Measurement of the nuclear polarization in optically-pumped ^{37}K: Progress towards a measurement of the β-asymmetry parameter

Benjamin Fenker

Texas A&M University Cyclotron Institute
TRIUMF Neutral Atom Trap

Symmetries in Subatomic Physics
Victoria, BC

June 8 2015

Acknowledgments

The TRINAT Collaboration

- TRIUMF - John Behr, Alexandre Gorelov, Konstantin Olchanski, Ioana Craiciu, Claire Warner, Claire Preston
- Texas A & M - Spencer Behling, Michael Mehlman, Dan Melconian, Praveen Shidling, Eames Bennett
- U of Manitoba - Melissa Anholm, Gerald Gwinner
- Tel Aviv - Daniel Ashery, Iuliana Cohen

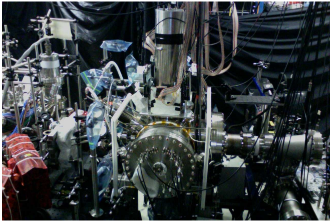
TRIUMF & ISAC Target & Beam Delivery Group

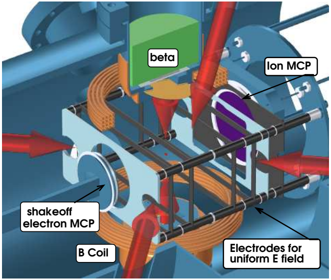
Funding Agencies

- USA: DOE DE-FG02-93ER40773 & Early Career ER41747
- Canada: NSERC, NRC through TRIUMF, WestGrid
- Israel: Israel Science Foundation

Outline

- Motivation - Testing the SM with nuclear physics
- TRINAT - TRIUMF's Neutral Atom Trap
- Polarization through optical pumping
- Systematics in the polarization measurement
- Outlook and future plans





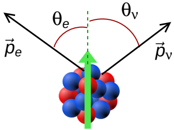
Motivation: Fundamental Symmetries

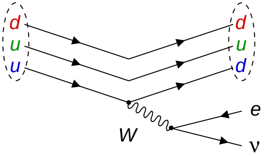
- Search for possible right-handed currents
  - $SU(2)_L \otimes U(1)_Y \xrightarrow{?} SU(2)_R \otimes SU(2)_L \otimes U(1)_Y$
- Contribute to independent check on the value of V_{ud}
- Energy dependence tests recoil-order corrections, weak magnetism, second-class currents

Angular correlations in β-decay are sensitive to new physics

- 10^{-3} precision constrains SM extensions, while 10^{-4} has discovery potential

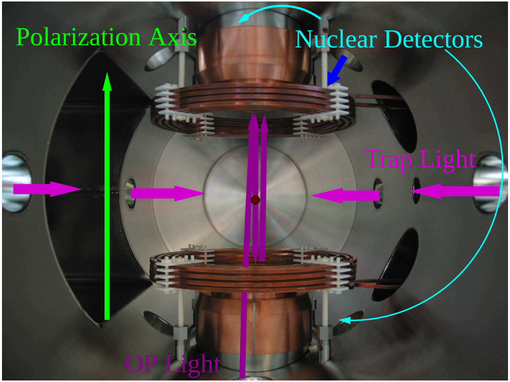
$$\frac{d^5W}{dEd\Omega_e d\Omega_\nu} \sim 1 + a_{\beta\nu}\frac{p_e p_\nu \cos(\theta_{e\nu})}{E_e E_\nu} + b\frac{m_e}{E_e} + P\left(A_\beta \frac{p_e}{E_e}\cos(\theta_e) + B_\nu \frac{p_\nu}{E_\nu}\cos(\theta_\nu)\right) + \ldots$$

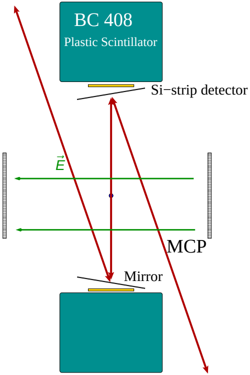




Overview

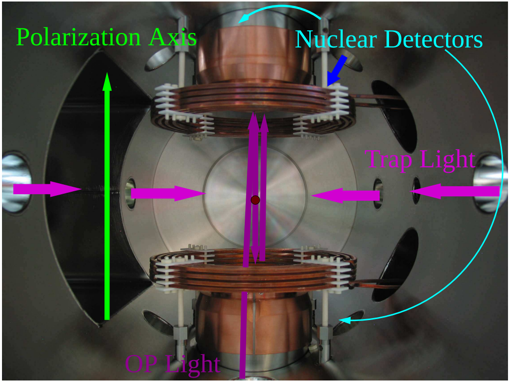
- Magneto-Optical Trap (MOT)
  - Provides a cold ($\sim 1\,\mathrm{mK}$), localized ($\sim \varnothing 1\,\mathrm{mm}$) source of atoms
  - Shallow trap so products emerge unperturbed

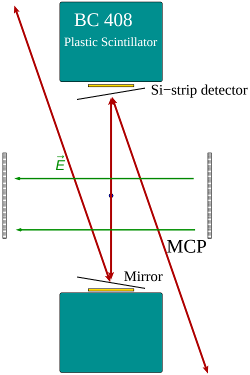




Overview

- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
  - $\sigma^{\pm}$ lasers drive biased random walk towards $P_{\mathrm{nucl}} = \pm 1$





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- Magneto-Optical Trap (MOT)
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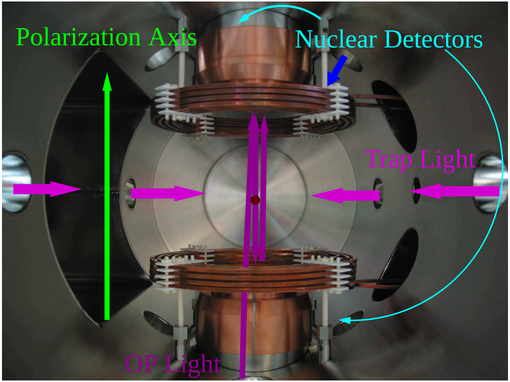
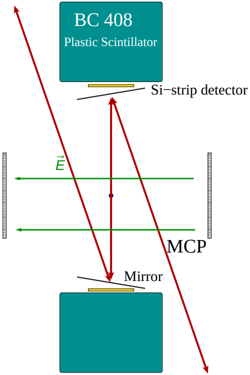
- Nuclear Detectors
  - β-telescopes measure position, energy along polarization axis





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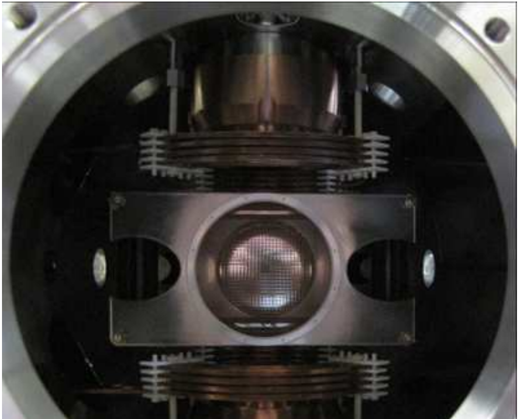
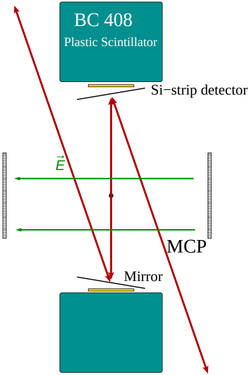
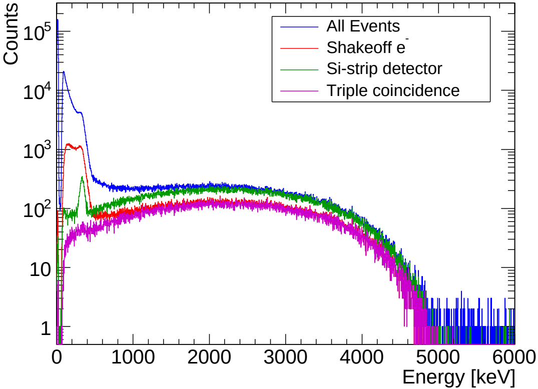
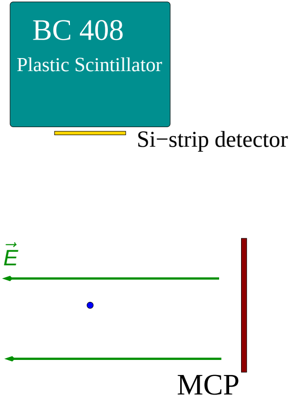




β-detection

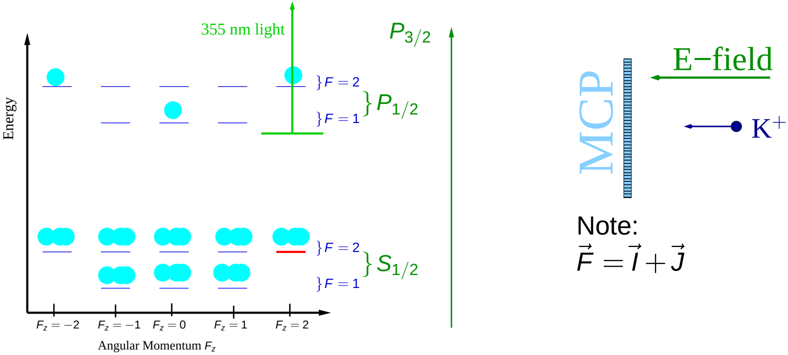
- Scintillators record full energy; backgrounds from untrapped atoms, annihilation
- Shake-off electron MCP tags events that decay from the trap
- Silicon ΔE detectors suppress background from γs
- Collected statistics for 0.2% measurement of A_{obs}





Optical Pumping

- Stretched state has $F = 2$, $M_F = 2$ or equivalently $I_z = \frac{3}{2}$, $J_z = \frac{1}{2}$
- Zeeman sublevels feel $B_z = 2\,\text{G}$ along quantization axis
- Stretched state corresponds to atomic and nuclear polarization
- Photoionization is a monitor of excited state population
- Use this to monitor trap size, position, temperature, polarization



Note:
$\vec{F} = \vec{I} + \vec{J}$

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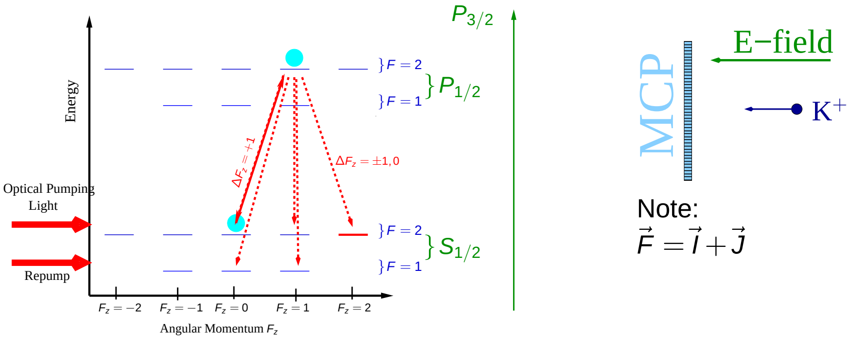

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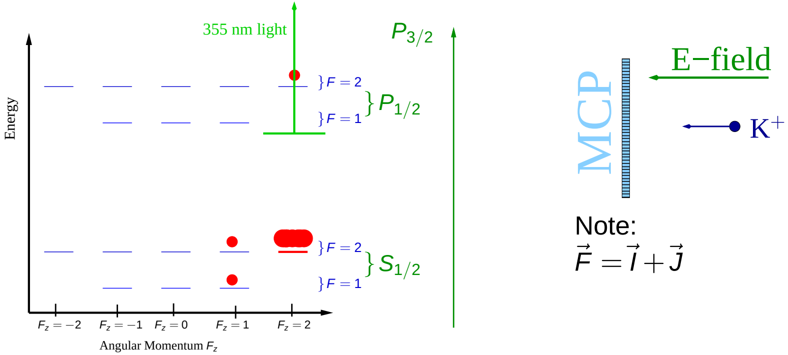

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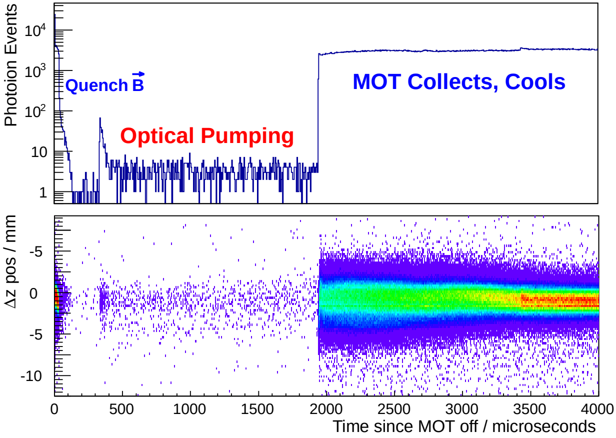
$\vec{F} = \vec{I} + \vec{J}$

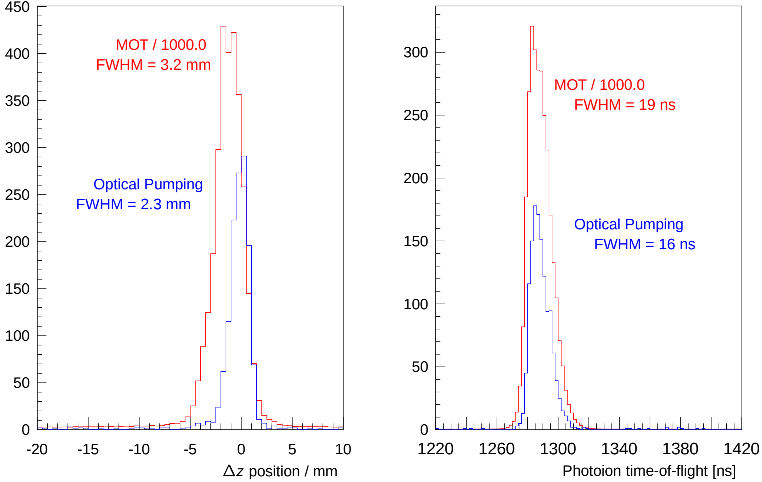
Photoions monitor trap parameters

- Polarized measurements must be done with MOT off
- With MOT off, cloud expands; alternate counting/trapping



Photoionization signal

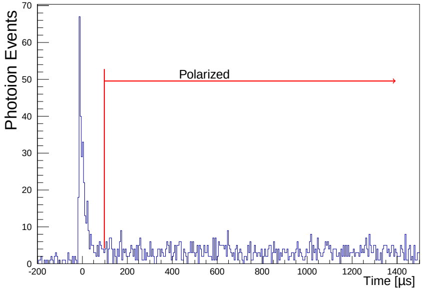
With time-of-flight *and* position cuts, this signal is very clean



Polarization Signal

This strong signal allows clean measurement of polarization

- Initial peak proportional to number of atoms, laser power, provides normalization
- Tail region provides information about the degree of polarization



- Directly measure non-stretched population, *but*
- Polarization depends on how this small population is distributed amongst sublevels
- Small tail measures *deviation from unity*

Polarization Signal

Polarization Model

$$\mathscr{H} = \underbrace{\underbrace{H_0}_{\text{Coulomb}} + \underbrace{H_{so}}_{\text{Spin-Orbit}} + \underbrace{H_{hf}}_{\text{Hyperfine}} + \underbrace{H_B}_{\text{Magnetic Field}}}_{\text{Atomic Hamiltonian}} \underbrace{- e\vec{d}\cdot\vec{E}(t)}_{\text{Laser Term}}$$

$$H_{SO} = \vec{L}\cdot\vec{S}$$
$$H_{hf} = \vec{I}\cdot(\vec{L}+\vec{S})$$
$$\vec{E}(t) = E_0 \cos(kz - \omega_L t)\hat{\varepsilon}_q$$

$$H_B = -\vec{\mu}\cdot\vec{B} = -g_F \mu_B \vec{B}\cdot(\vec{I}+\vec{L}+\vec{S})$$

$$\langle P \rangle = Tr(\hat{\rho}\hat{P}) = Tr(\hat{\rho}\hat{I}_z) \qquad \langle T \rangle \sim Tr(\hat{\rho}\hat{I}_z^2)$$

Density Matrix:

ρ_{ii} - population of state i

ρ_{ij} - correlation between i, j

Time evolution:

$$\frac{d\hat{\rho}}{dt} = \frac{1}{i\hbar}[\mathscr{H}(t), \hat{\rho}] + R(t)$$

Tremblay, P. and Jacques C. PRA **41**(9), 4989 (1990)

Renzoni, F. *et al.* PRA **63**(6), 065401 (2001)

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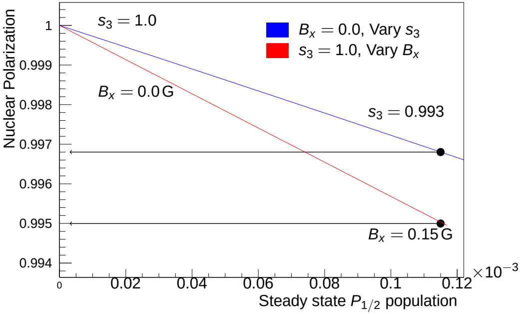
Systematics in the polarization measurement

- Photoionization signal is an indirect measure of the polarization
- Light ellipticity and a transverse magnetic field affect the photoionization curve similarly but result in different polarization



- Off-line studies: $B_x \leq 66\,\text{mG}$
- Stokes parameter:

$$\langle s_3 \rangle = \frac{I_+ - I_-}{I_+ + I_-}$$
$$\geq +0.9893$$
$$\leq -0.9983$$

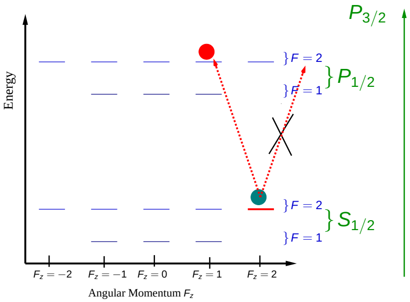
- CPT "dark" states are minimized

Depolarizing mechanisms - Stokes Parameter s_3

- s_3 characterizes the degree of circular polarization
- s_0 is equivalent to the total power contained in the beam

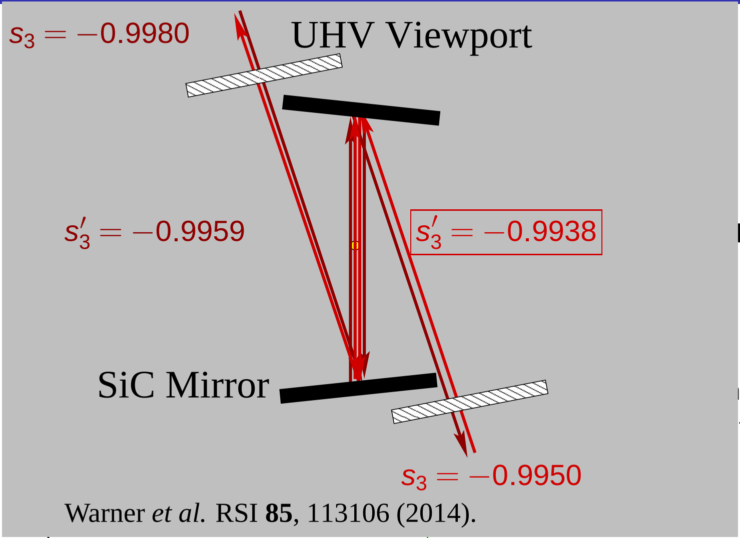
$$\frac{s_3}{s_0} = \frac{I_+ - I_-}{I_+ + I_-}$$

- If $|s_3|/s_0 < 1.0$, atoms can be pumped out of the stretched state



Equilibrium is reached with not all atoms in the fully stretched state

Depolarizing mechanisms - Stokes Parameter s_3



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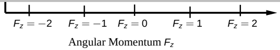
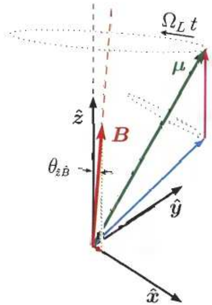


Depolarizing mechanisms - Transverse magnetic field

- Magnetic field perpendicular to polarization axis causes precession



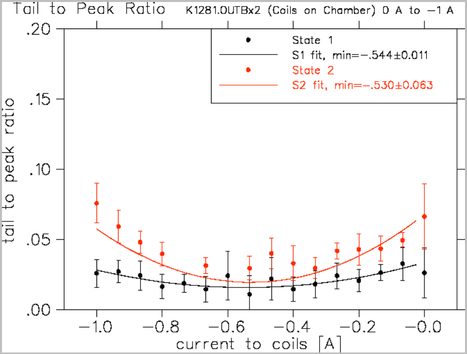
Atoms in the stretched state precess to other ground states

$$\vec{B} = B_x\hat{x} + B_z\hat{z}$$
$$H_{\vec{B}} = -\vec{\mu}\cdot\vec{B}$$
$$H_{B_x} = g_F\mu_B B_x F_x = g_F\mu_B B_x \frac{F_+ + F_-}{2}$$

Depolarizing mechanisms - Transverse magnetic field

Trim coils minimize transverse magnetic field

Scan current and minimize optical pumping tail to find I_{ideal}

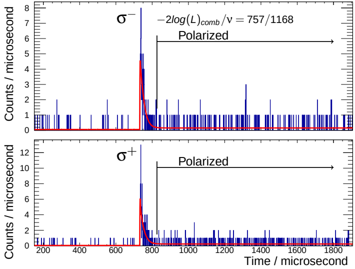


ess to

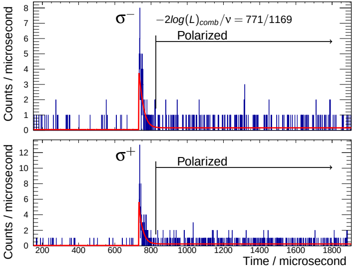
- Compare I_{ideal} and I_{actual}, find $B_x = 33\,\text{mG}$.
- Conservatively assign 100% uncertainty $\rightarrow$ $B_x \leq 66\,\text{mG}$

Preliminary Results

- Depolarizing mechanisms are almost 100% correlated
- Perform separate fits with either s_3 or $B_\perp$ fixed



$B_x = 66\,\mathrm{mG}$



$B_x = 4(36)\,\mathrm{mG}$

$I(\sigma^-) = 2.2(3)\,\mathrm{W\,m^{-2}}$
$s_3(\sigma^-) = -0.9967(9)$
$P = -0.994(1)_{stat}$

$I(\sigma^+) = 2.1(2)\,\mathrm{W\,m^{-2}}$
$s_3(\sigma^+) = +0.9915(16)$
$P = +0.990(2)_{stat}$

$I(\sigma^-) = 2.0(2)\,\mathrm{W\,m^{-2}}$
$s_3(\sigma^-) = -0.9938$
$P = -0.9916(4)_{stat}$

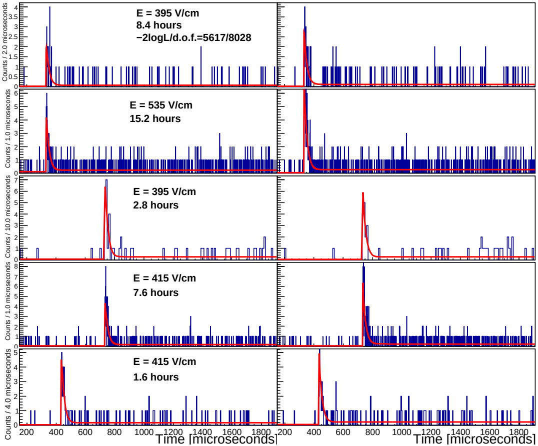
$I(\sigma^+) = 2.0(2)\,\mathrm{W\,m^{-2}}$
$s_3(\sigma^+) = +0.9893$
$P = +0.9890(3)_{stat}$

Preliminary Results - Global Fit

Vary delay-time after AC-MOT

Fit with common s_3 and B_x

σ^- σ^+



Preliminary Results

Uncertainties / 10^{-4}				
	σ^{+}		σ^{-}	
	Polarization	Alignment	Polarization	Alignment
Depolarizing Mechanism	8	15	4	5
Global Fit vs. Average	1	3	1	2
Fit Δ vs. Fit I	3	6	3	6
Uncertainty in B_z	1	3	1	1
Binning	2	3	2	5
Initial Alignment ($T_0 = -1$)	**18**	**42**	**15**	**36**
Hyperfine Pumping	1	2	1	3
Sum Systematics	**20**	**45**	**16**	**37**
Statistics	**6**	**16**	**8**	**19**
Uncertainty	**22**	**48**	**18**	**42**
Central Value	**0.9898**	**-0.9761**	**-0.9920**	**-0.9808**

$$\bar{P} = \frac{\langle M_I \rangle}{I} = 0.991(2)$$

$$\bar{T} = \frac{I(I+1) - 3\langle M_I^2 \rangle}{I(2I-1)} = -0.978(5)$$

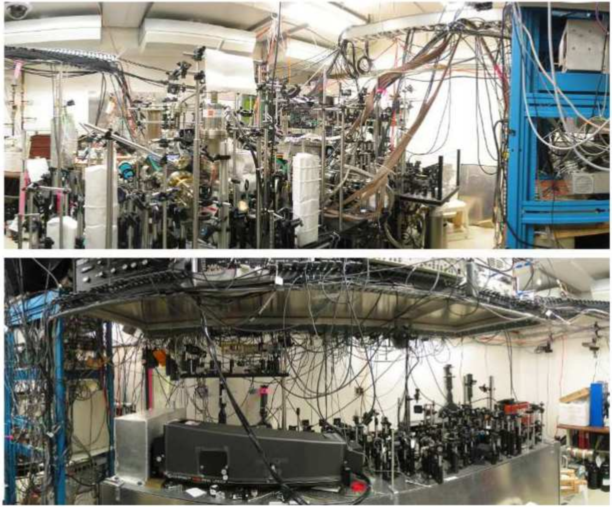
Conclusions

- Nuclear polarization gives access to more β-decay observables
- Optical pumping achieves high polarization in an open geometry $\rightarrow \bar{P} = 0.991 \pm 0.002$
  - Will not dominate the uncertainty for present data set
  - We expect $\frac{dA_\beta}{A_\beta} \leq 0.5\%$ ($A_\beta^{SM} = -0.5706(7)$)
- Future plans include modeling our MOT to reduce uncertainty from initial sublevel distribution
- Polarization measurement at 10^{-4} precision requires more systematic studies

	Uncertainty / 10^{-4}	
	2012	2014
Asymmetry (Stat.)	62	20
Polarization (Stat.)	**60**	**7**
Polarization (Systematics)	**56**	**18**
Detector Response	64	
Asymmetric Number of Trapped Atoms	25	
Trap Movement	18	
Timing Errors	9	
Mirror Thickness	2	

S. Behling "Measurement Of The Standard Model Beta Asymmetry Parameter, A_β, in ^{37}K" Ph. D Thesis. Texas A & M University, 2015.

THANK YOU



Backup slides . . .

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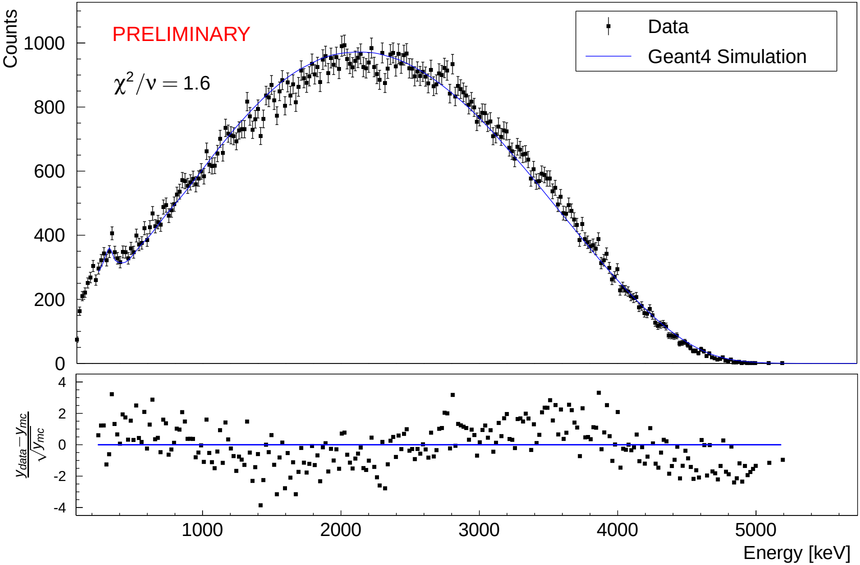
Comparison with Geant4



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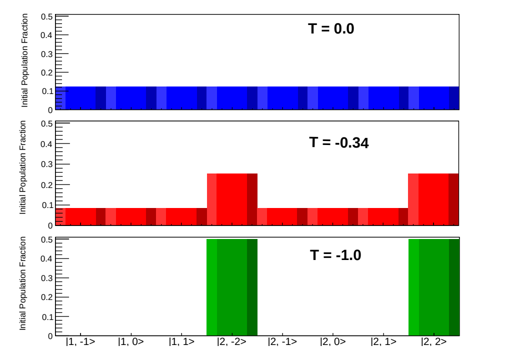
Preliminary Results

Future work: Initial sublevel distribution?

- Has little effect on equilibrium state but can affect the shape of the initial peak
- Polarization is limited by "unpolarized" β-asymmetry
- Alignment (T) unconstrained (for now)



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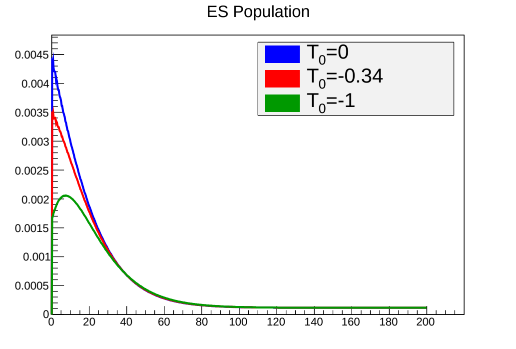

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Future work: Initial sublevel distribution?

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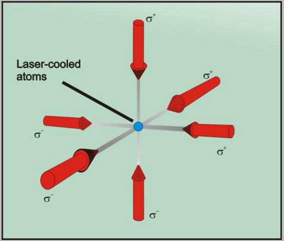
- Polarization is limited by “unpolarized” β-asymmetry
- Alignment (T) unconstrained (for now)
- Model MOT dynamics to limit initial alignment



- *Work in progress*

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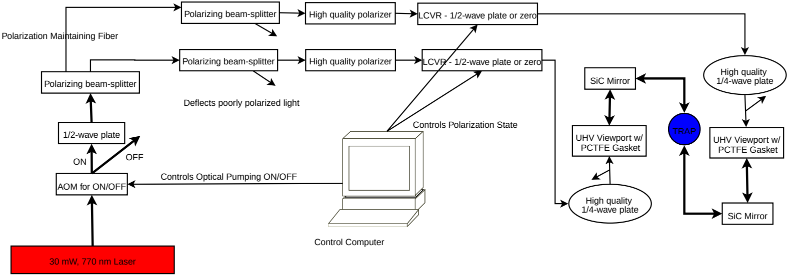
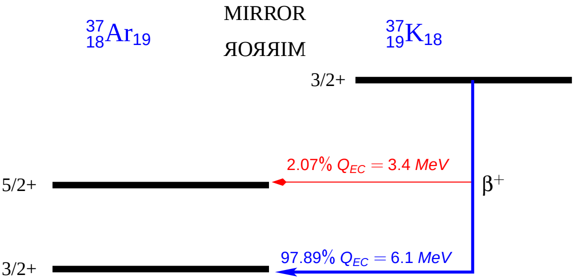
Optics Layout



Why ^{37}K?

- Atomic structure allows for laser-trapping *AND* optical pumping
- Isobaric analogue decay simplifies nuclear structure corrections
- Strong branch to ground state is a very clean decay
- $I^{\pi} = \frac{3}{2}^{+} \rightarrow \frac{3}{2}^{+}$ is a mixed Fermi-Gamow Teller decay

$\Delta t_{1/2} = 0.08\%$
(Shidling *et al.* 2014)
$\Delta BR = 0.14\%$
$\Delta Q_{EC} = 0.003\%$



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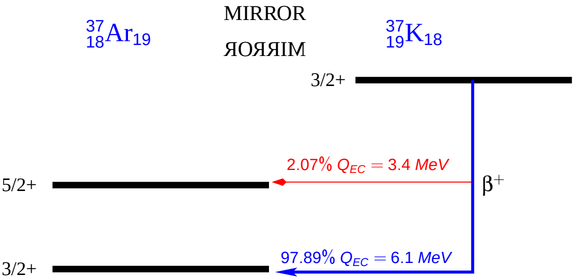
$\Delta \mathcal{F}t = 0.18\%$
$\Delta \rho = 0.4\%$



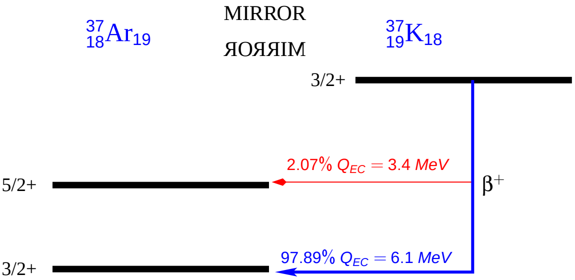
Why ^{37}K?

- Atomic structure allows for laser-trapping *AND* optical pumping
- Isobaric analogue decay simplifies nuclear structure corrections
- Strong branch to ground state is a very clean decay
- $I^{\pi} = \frac{3}{2}^{+} \rightarrow \frac{3}{2}^{+}$ is a mixed Fermi-Gamow Teller decay

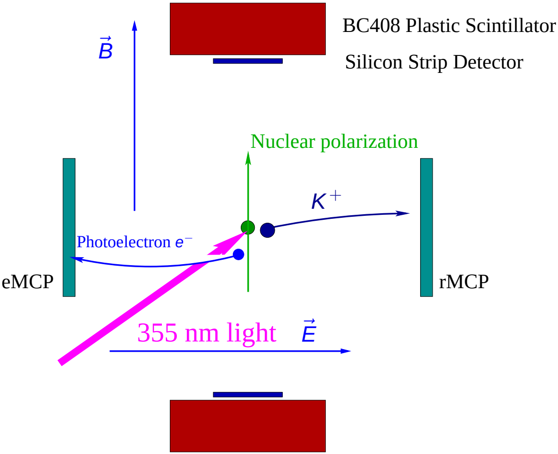
$\Delta t_{1/2} = 0.08\%$
(Shidling *et al.* 2014)
$\Delta BR = 0.14\%$
$\Delta Q_{EC} = 0.003\%$

$\Delta \mathcal{F}t = 0.18\%$
$\Delta \rho = 0.4\%$

$A_{\beta}(0) = -0.5706(7)$
$\rightarrow \Delta A_{\beta} = 0.12\%$

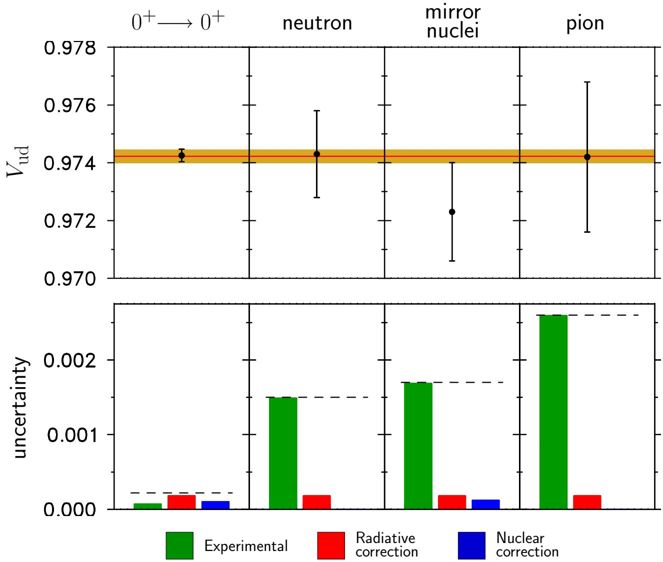


Photoionization Events



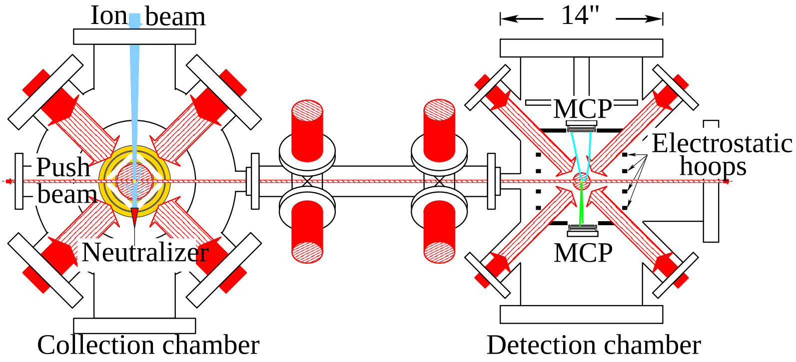
- Monitor of trap position, size, temperature
- Ultra-clean measure of nuclear polarization P

Measure V_{ud} with mirror nuclei



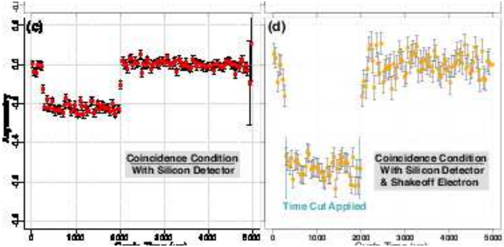
TRINAT's x2-MOT System

- Collection trap is coupled to TRIUMF-ISAC beam line
- Transfer atoms to second trap for precision measurement



Initial Polarization

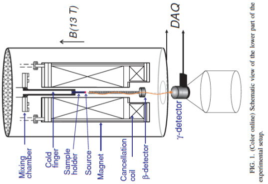
- Atoms can be polarized in a MOT if beams are unbalanced. We avoid this
- Use β-asymmetry of trapped *(unpolarized)* atoms to constrain initial polarization



S. Behling "Measurement Of The Standard Model Beta Asymmetry Parameter, A_β, in ^{37}K" Ph. D Thesis. Texas A & M University, 2015.

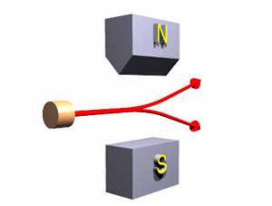
Correlation measurements with polarized nuclei

LTNO



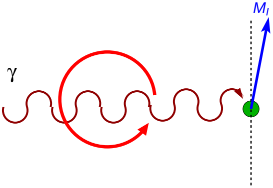
- Brute-force alignment of nuclear spin
- P calculated knowing the temperature
- Backscattering from source holder

Stern-Gerlach



- Physically separate polarized atoms
- Very high polarization, but inefficient

Optical Pumping



- State selection; very high P
- Open geometry minimizes backscattering
- Must measure polarization