Precise Measurement of the Positron Asymmetry in the Decay of Spin-polarized ^{37}K

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Texas A&M University Cyclotron Institute
TRIUMF Neutral Atom Trap
American Physical Society: Division of Nuclear Physics

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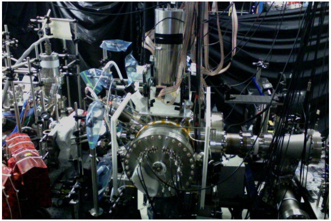
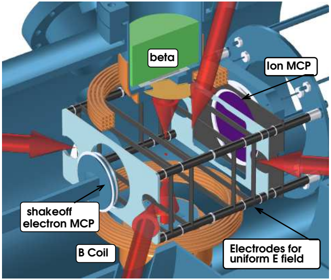
D. Melconian, J. A. Behr, M. Anholm, D. Ashery, R. S. Behling, I. Cohen, I. Craiciu, A. Gorelov, G. Gwinner, L. Lawrence, J. McNeil, M. Mehlman, K. Olchanski, C. Preston, P. Shidling, C. Warner

Outline

- Motivation - Testing the SM with nuclear physics
- TRINAT - TRIUMF's Neutral Atom Trap
    - Magneto-optical trapping
    - Polarization through optical pumping
    - β-detection
- Polarization measurement
- β-asymmetry results
- Interpretation





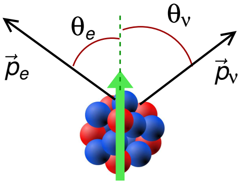
Motivation: Fundamental Symmetries

Angular correlations in β-decay are sensitive to new physics

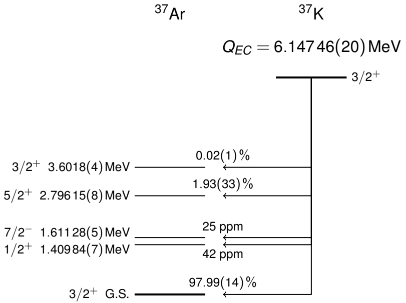
- 10^{-3} precision constrains SM extensions, while 10^{-4} has discovery potential V. Cirigliano *et al.* JHEP **02** (2013) 046

$$\frac{d^5W}{dE d\Omega_e d\Omega_\nu} = \frac{G_F^2}{(2\pi)^5} |V_{ud}|^2 p_E E_e (E_0 - E_e)^2 F(E_e, Z') \xi \left[1 + a_{\beta\nu} \frac{p_e p_\nu \cos(\theta_{e\nu})}{E_e E_\nu} + b \frac{m_e}{E_e} + P\left(A_\beta \frac{p_e}{E_e} \cos(\theta_e) + B_\nu \frac{p_\nu}{E_\nu} \cos(\theta_\nu) \right) + \ldots \right]$$

Isobaric analogue decay
Mixed Fermi/Gamow-Teller decay
$\rho = C_A M_{GT} / C_V M_F = 0.5768 \pm 0.0021$



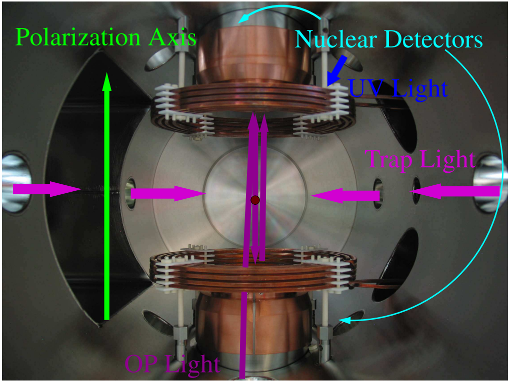
J. Jackson *et al.* PR **106** (1957) 517

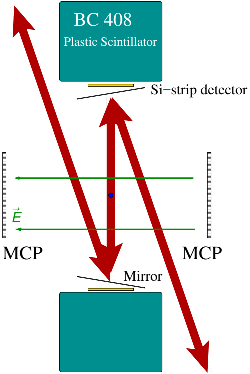


N. Severijns *et al.*, PRC **78**, 055501 (2008)
Nuclear Data Sheets **113**, 365 (2012)

Overview

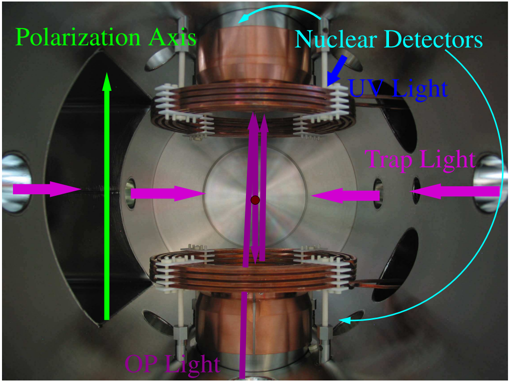
- Magneto-Optical Trap (MOT)
  - Provides a cold (3.8 mK), localized ($V = 2.3\,\text{mm}^3$) source of ^{37}K
  - Decay products are unperturbed by the trapping potential

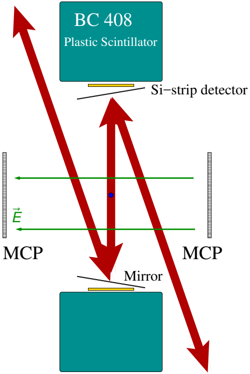




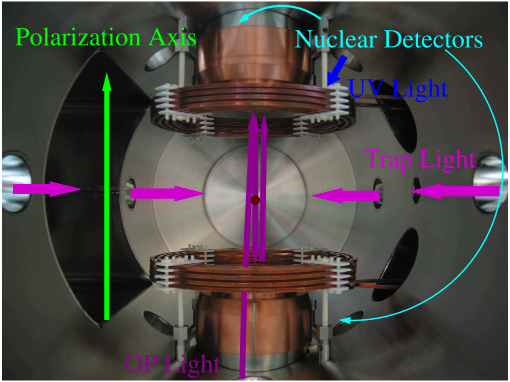
Overview

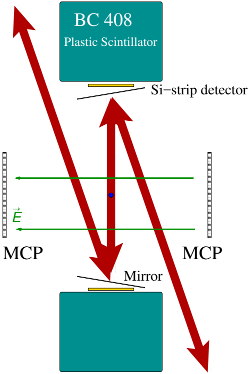
- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
  - $\sigma^{\pm}$ lasers drive biased random walk towards $P_{\mathrm{nucl}} = \pm 1$





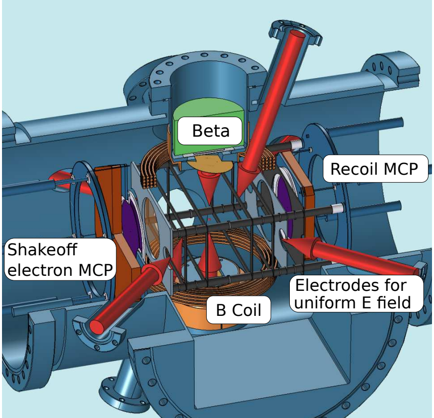
- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
- Nuclear Detectors
    - β-telescopes measure position, energy along polarization axis

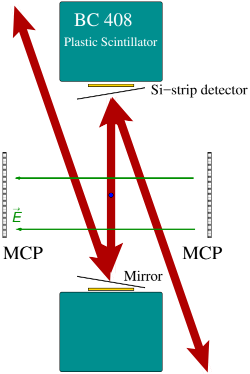




Overview

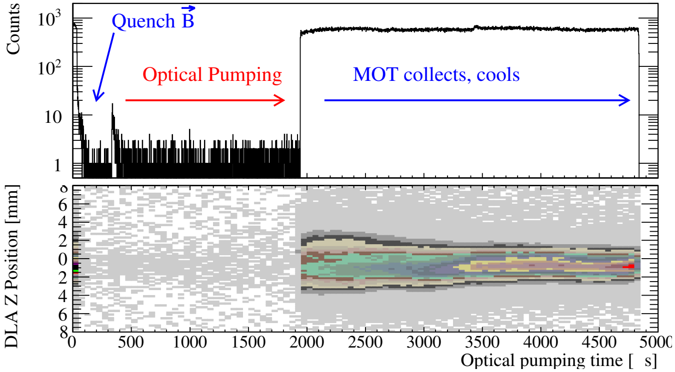
- Magneto-Optical Trap (MOT)
- Optical Pumping Polarizes the Atoms
- Nuclear Detectors
- Microchannel plate detectors
  - Detect low-energy charged products (e^-, $^{37}\mathrm{Ar}^+$, $^{37}\mathrm{K}^+$)





Photoions monitor trap parameters

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



Polarization Results

- Initial alignment models MOT distribution of atoms
- Results are 11$\times$ more precise than previous work
- Polarization uncertainty will not limit measurement

$$\langle |P| \rangle = 0.9913 \pm 0.0009$$

- Details presented last session by J. A. Behr

Source	ΔP [$\times 10^{-4}$] σ^-	σ^+
Systematics		
Initial alignment	3	3
Global fit vs. average	2	2
Uncertainty on s_3^{out}	1	2
Cloud temperature	2	0.5
Binning	1	1
Uncertainty in B_z	0.5	3
Initial polarization	0.1	0.1
Require $I_+ = I_-$	0.1	0.1
Total systematic	5	5
Statistics	7	6
Total uncertainty	9	8

^{67}Cu: LTNO, $T_\mu = 6\,\text{s}$ to $11\,\text{s}$

$t_{1/2} = 61.83\,\text{h}$

G. Soti *et al.* PRC **90**, 035502 (2014)

n (PERKEOII): $P = 0.997 \pm 0.001$

D. Mund *et al.* PRL **110**, 172502 (2013)

n (UCNA): $P = 0.993 \pm 0.003$

M. Mendenhall *et al.* PRC **87**, 032501(R) (2013)

- Nuclear alignment also:

$$\langle T \rangle = -0.9767 \pm 0.0025$$

Polarization Results

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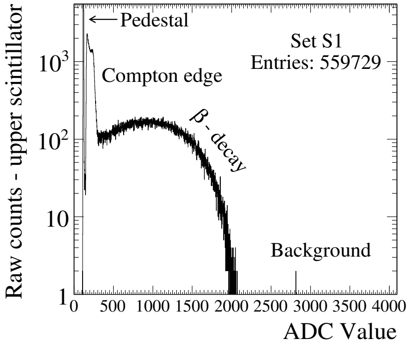
PAPER

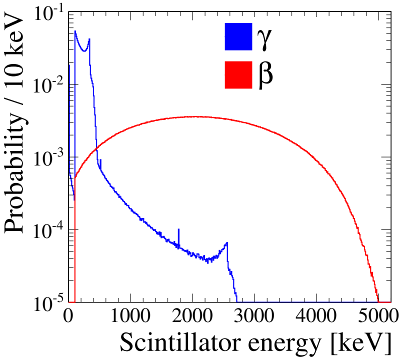
Precision measurement of the nuclear polarization in laser-cooled, optically pumped ^{37}K

B Fenker[1,2,7], J A Behr[3], D Melconian[1,2,7], R M A Anderson[3], M Anholm[3,4], D Ashery[5], R S Behling[1,6], I Cohen[5], I Craiciu[3], J M Donohue[3], C Farfan[3], D Friesen[3], A Gorelov[3], J McNeil[3], M Mehlman[1,2], H Norton[3], K Olchanski[3], S Smale[3], O Thériault[3], A N Vantyghem[3] and C L Warner[3]

Plastic Scintillators

- β^+-decay $\longrightarrow$ Background of 511 keV γs
- Calibrate to sum of two spectrum: γs and βs
- Include resolution of detectors and use linear calibration





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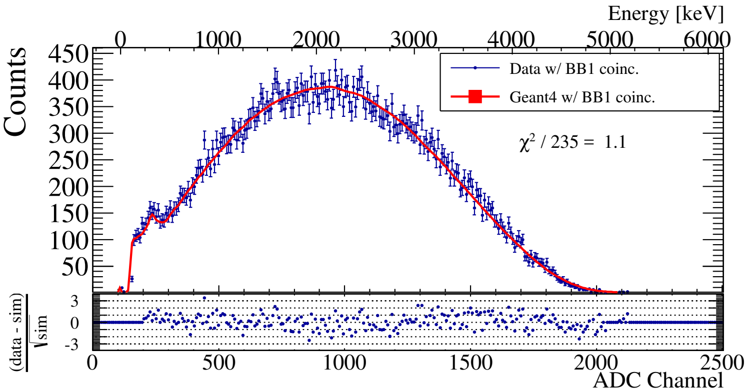
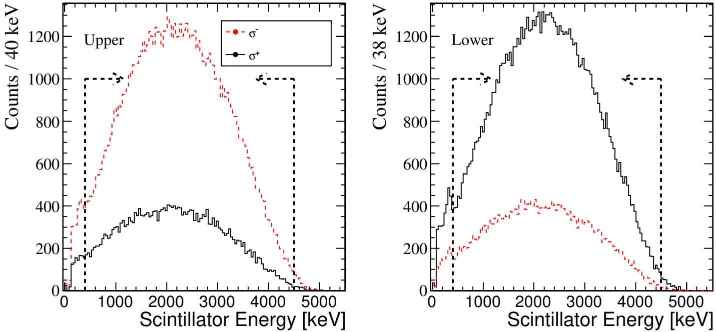


β-asymmetry

- Two detectors & polarization states reduce syst. uncertainties
- Calculate asymmetry using all the information (super-ratio):

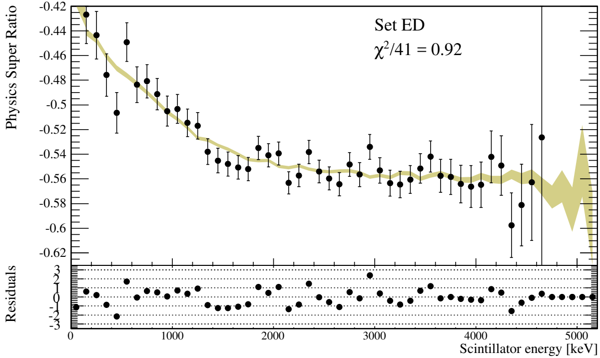
$$A_{\mathrm{obs}}^{\mathrm{SR}}(E_e) = \frac{1 - s(E_e)}{1 + s(E_e)} \qquad s(E_e) = \sqrt{\frac{r_1^-(E_e)\, r_2^+(E_e)}{r_1^+(E_e)\, r_2^-(E_e)}}.$$

- Accounts for different detector efficiencies, trap loading
  - Including effects of off-center trapped atoms



β-asymmetry

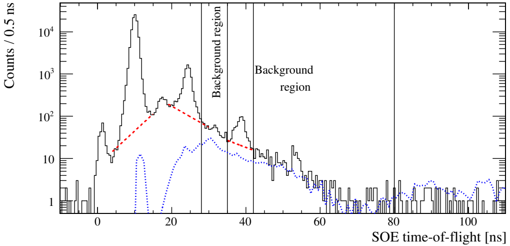
- Compare data to GEANT4 simulation → accounts for scattering
- Calculate χ^2 with a range for values of axial-vector component



- Result has $dA_\beta / A_\beta = 0.26\,\%$ statistical uncert.
- Energy dependence is sensitive to *S* and *T* currents (in

Background correction

- β^+-decay leaves nucleus with 1 extra, unbound e^-
- This shakeoff electron is accelerated onto MCP, detected
- Provides tag for events decaying from the optical-pumping region



- S/N is 390 : 1
- ^{37}K escaping the OP region?
- Asym. of bkg. unknown

Average of $A_N = 0.0$ and $A_N = A_\beta$ gives $|A_\beta - A_\beta^{\mathrm{obs}}| = 0.0007 \pm 0.0007$

Result & Other Systematics

- Background correction uncertainty is largest systematic
  - Uncert. with † → relates to β^+-scattering
  - Uncert. in red → is greater than 0.1 %

Source	Correction	ΔA_β [$\times 10^{-4}$]
Systematics		
Background	1.0007	7
Trap parameters		
Position		4
Sail velocity		5
Temperatue & width		1
Thresholds		
BB1 Radius†		4
BB1 Energy agreement		2
BB1 threshold		1
Scintillator threshold		0.3
GEANT4 physics list†		4
Shakeoff electon t.o.f. region		3
Geometry definition		
SiC mirror thickness†		1
Be window thickness†		0.9
BB1 thickness†		0.1
Scintillator or summed†		1
Scintillator calibration		0.1
Total systematics		12
Statistics		13
Polarization		5
Total uncertainty		18

$$A_\beta = -0.5707 \pm 0.0018$$

$$A_\beta^{\mathrm{SM}} = -0.5706 \pm 0.0007$$

With r.o.c.:

$$A_\beta^{\mathrm{SM}} = -0.5715 \pm 0.0007$$

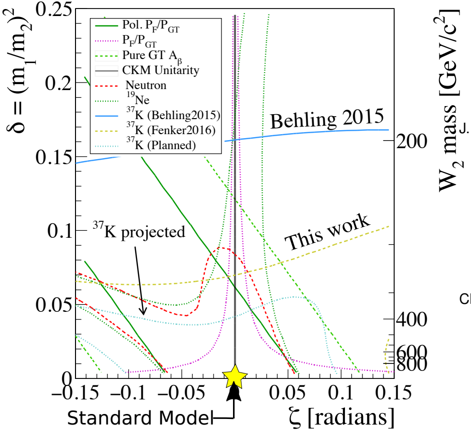
- 0.35 % measurement
- Smallest rel. uncert. for A_β
  - Including neutron meas.

Systematics studied:

- Position of atoms
- β-scattering
- Analysis choices

Minimally $L - R$ symmetric model

- Coupling constants identical $g_L = g_R$
- CKM matrices identical $V_{ij}^L = V_{ij}^R$
- At $\zeta = 0$, $m_2 = m_R > 300\,\text{GeV}$ (90 % C. L.)



- μ-decay Michel parameters:

$$m_2 > 592\,\text{GeV}$$
$$-0.020 < \zeta < 0.017$$

J. F. Bueno *et al.* PRD **84** (2011) 032005

- Direct production (LHC)

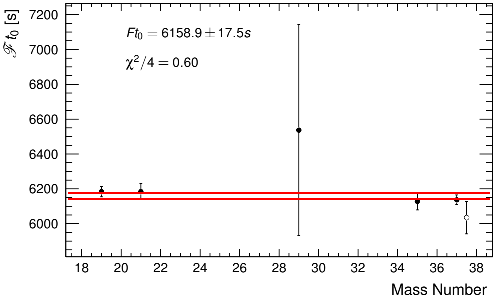
$$m_2 > 3.6\,\text{TeV}$$

CMS Collaboration Eur. J. Phys. C **74** (2014) 3149

- β-decay limits competitive in more general models
  - e.g. $g_R > g_L$

Summary

- $A_\beta = -0.5707 \pm 0.0018$ in $^{37}\mathrm{K}$ is best *relative* uncertainty to-date
- Polarization measured to $< 10^{-4}$ and does not limit measurement
- Article in preparation
- Result is among best nuclear limits on mass of W coupling to right-handed ν: $m_R > 297\,\mathrm{GeV}$
- Energy dependence probes scalar, tensor currents
- Overall result provides measurement of $\mathscr{F}t_0$
    - Extract V_{ud} and test CVC complementary to pure-Fermi decays



Acknowledgments

The TRINAT Collaboration

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

TRIUMF & ISAC Target & Beam Delivery Group

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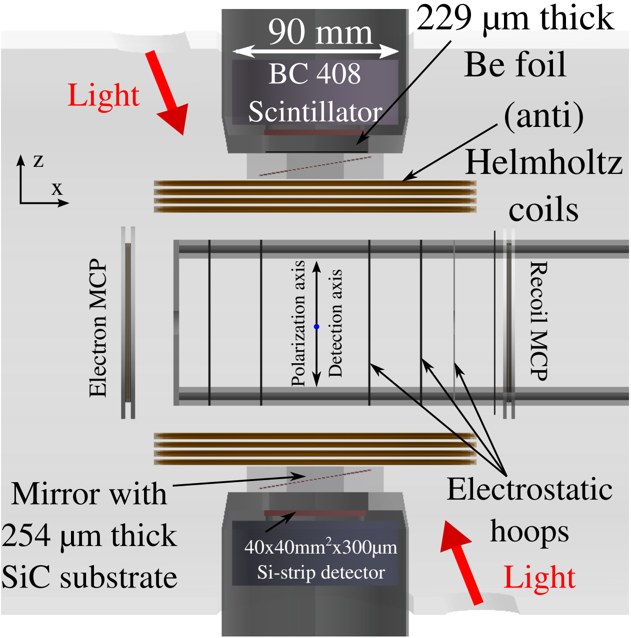
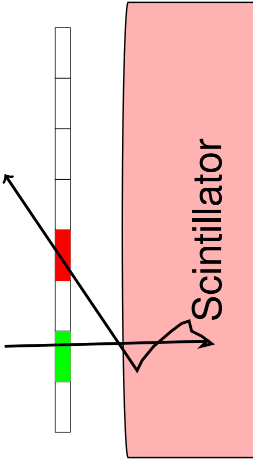
- Canada: NSERC, NRC through TRIUMF, WestGrid
- Israel: Israel Science Foundation

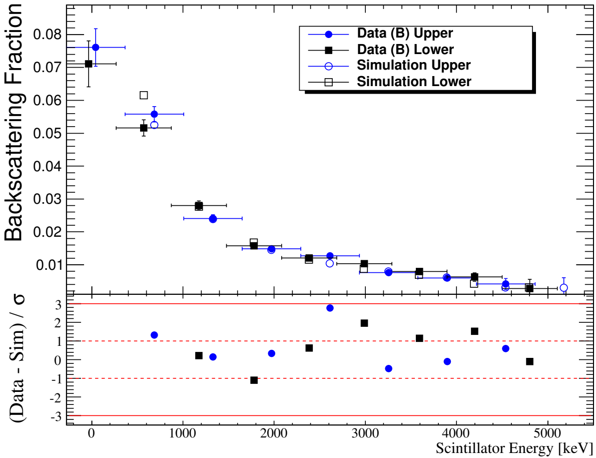
GEANT4 simulations

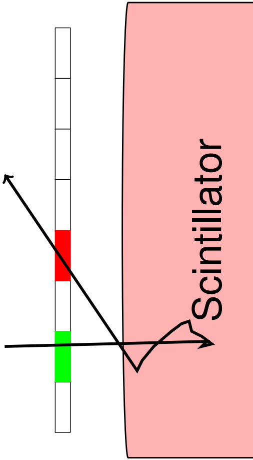




GEANT4 simulations

- Backscattered events hit *two* Si-detector pixels





- Reproduces backscattered fraction to within 1.5 %

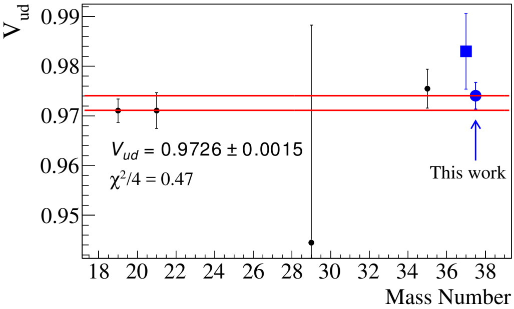
V_{ud} in mirror decays

- Can assume SM currents, interpret as:

$$\rho = \frac{C_A M_{GT}}{C_V M_F} = 0.577 \pm 0.006$$

- With Gamow-Teller component accounted for, measure:

$$V_{ud}^{\mathrm{K}} = 0.9741 \pm 0.0027$$



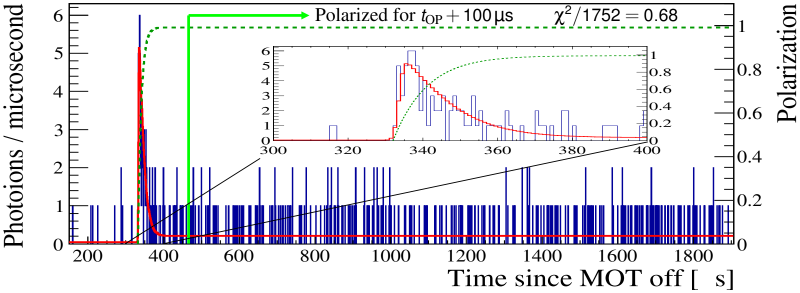
Pure-Fermi decays:

$V_{ud} = 0.97417 \pm 0.00021$

All mixed decays:

$V_{ud} = 0.9726 \pm 0.0015$

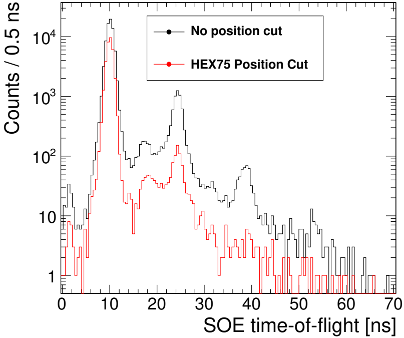
Polarization results

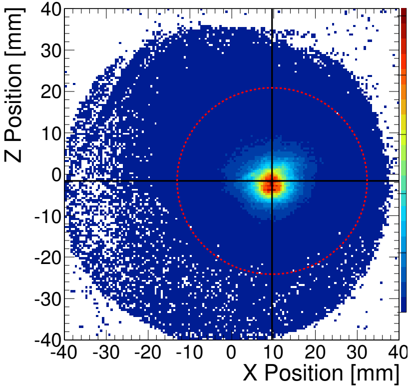


Parameter	σ^-	σ^+
Misaligned field, B_x [mG]	124(8)	
Average S/N	4.7(6)	
Laser intensity [W/m^2]	2.33(19)	2.26(13)
Nuclear polarization	$-0.9912(7)$	$+0.9913(6)$

HEX75 position cuts

- Can reduce background by requiring e^- position as expected
- Low eMCP efficiency $\rightarrow$ events below threshold $\rightarrow$ no position info





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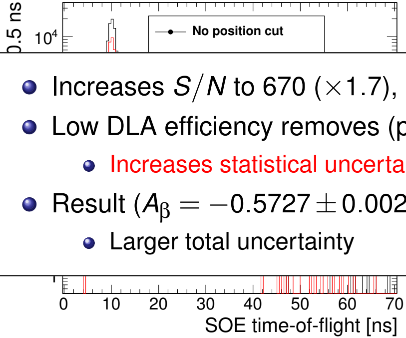
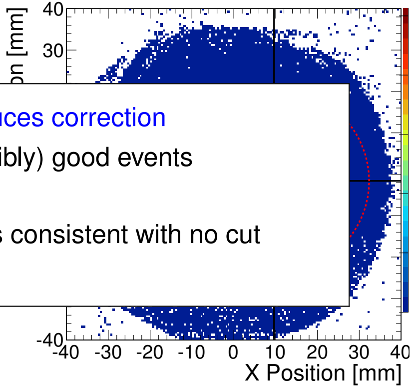
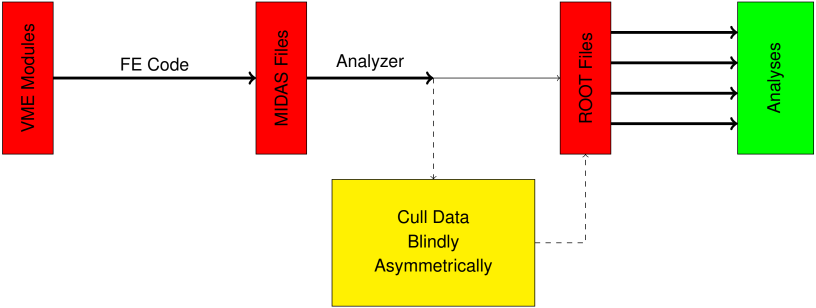




- Increases S/N to 670 ($\times 1.7$), reduces correction
- Low DLA efficiency removes (possibly) good events
  - Increases statistical uncertainty
- Result ($A_\beta = -0.5727 \pm 0.0024$) is consistent with no cut
  - Larger total uncertainty

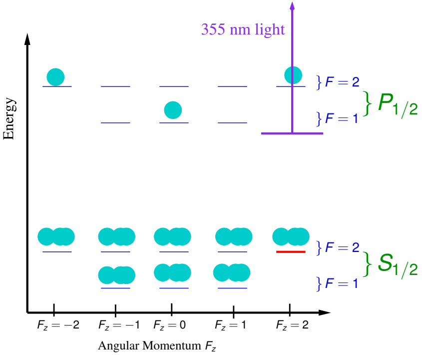
Blind analysis

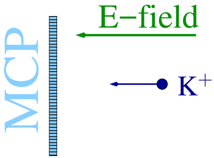
- Artificially bias β-asymmetry to minimize experimenter's bias
- Once all analysis cuts, correction are finalized: remove bias
- Results shown are un-blinded



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 $B_z = 2\,\mathrm{G}$ 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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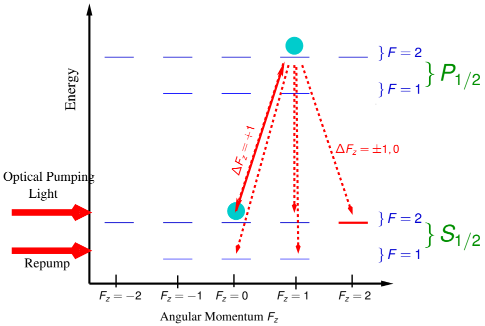

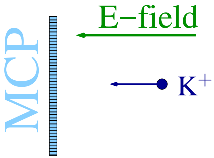

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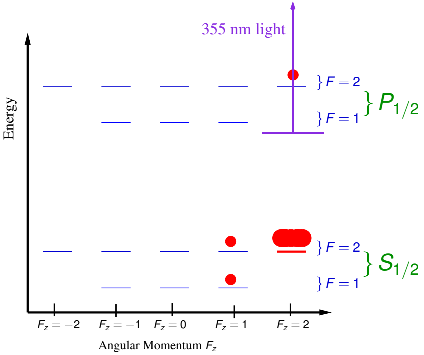
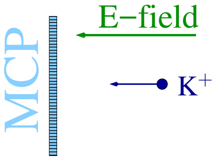




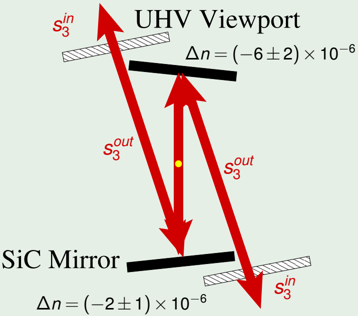
Note:
$\vec{F} = \vec{I} + \vec{J}$

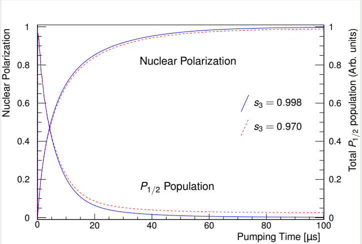
Theoretical Model

- Time evolution of the density matrix
- Spontaneous decay added phenomenologically

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

s_3 parameterizes quality of light's circular polarization





	Laser port	s_3^{in}	s_3^{out}
σ^-	Upper	$-0.9980(4)$	$-0.9958(8)$
	Lower	$-0.9990(10)$	$-0.9984(13)$
σ^+	Upper	$0.9931(9)$	$0.9893(14)$
	Lower	$0.9997(3)$	$0.9994(5)$

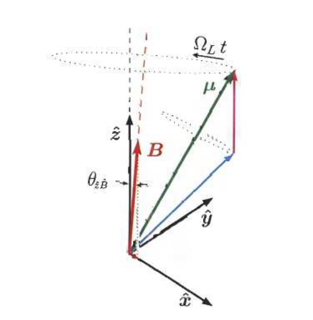
C. Warner *et al.* RSI **85** 11 (2014)
P. Tremblay and C. Jacques PRA **41** 4989

Theoretical Model

- Time evolution of the density matrix
- Spontaneous decay added phenomenologically

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

Transverse magnetic field



F. Renzoni *et al.* PRA **63** (2001) 0653401

Atoms in the stretched state precess to other ground states

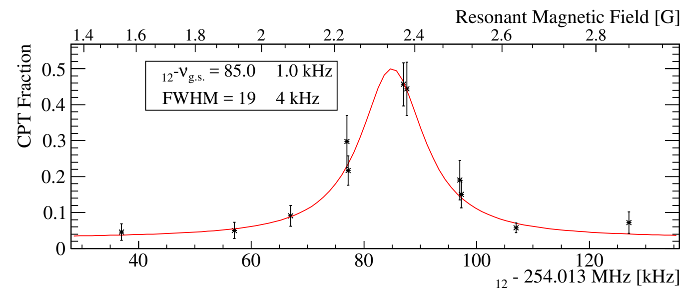
$$\vec{B} = B_x\hat{x} + B_z\hat{z}$$
$$H_{\vec{B}} = -\vec{\mu}\cdot\vec{B}$$
$$H_{B_x} = g_F\mu_B B_x F_x = g_F\mu_B B_x \frac{F_+ + F_-}{2}$$

Theoretical Model

- Time evolution of the density matrix
- Spontaneous decay added phenomenologically

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

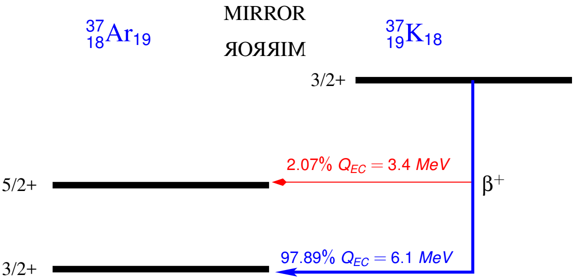
- Coherent Population Trapping
- Atoms are not available to be photoionized but *not fully polarized*
- *Narrow* resonances are avoided in experiment



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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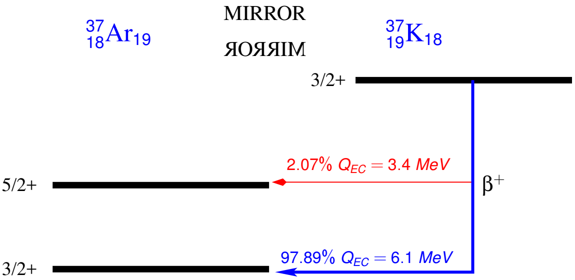

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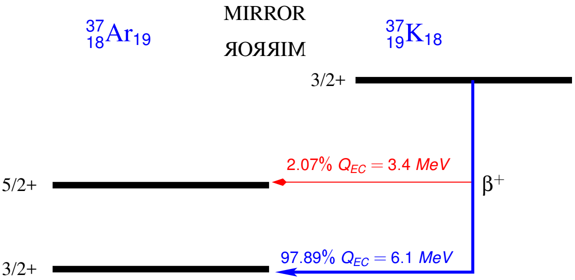
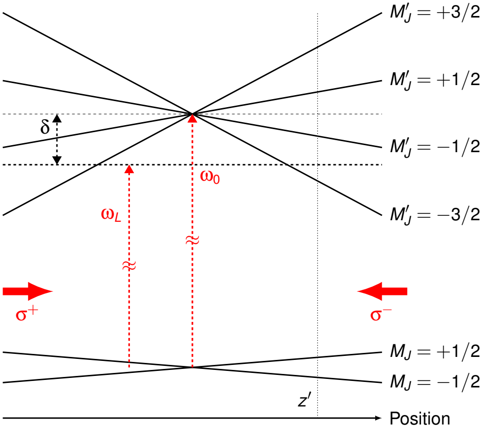
$\rightarrow \Delta A_{\beta} = 0.12\%$



Magneto-optical trapping

- $p_{\mathrm{K}} \gg p_\gamma \longrightarrow$ cycling transition: $S_{1/2} \leftrightarrow P_{3/2}$
- Red-detuned lasers provides drag/cooling potential: $\vec{F} \approx -\vec{v}$
- Quadrupole $\vec{B}$-field + $\sigma^\pm$ light $\rightarrow$ confining potential: $\vec{F} \approx -\vec{r}$
- Alternating current (AC) trap allows quick shutoff of magnetic field



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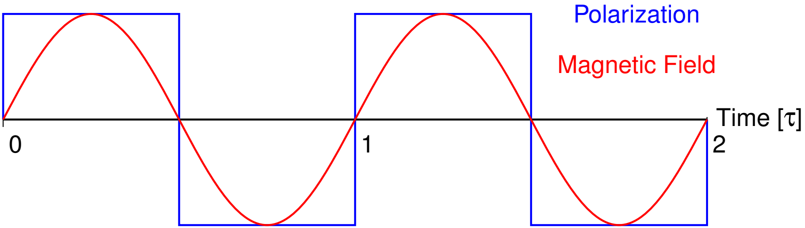
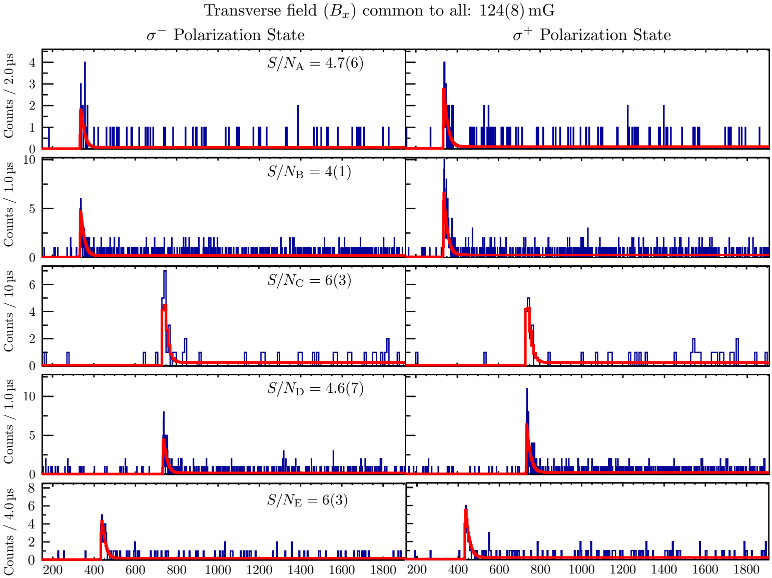


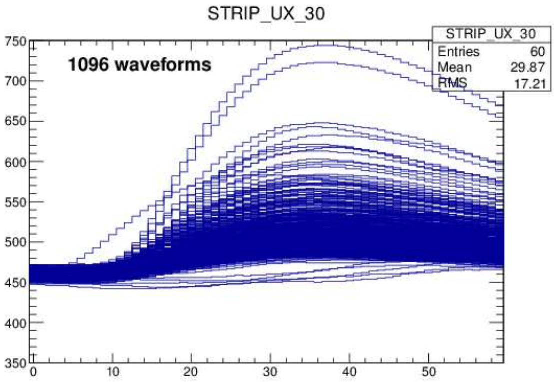
M. Harvey and A. J. Murray PRL **101** (2008) 173201

Preliminary Results

Therefore, perform global fit



Si-Strip (BB1) Detectors



- Waveform digitized at sampling speed of 16.7 ns

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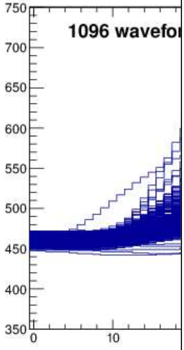

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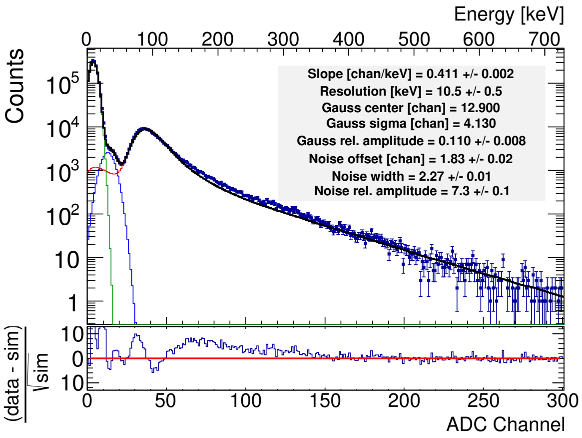
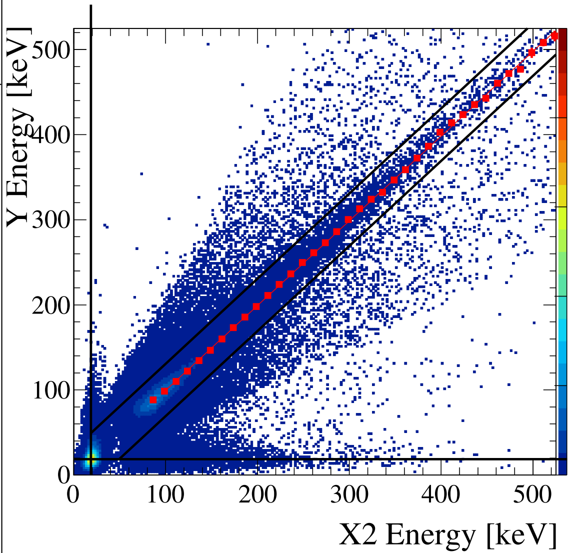
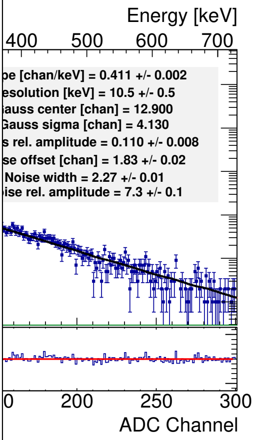


- 160 channels are calibrated independently

Si-Strip (BB1) Detectors



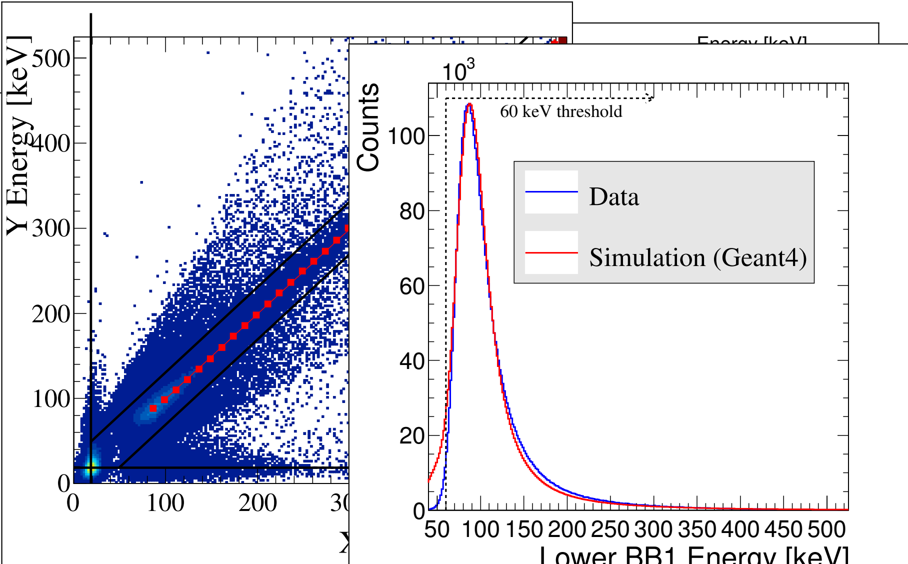


ted independently

- Can check $\hat{x}$-$\hat{y}$ energy agreement

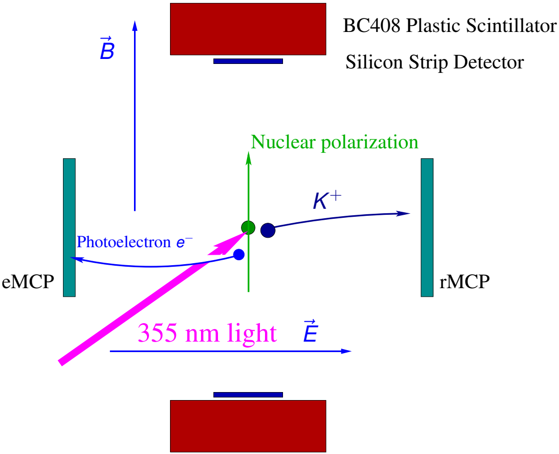
ns

Si-Strip (BB1) Detectors



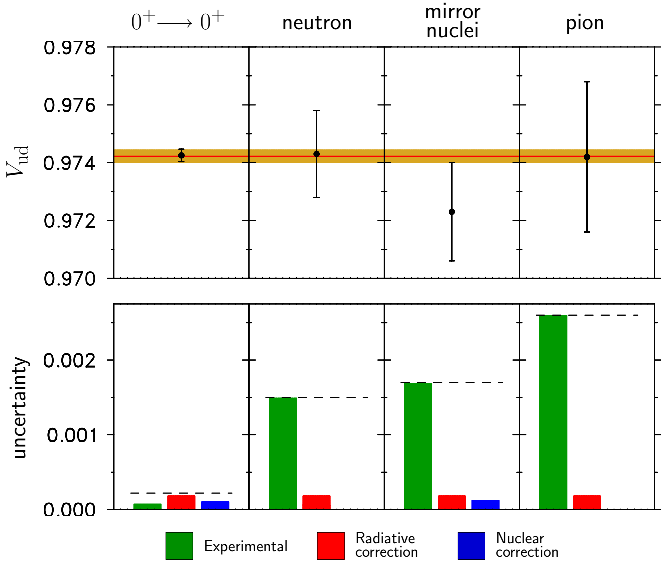
- Can check $\hat{x}$-$\hat{y}$ energy ag
- Good agreement with simulation

Photoionization Events



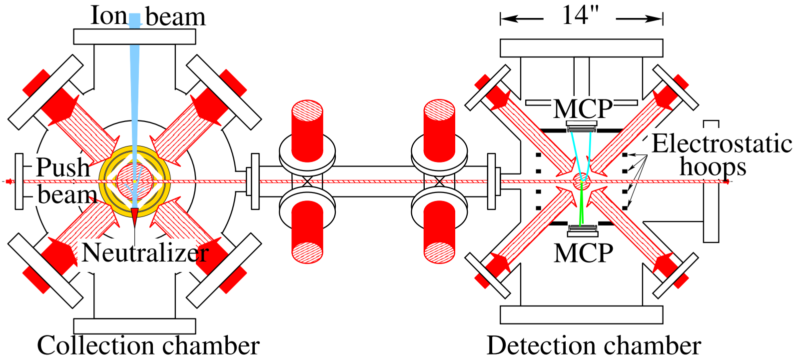
- Monitor of trap position, size, temperature
- Ultra-clean measure of nuclear polarization P

Measure V_{ud} with mirror nuclei



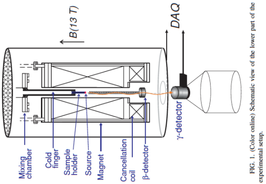
TRINAT's x2-MOT System

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



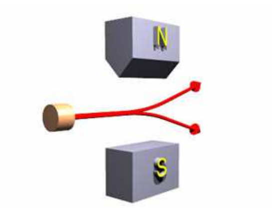
Correlation measurements with polarized nuclei

LTNO



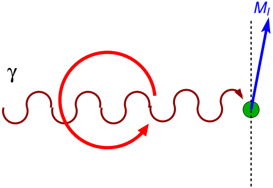
- Brute-force alignment of nuclear spin
- *P* calculated knowing the temperature
- Backscattering from source holder

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