-**O**ptic **M**odulator) for constructing the sidebands which allows for easier tuning of sideband locations as well as greatly improved lock stability.

Probe Setup

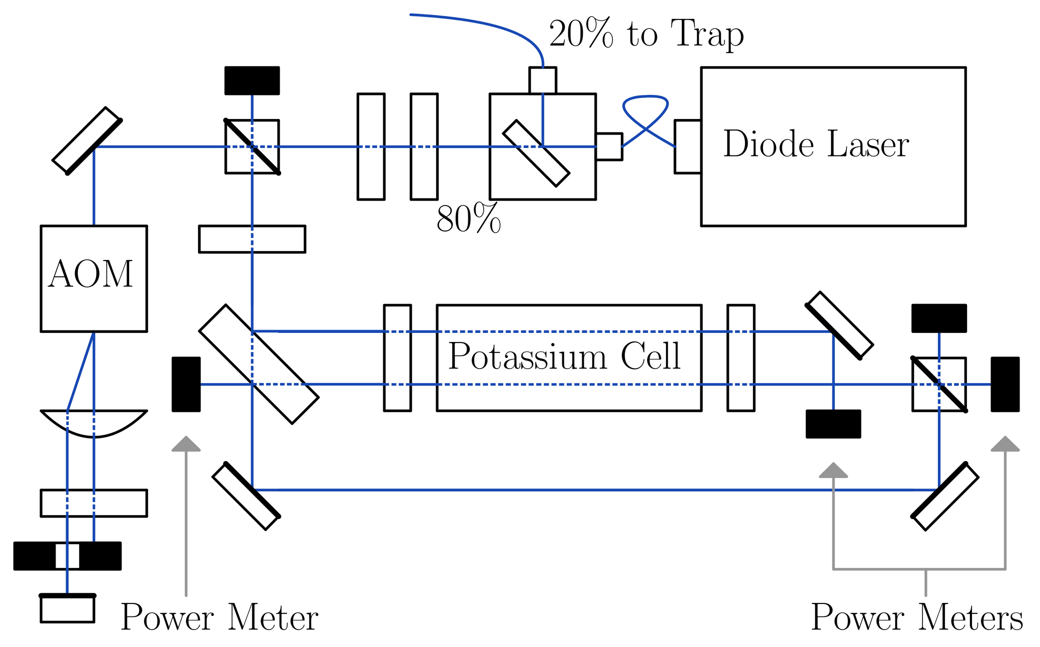

Fig. 2: Schematic of doppler free saturation absorption spectroscopy setup used to lock the 405 nm laser. The two power meters on the right are used to subtract the doppler broadened gaussian from the saturated signal. Instead of dithering the AOM or the laser we Zeeman dither the potassium cell using a coil around it (not shown here).

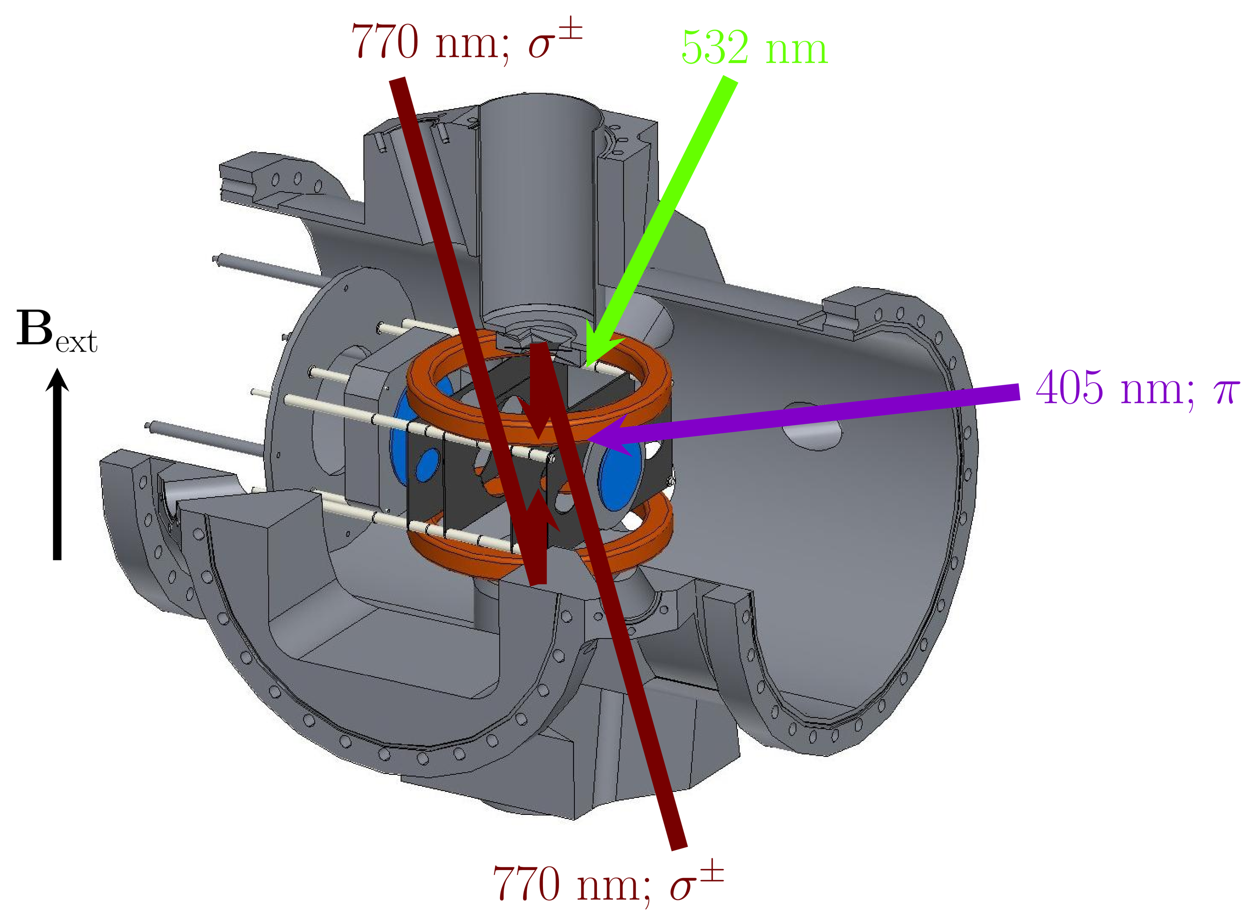

Fig. 3: Laser beams inside the MOT chamber. The optical pumping light enters the trap at an angle and is aligned by two very thin pellicle mirrors (70 nm Au on 4 μm capton). Note that the probe light enters the trap from the side in order to preserve the π-polarization with respect to the quantization axis formed by the optical pumping light beams.

^{41}K Probe Results

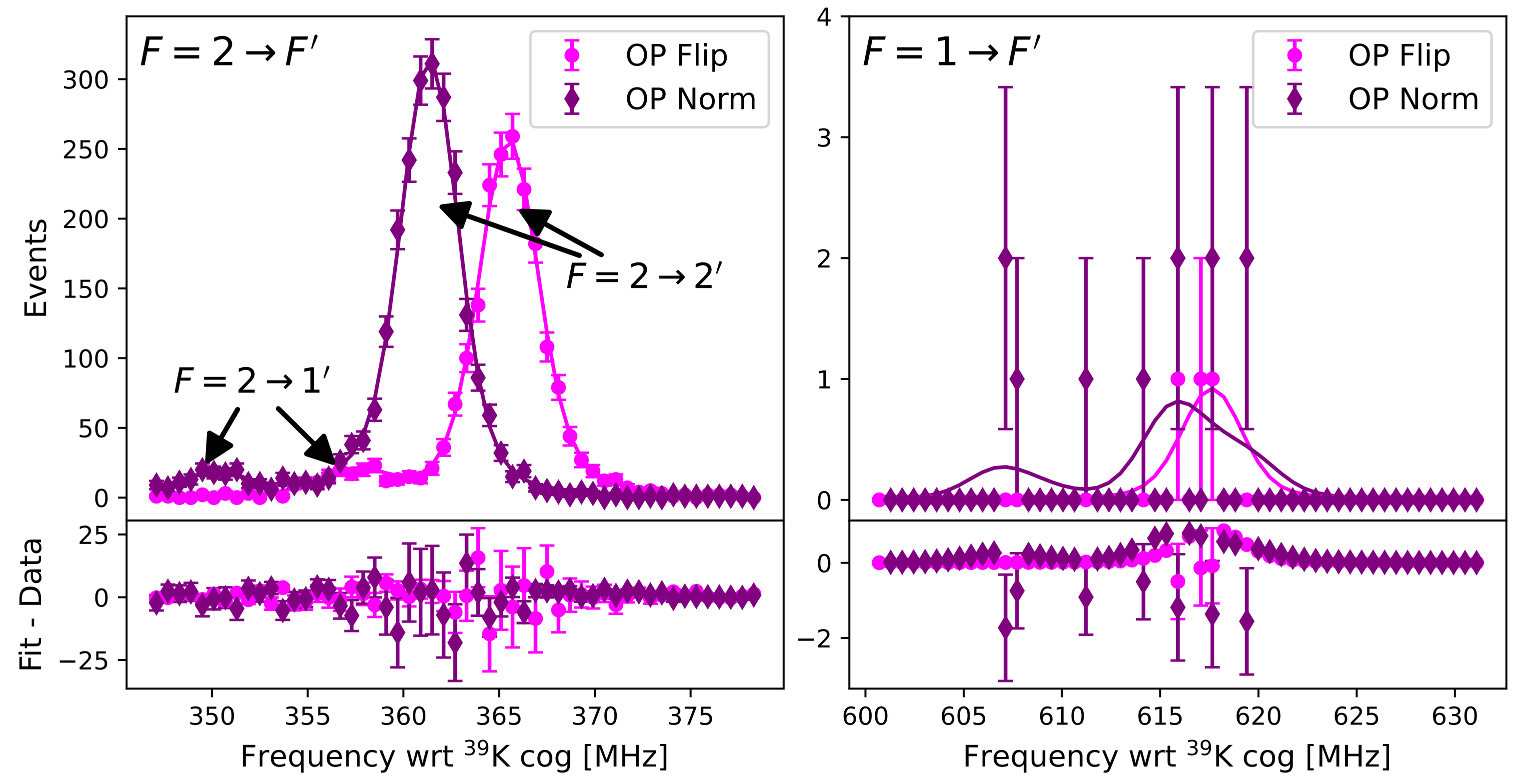

Fig. 4: Spectrum of transition populations of the $F = 1$ and $F = 2$ groundstates. Note that hyperfine structure is clearly observed with clear differentiation between $F = 2 \to 1'$ and $F = 2 \to 2'$ transitions. Centroid between the two $2'$ peaks is 363.4(1.0) MHz which is close to the literature value of 363.61(48) MHz with respect to (wrt) the center of gravity (cog) of ^{39}K. Nearly all of the atoms are in the $F = 2$ groundstate and excited along the $F = 2 \to 2'$ transition, showing that our optical pumping scheme works correctly.

We are able to measure the hyperfine populations of the $F = 1$ and $F = 2$ groundstates of the $4s_{1/2} \to 5p_{1/2}$ transition. For the spectra in Figure 4 we measured the nuclear polarization to be:

$$P_{\text{norm}} = -0.900(52) \quad P_{\text{flip}} = 0.903(57)$$

Note that the polarization error does not take the uncertainty of the locking point into account and should really be seen as a lower bound.

Problems and Planned Improvements

There are a number of open issues of within our analysis and our setup at the moment:

- Large relative uncertainty in nuclear polarization
- Fitting a model to $F = 1$ populations is not very robust due to low counts
- The $F \to 1'$ peaks of the two polarizations should be separated by the same frequency or less than the $F \to 2'$ peaks however we are seeing about twice the separation at the moment (≈ 8 MHz) compared to the expected Zeeman shift (≈ 4 MHz)
- Probe laser is significantly perturbing the polarization of the atoms

We have some ideas for tackling some of the issues described above:

- Shutter for probe laser to try and limit perturbing of polarization during the main optical pumping period
- Increase power through optical pumping setup to 'fight' probe laser
- Work on improving **B** field during the optical pumping cycle
  - Improve consistency
  - Reduce polarization spoiling eddy currents in metal vacuum enclosure

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