The Weak Interaction: A Drama in Many Acts

- 1890's: Roentgen discovers β rays

Thought Uranium salts were affected by the sun but rainy Paris soon helped showing otherwise.

- 1920's: Pauli proposes ν

To explain continuous β spectrum: only way to save conservation of energy.

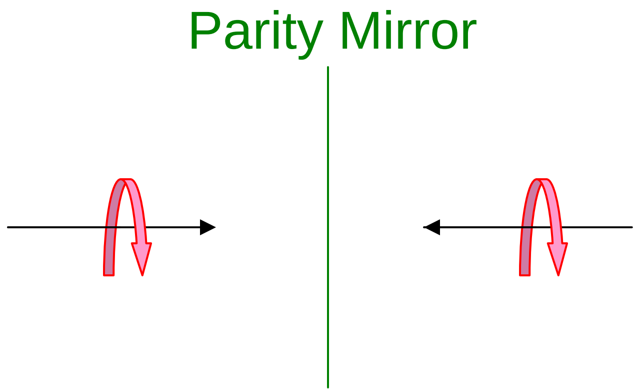
- 1950's Parity Violation

To explain identical properties of θ and τ particles. Then clearly proven in Madame Wu's experiment.

- 1960's CP-Violation

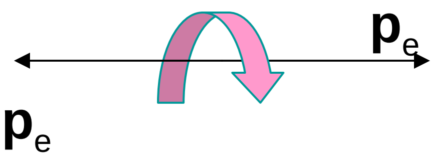
Parity Violation

- $\mathbf{x} \rightarrow -\mathbf{x}$
- $\mathbf{p} \rightarrow -\mathbf{p}$
- $\mathbf{r}\times\mathbf{p} \rightarrow \mathbf{r}\times\mathbf{p}$
- $\mathbf{J} \rightarrow \mathbf{J}$



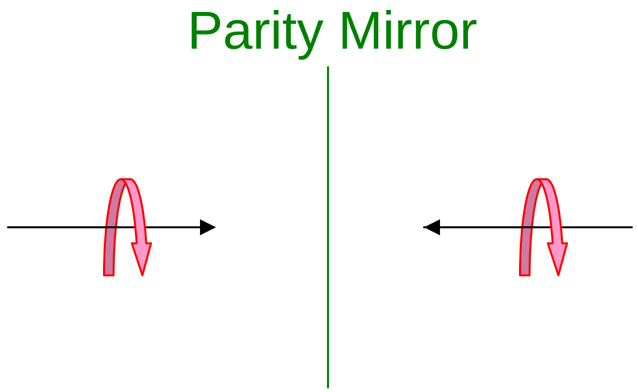
Madame Wu's experiment:
Polarize ^{60}Co and look at the direction of the emitted β's.

In a Parity-symmetric world we would see as many electrons emitted in the direction of **J** as opposite **J**.



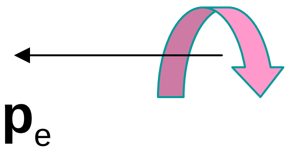
Parity Violation

- **x → -x**
- **p → -p**
- **r×p → r×p**
- **J → J**



Madame Wu's experiment:
Polarize ^{60}Co and look at the direction of the emitted β's.

But in the real world we see only electrons emitted in the direction opposite **J**.



P,C,T

P: x → -x
C: particles → anti-particles
T: t_f → $-t_i$ (running the movie backwards)

CPT theorem: all Lorentz-invariant local field theories are symmetric with respect to CPT

Time-reversal symmetry breaking in neutron beta decay

emiT Collaboration

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T. Chupp, R.L. Cooper, K. Coulter

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Hamilton College
G.L. Jones

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S.J. Freedman, B.K. Fujikawa

Standard Model Interaction at low energies:

$$H = \overline{\Psi}_f \gamma^{\mu} \Psi_i \quad 2C_V \, \overline{e}^{L} \gamma_{\mu} \nu_e^{L} + \overline{\Psi}_f \gamma^{\mu} \gamma_5 \Psi_i \quad 2C_A \, \overline{e}^{L} \gamma_{\mu} \gamma_5 \nu_e^{L}$$

Resulting decay rate:

$$dw = dw_0 \left[1 + a \frac{\overrightarrow{p_e}}{E_e} \cdot \frac{\overrightarrow{p_\nu}}{E_\nu} + b \frac{\Gamma m_e}{E_e} + \right.$$

$$\left. \frac{\langle \vec{J} \rangle}{J} \bullet \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} \boxed{+ D \frac{\vec{p}_e}{E_e} \times \frac{\vec{p}_\nu}{E_\nu}} \right) \right]$$

$$D \approx 2 \frac{|\lambda| \sin \varphi}{3|\lambda|^2 + 1}$$

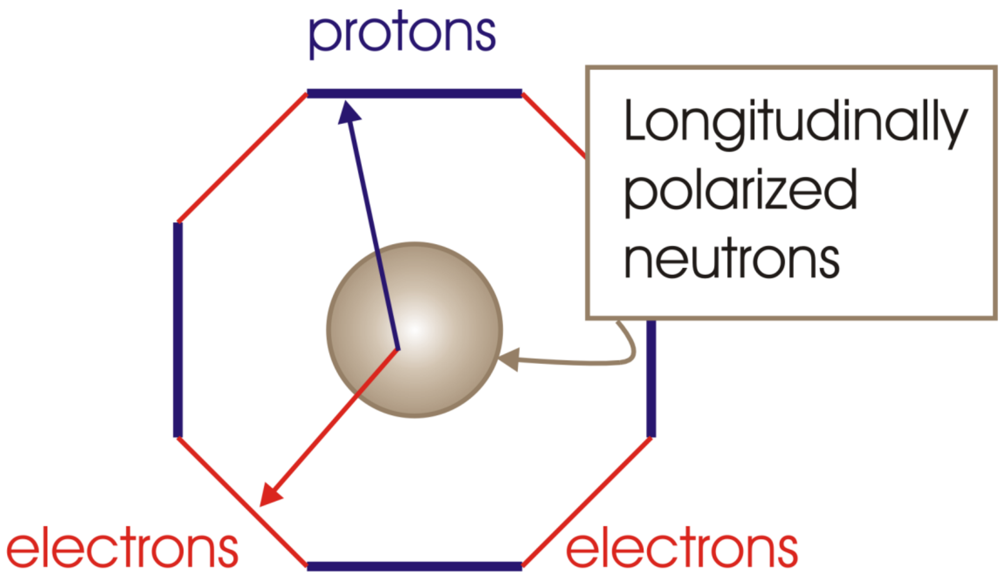
Sensitive to a phase
between the axial and vector
(or T and S) currents

Cheaper than searches at Belle (¥¥¥) or Babar ($$$), →

emiT is a `null experiment'.

Model	*D*
CKM phase	$<10^{-12}$
Theta-QCD	$<10^{-14}$
Supersymmetry	$<10^{-7}-10^{-6}$
Left-Right symmetry	$<10^{-6}-10^{-5}$
Exotic Fermion	$<10^{-6}-10^{-5}$
Leptoquark	*<present limit* $\sim 10^{-3}$

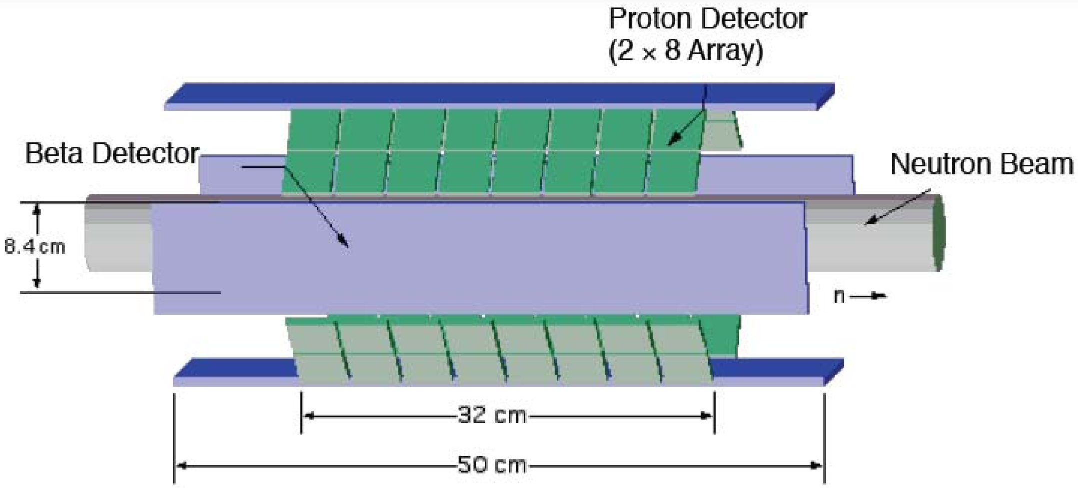
The basic idea: polarized neutrons;
detect protons and electrons.

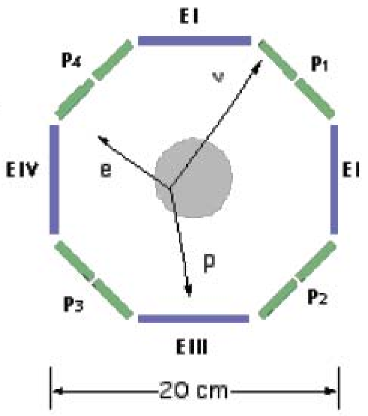


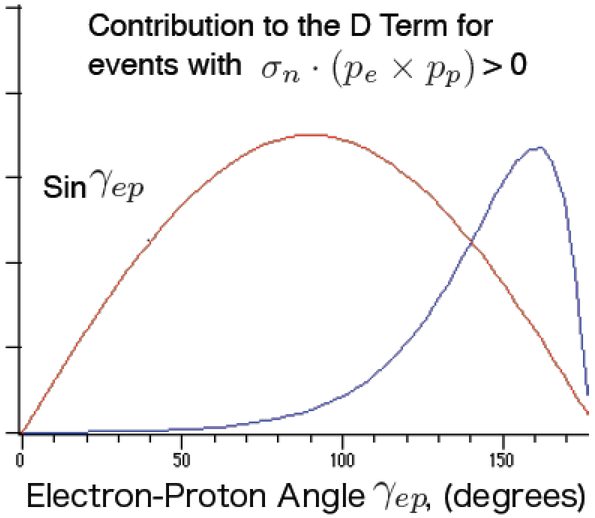
Some challenges:
1) Polarize/flip neutrons;
2) Detect <1 keV protons;
3) Detect electrons down to
90 keV with minimal backscatter;

Solutions:
1) Supermirrors (polarize n’s by magnetic
component in scattering); flipper=current sheet.
2) Accelerate protons to Si detectors (28 kV);
3) Scintillators with low threshold
and position resolution (achieved via timing).

emiT Detector: basic concept and design criteria



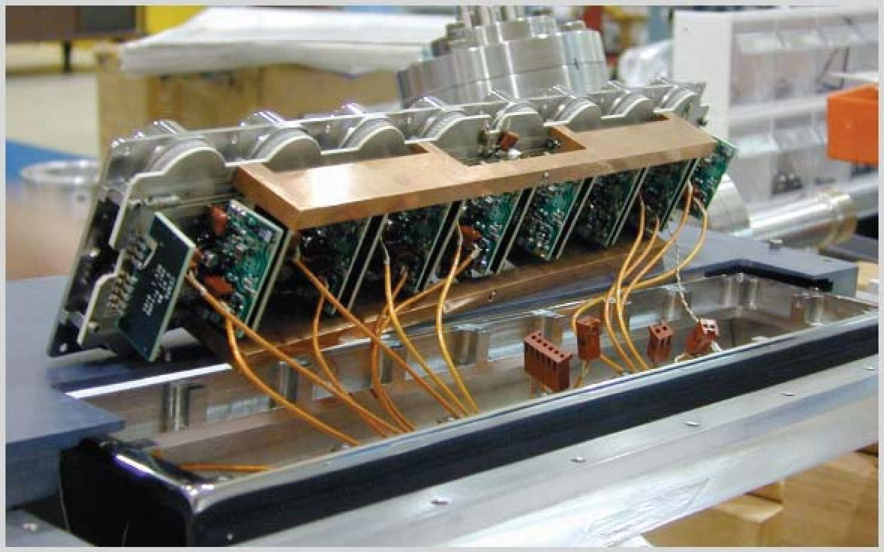


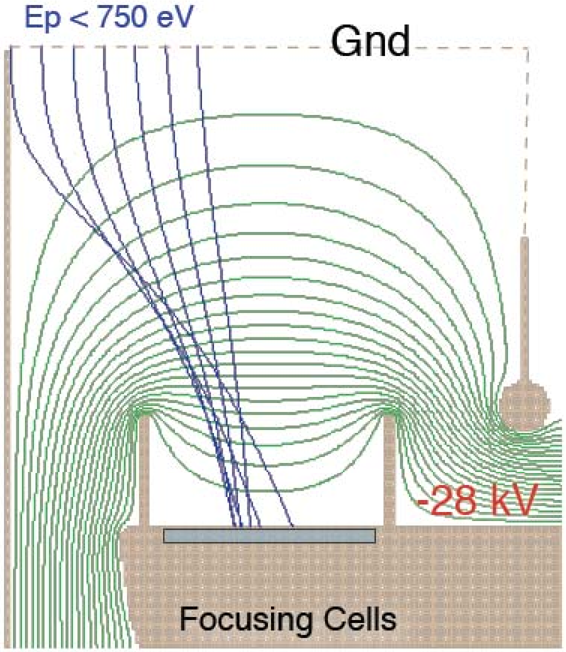

Contribution to the D Term for events with $\sigma_n \cdot (p_e \times p_p) > 0$

- Statistical precision requires highest possible coincidence rate
- High continuous neutron flux (1.7×10^8 cm^{-2} s^{-1} at "C2" collimator)
- Symmetrical, segmented detector to minimize or cancel instrumental asymmetries that could yield false coincidences
- Detector geometry to maximize sensitivity to $D\sigma_n \bullet (p_e \times p_\nu)$
  (minimize sensitivity to other terms in decay distribution)

emiT gained a factor of three increase in "effective" beam flux over previous "right angle" geometry beam experiments

emiT Detector: Proton Paddle Assembly





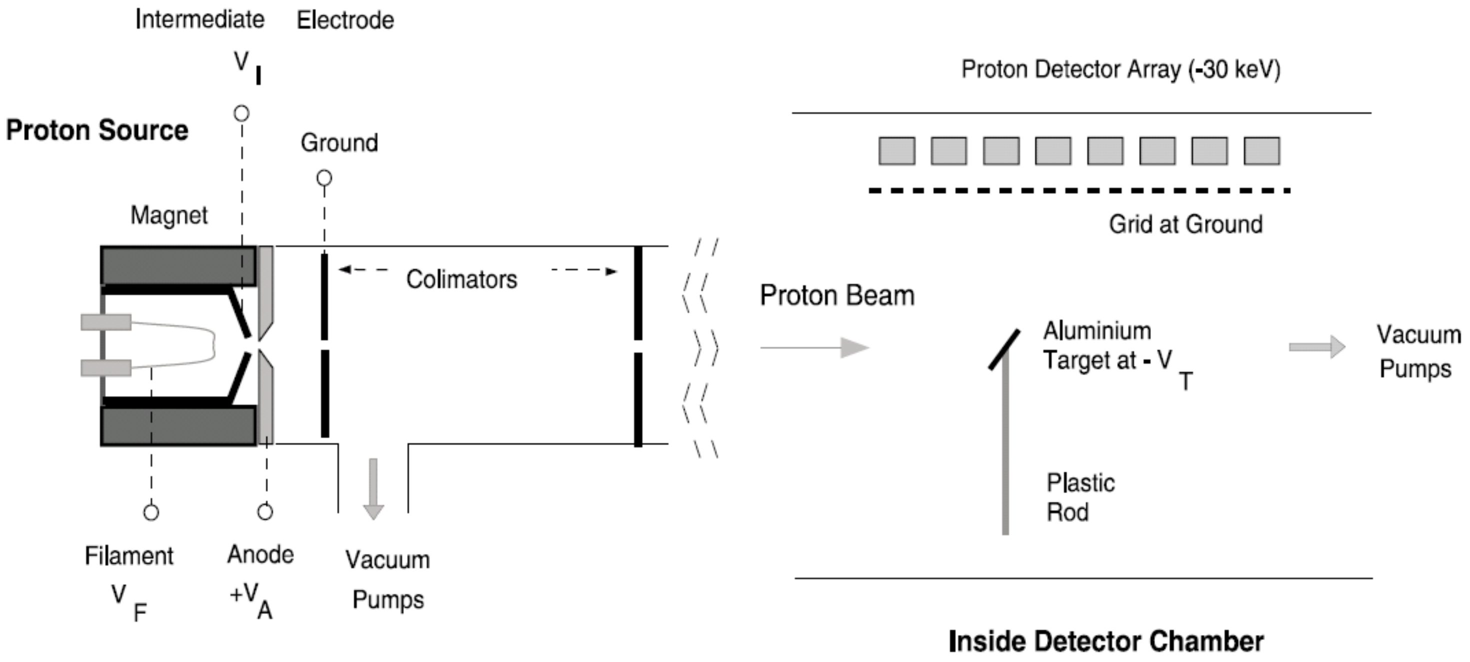
Focusing efficiency reaches 90%
(Voltage Dependent)

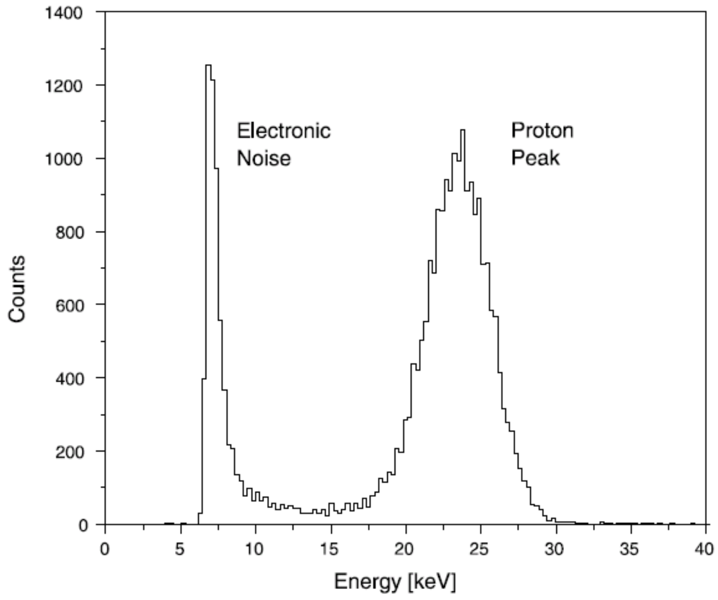
Required detector area reduced by ~ 80%

Surface barrier detectors

- 20 µg Au (less energy loss)
- 300 mm^2 active area
- 300 µm depletion depth
- Room temperature leakage current ~ µA

Developed a proton source (duo-plasm) to test detector.



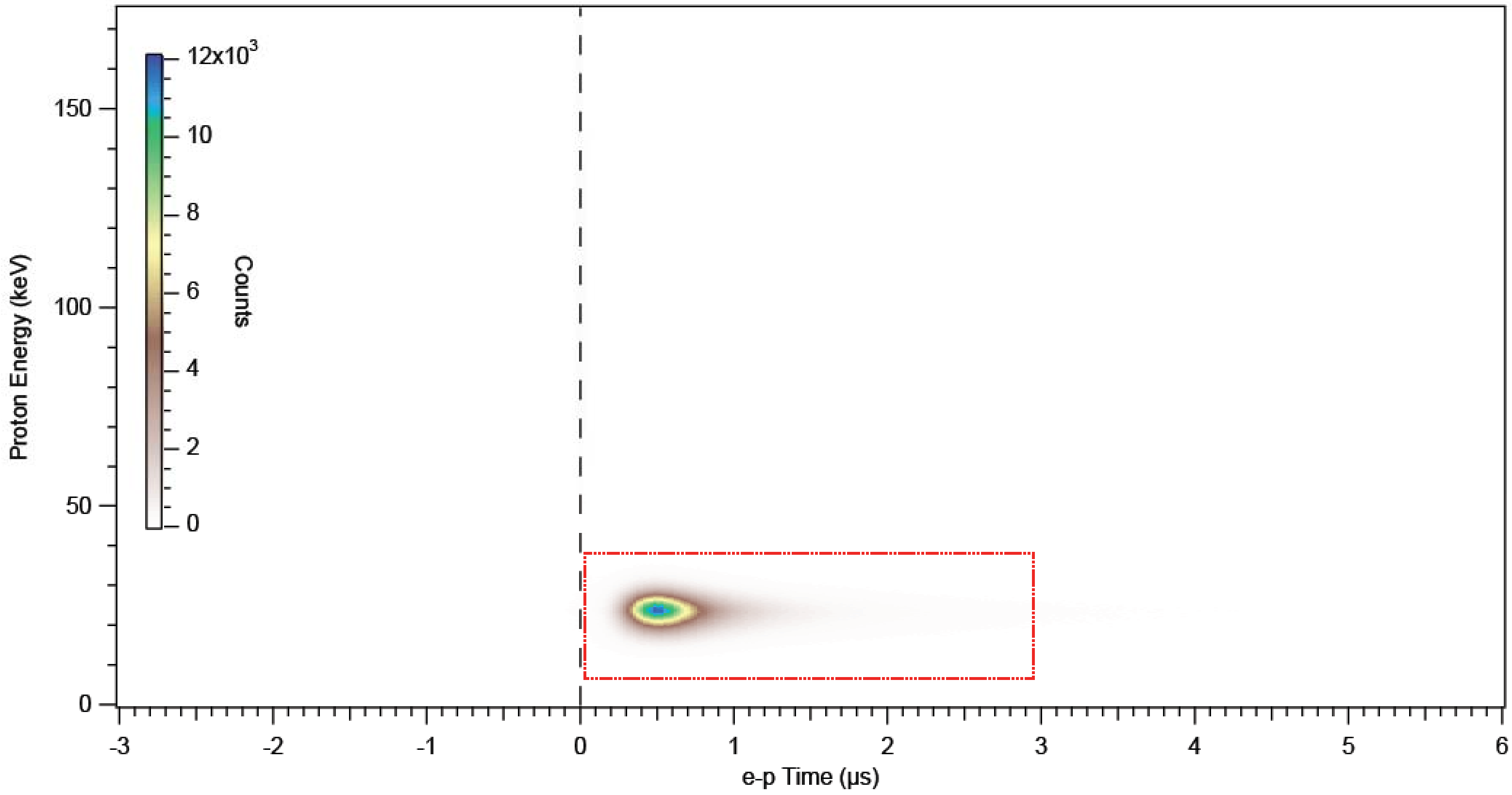


Detector showed good performance and good signal above noise.

F. Naab et al.

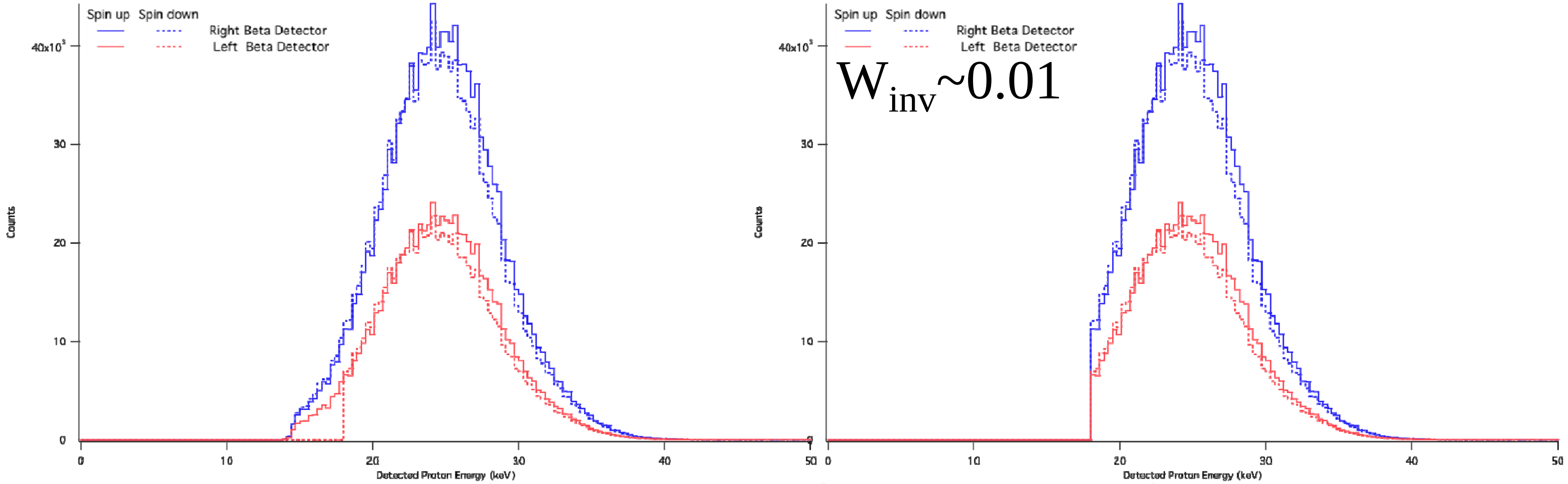
NIM **197**, 278 (2002)

emiT: flitered coincidence data

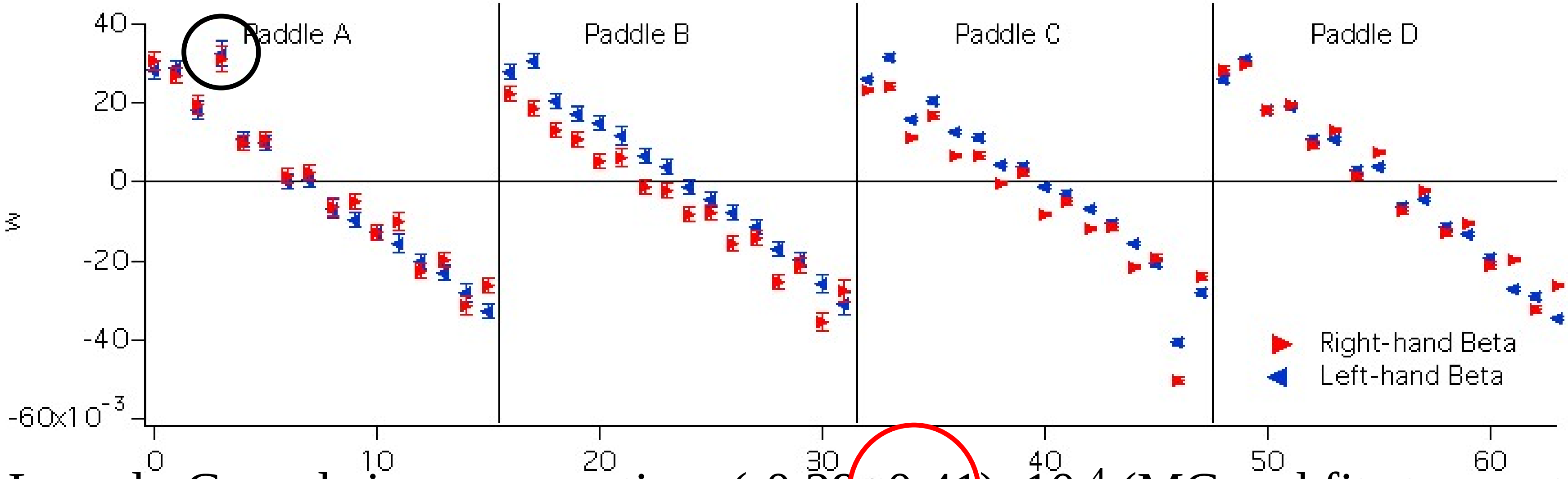


- 3 Hz singles per proton Surface Barrier det
- 0.55 Average coincidence rate per pair
- 25 Hz average coincidence rate
- Essentially no high voltage noise (Modified focusing assembly)
- Signal to noise better than 100/1
- Clear separation of cosmic Landau peak

Proton threshold effect



W_{inv}~0.01

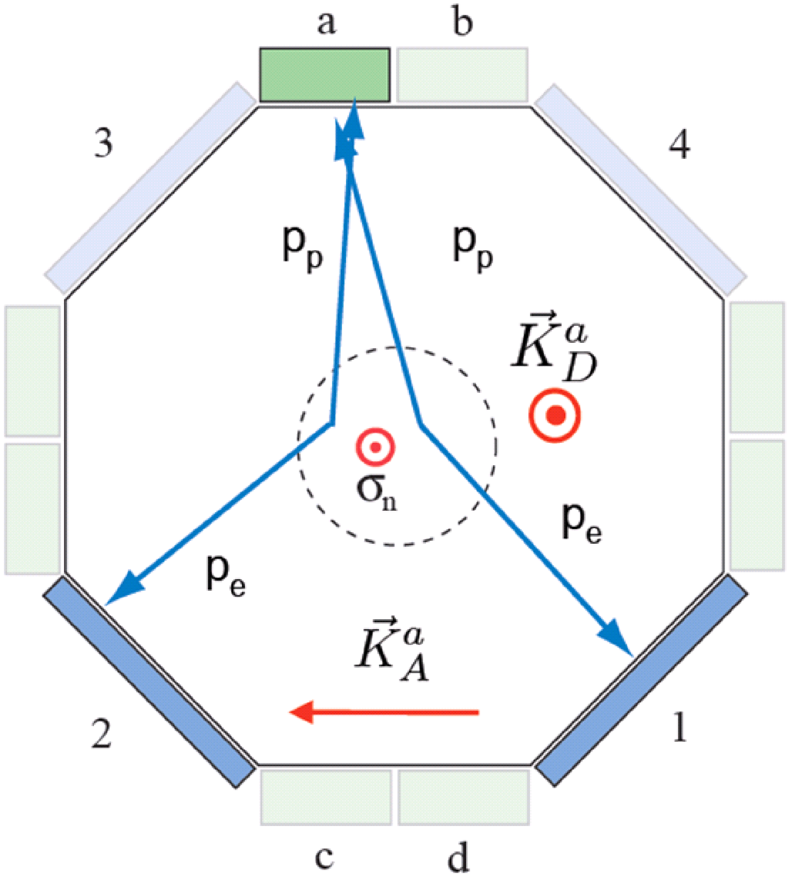


Largely Cancels in *ν* - correction: (-0.29±0.41)x10^{-4} (MC and fits to spectra)

threshold variations, etc.

Expect number of coincidences between a proton and beta detector:

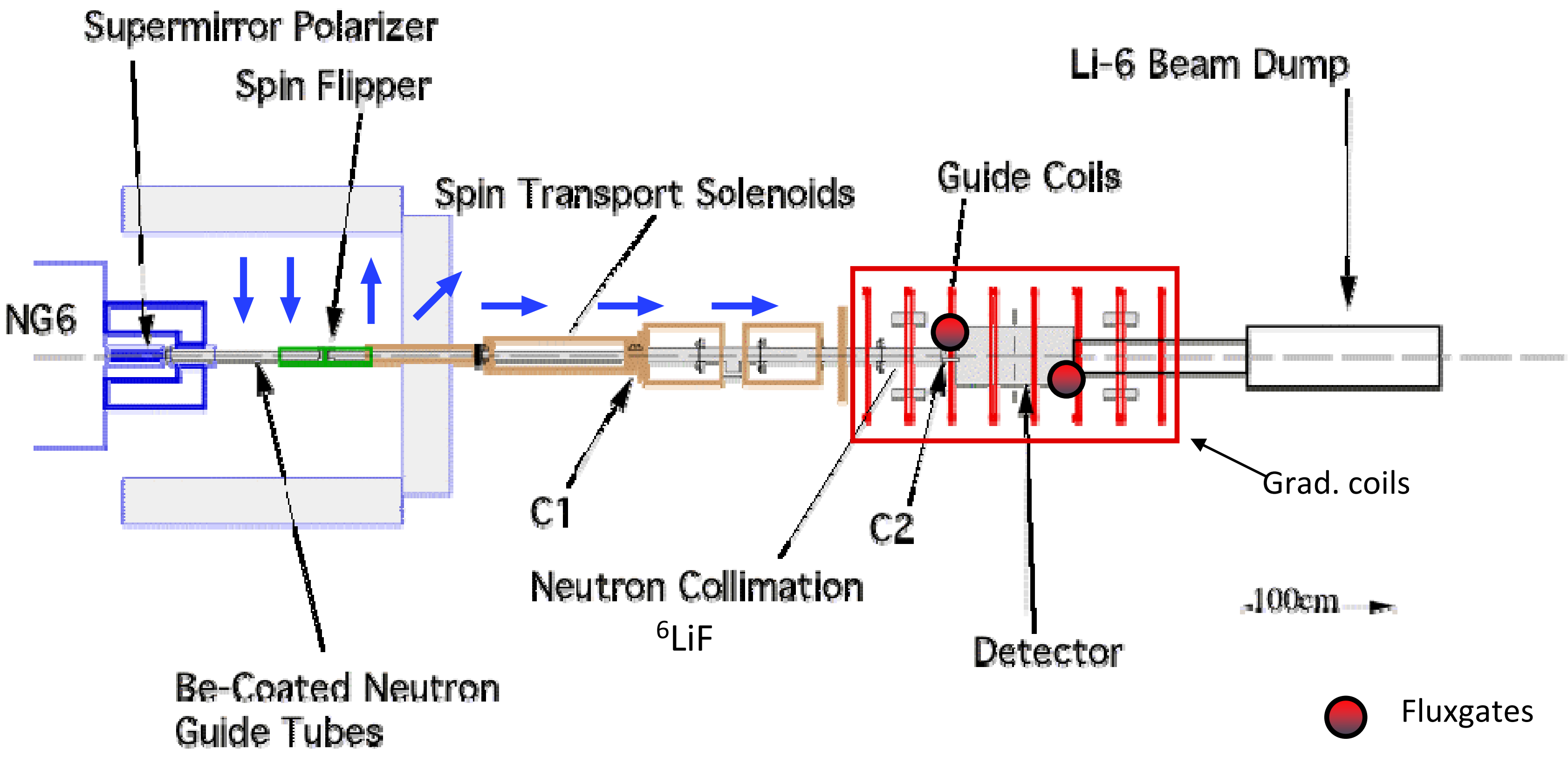
$$N^{\vec{J},R} = N\varepsilon_R\varepsilon_p\left(K_1^{R} + aK_a^{R}\right)\left\{1+\vec{J}\cdot\left(A\vec{K}_A^{R} + B\vec{K}_B^{R} + D\vec{K}_D^{R}\right)\right\}$$



To extract signal

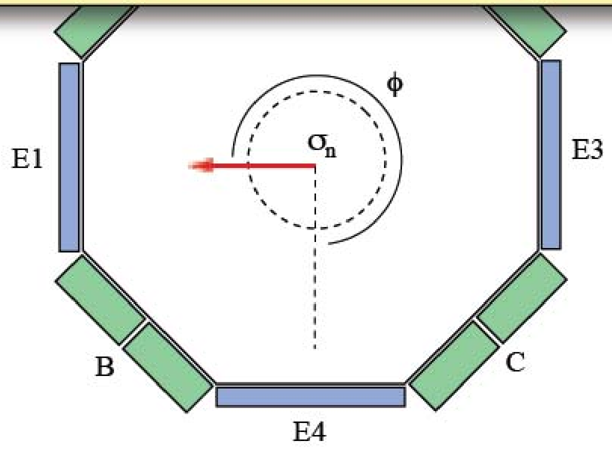
$$v_a = R - 1 = \frac{N_{1,a}^{\uparrow}\; N_{2,a}^{\downarrow}}{N_{1,a}^{\downarrow}\; N_{2,a}^{\uparrow}} - 1$$

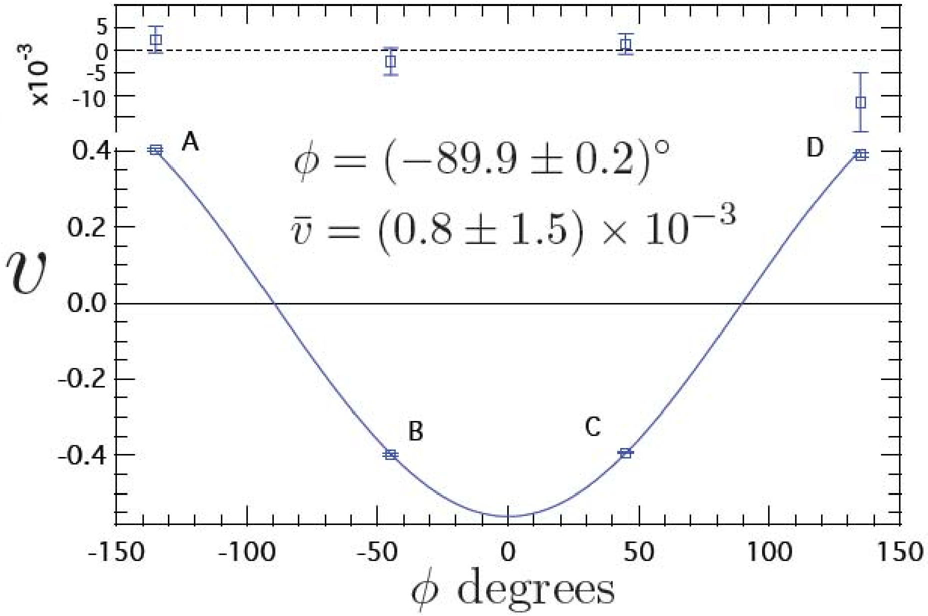
Spin transport

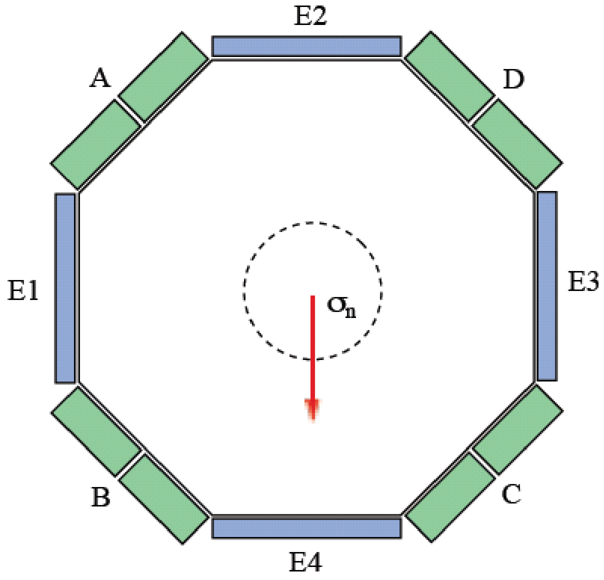


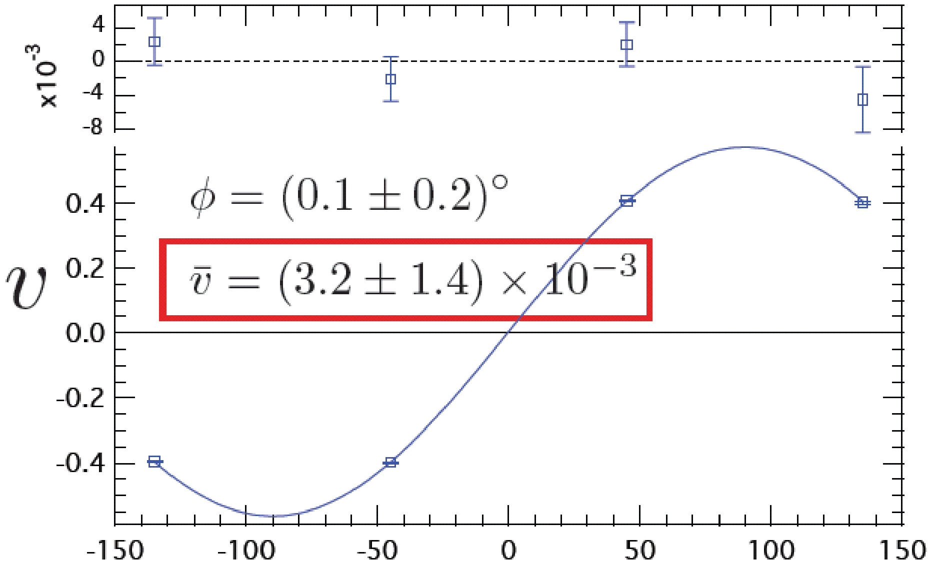
- High neutron flux (1.7 x 10^8 cm^{-2} s^{-1} at “C2”) fission chamber.measurement
- 560 μT guide field, monitored during run
- Beam profile at 3 positions via Dysprosium foil activation
- Polarization measured with supermirror analyzer flipping ratio measurement

Intentional field rotation
(Maximal polarization misalignment)



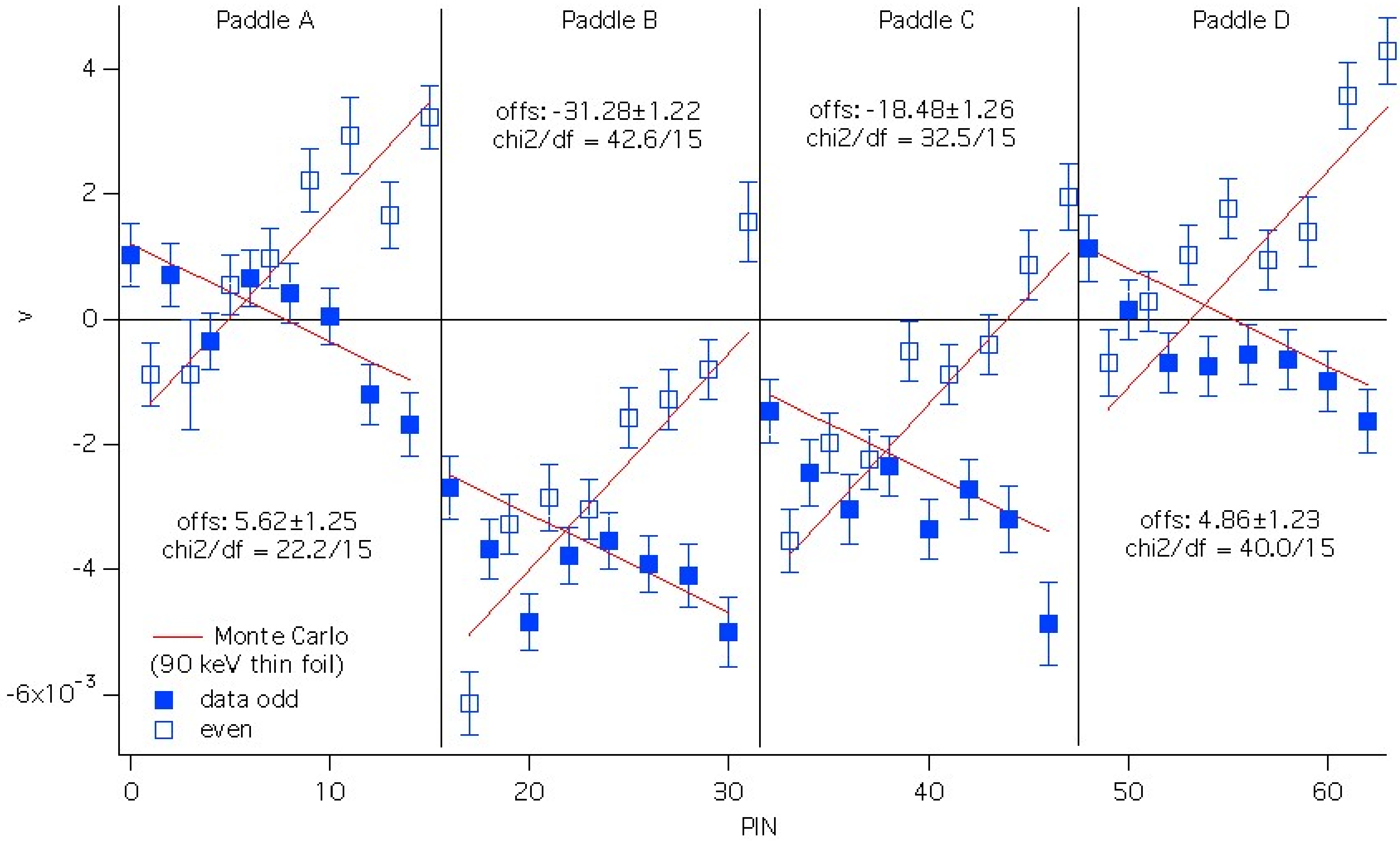






Comparison between data and expectations look good

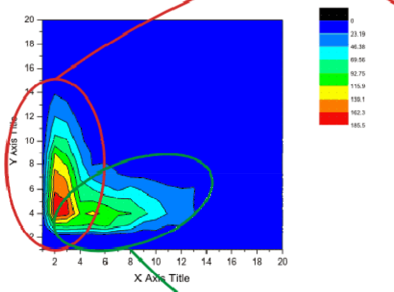
V factors

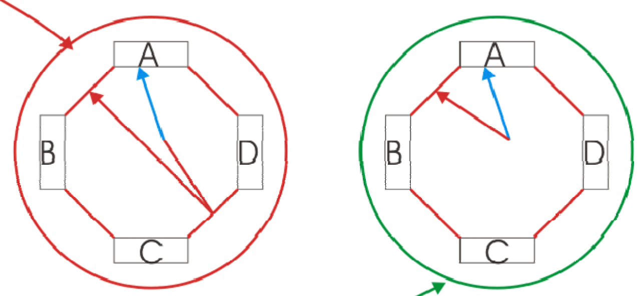


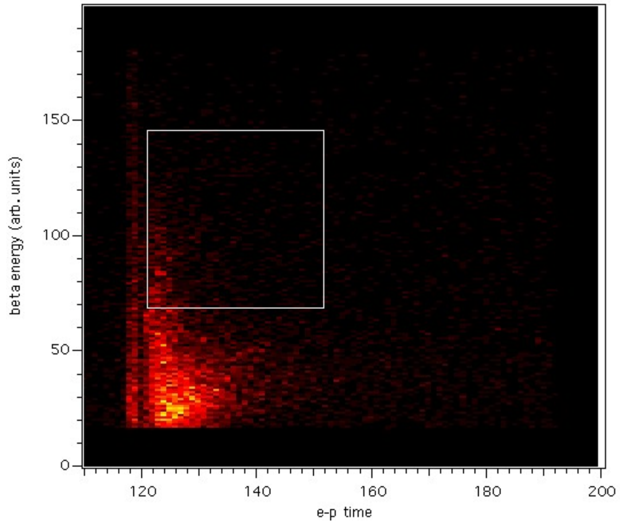
Another subtle issue: beta and proton backscattering

Data at 45 degrees

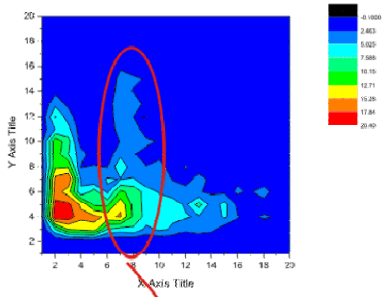
Only beta bksct

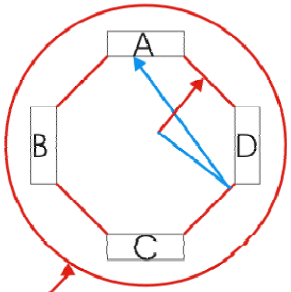


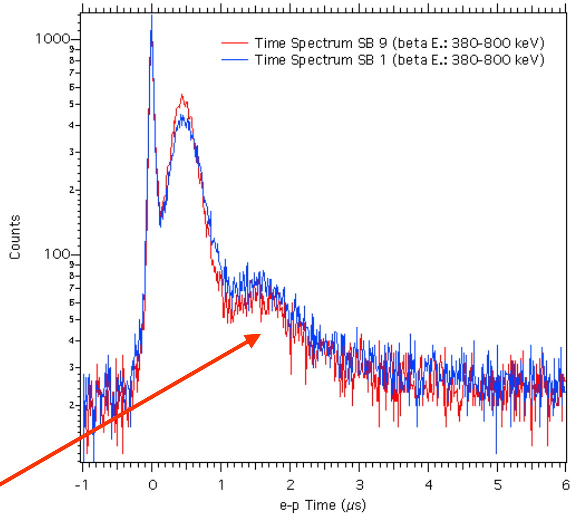


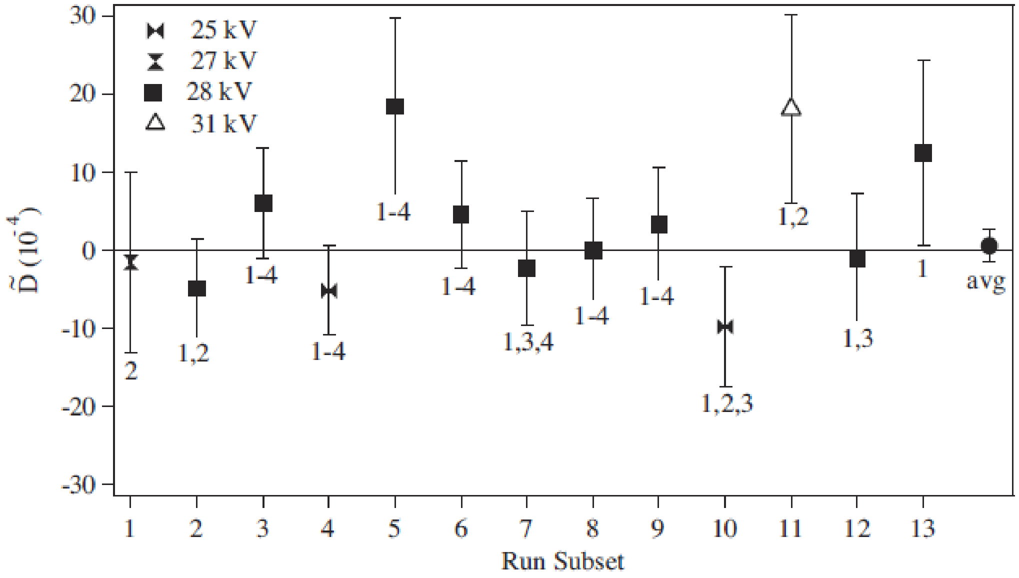


Beta AND proton bksct

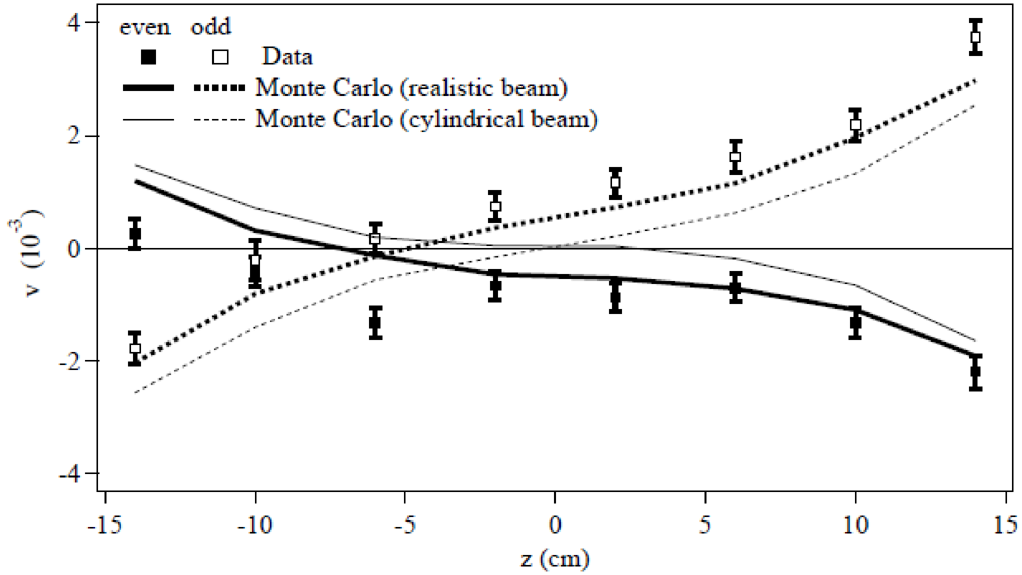








Results versus time (run number)
The experiment was stable.



Results versus axial coordinate
The average of all these results
is our final value.

FIG. 3: Solid (open) squares show the values of v averaged

Corrections (10^{-4})

All studies completed while data were still "blind"

Source	Correction	Uncertainty
BR asymmetry	upper limit	0.30
BR subtraction	0.03	0.00
Electron Backscattering	0.11	0.03
Proton Backscattering	upper limit	0.03
Beta threshhold uniformity	0.04	0.10
Proton threshhold effect	-0.29	0.41
Beam Expansion/**B**-field	-1.50	0.40
Pol uniformity	upper limit	0.10
Asymmetric-beam/Trans. Pol (ATP)	-0.07	0.72
ATP twist	upper limit	0.24
Spin correlated flux	<1e-6	0.00
Spin correlated polarization[a]	<1e-6	0.00
Polarization (95±5%)	Included in $\tilde{D}$	0.04
K_D (0.378±0.019)	Included in $\tilde{D}$	0.05
Total	-1.68	1.01

[a] Includes spin-flip time, cycle asymmetry, and flux variation.

Previous results:

$$D(^{19}Ne) = (4 \pm 8) \times 10^{-4}$$

Hallin et al.,

Phys. Rev. Lett. **52**, 337 (1984).

$$D(n) = \left(-0.6 \pm 1.2_{syst} \pm 0.5_{stat}\right) \times 10^{-3}$$

Lising et al.,

Phys. Rev. C **81**, 49 (2000).

$$D(n) = (-2.8 \pm 7.1) \times 10^{-4}$$

Soldner et al.,

Phys. Lett. **B581**, 49 (2004).

$$D(n) = \left(-0.96 \pm 1.01_{syst} \pm 1.89_{stat}\right) \times 10^{-4}$$

Mumm et al.,

Phys. Rev. Lett., in press

Searches for Scalar and Tensor currents in beta decay

32Ar

With E. G. Adelberger, D. Melconian, O. Tengblad, M. J. G. Borge, I. Martel…

6He

With A. Knecht, P. Mueller, Z.-T. Lu, O. Navillat-Cuncic, H. Robertson, D. Zumwalt…

Interaction:

$$H = \overline{\Psi}_f \gamma^\mu \Psi_i \quad 2C_V \, \overline{e}^L \gamma_\mu \nu_e^L +$$

$$\boxed{\overline{\Psi}_f \Psi_i \quad \left[(C_S - C_S') \overline{e}^L \nu_e^R + (C_S + C_S') \overline{e}^R \nu_e^L \right]}$$

Consequence:

$$dw = dw_0 \left[1 + a \frac{\overrightarrow{p_e}}{E_e} \cdot \frac{\overrightarrow{p_\nu}}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

Do these exist?

with:

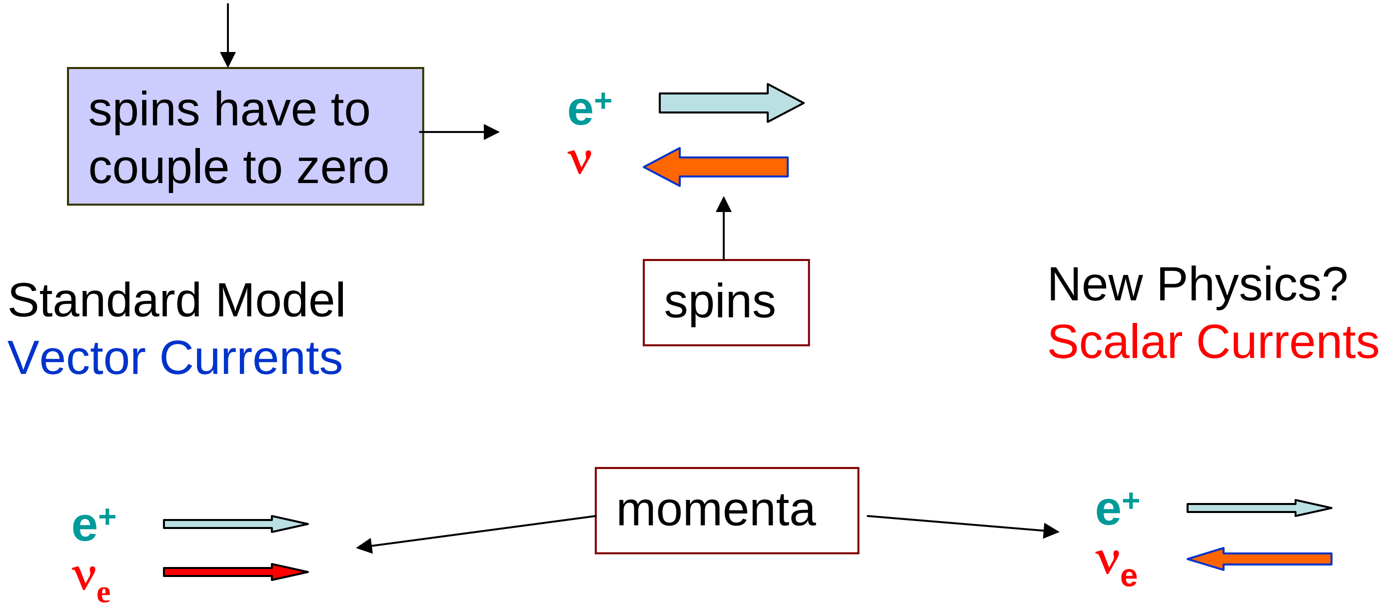
$$a \approx \frac{2|C_V|^2 - \boxed{|C_S|^2 + |C_S'|^2}}{2|C_V|^2 + \boxed{|C_S|^2 + |C_S'|^2}}$$

and:

$$b \approx \frac{\mathrm{Re}\left[2C_V \boxed{(C_S + C_S')} \right]}{2|C_V|^2 + \boxed{|C_S|^2 + |C_S'|^2}}$$

Detecting Scalar currents in weak decays

The e-ν correlation depends strongly on the nature of the carrier (we take a $0^+ \rightarrow 0^+$ transition).



spins have to couple to zero

spins

Standard Model
Vector Currents

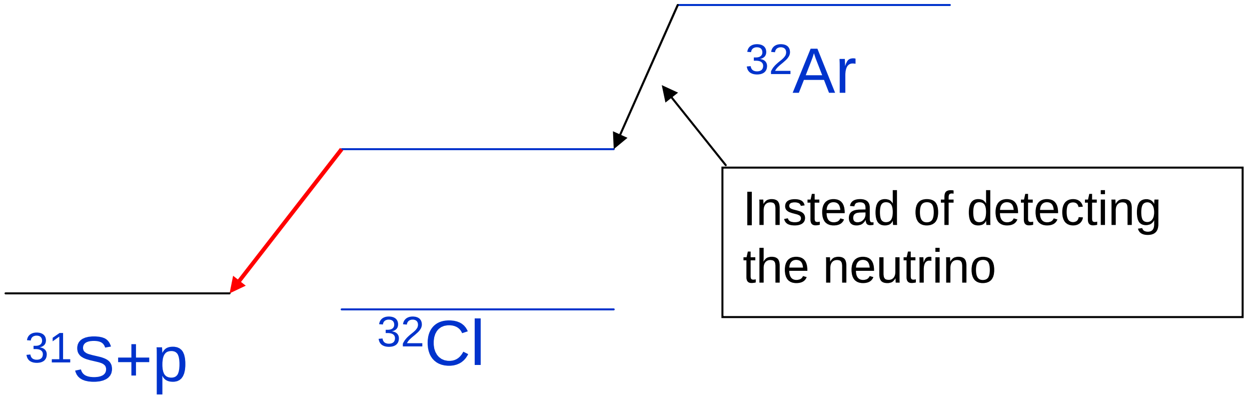
New Physics?
Scalar Currents

momenta

$dW/d\Omega = 1 + \mathbf{p}_{e.}\mathbf{p}_\nu / E_e\, E_\nu$

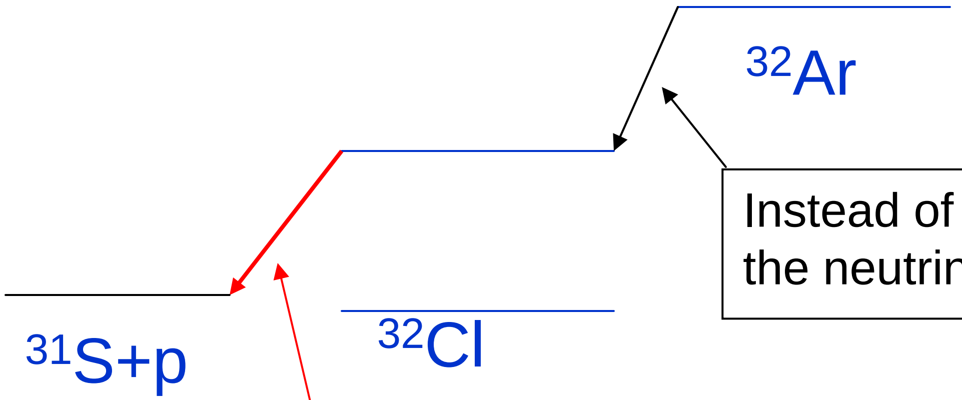
$dW/d\Omega = 1 - \mathbf{p}_{e.}\mathbf{p}_\nu / E_e\, E_\nu$

A trick to avoid detecting the neutrino



Instead of detecting the neutrino

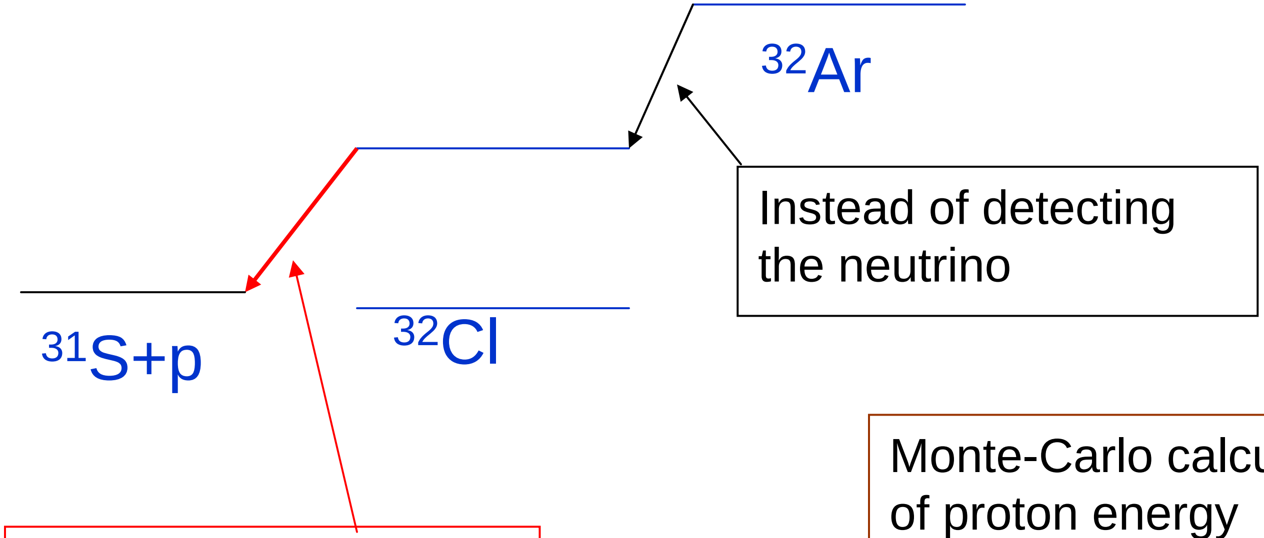
A trick to avoid detecting the neutrino



Instead of detecting the neutrino

We detect the proton that contains the info about the ^{32}Cl recoil (Doppler)

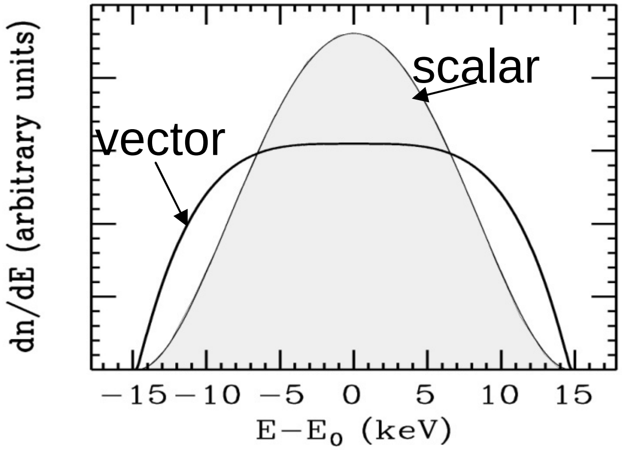
A trick to avoid detecting the neutrino



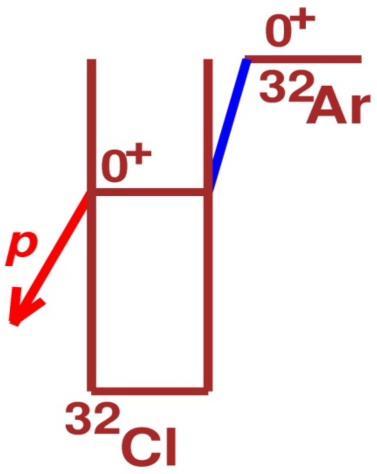
Instead of detecting the neutrino

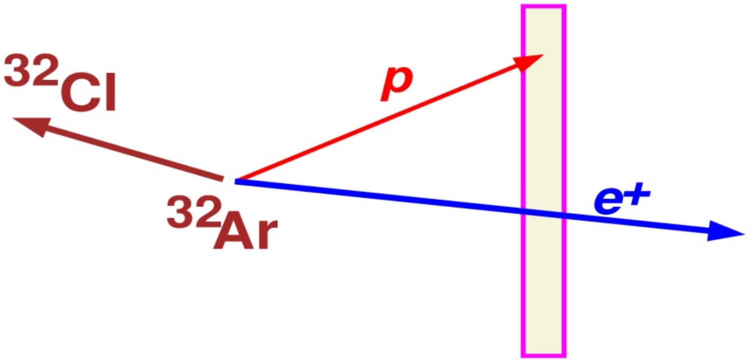
We detect the proton that contains the info about the ^{32}Cl recoil (Doppler)

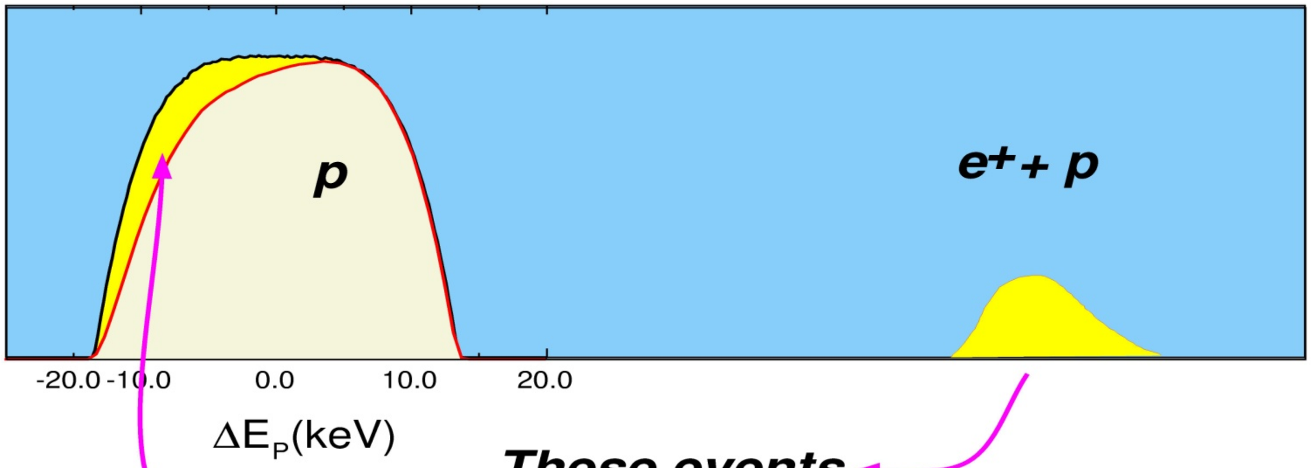
Monte-Carlo calculation of proton energy



Problem: Summing with positrons distorts the shape of the proton peak

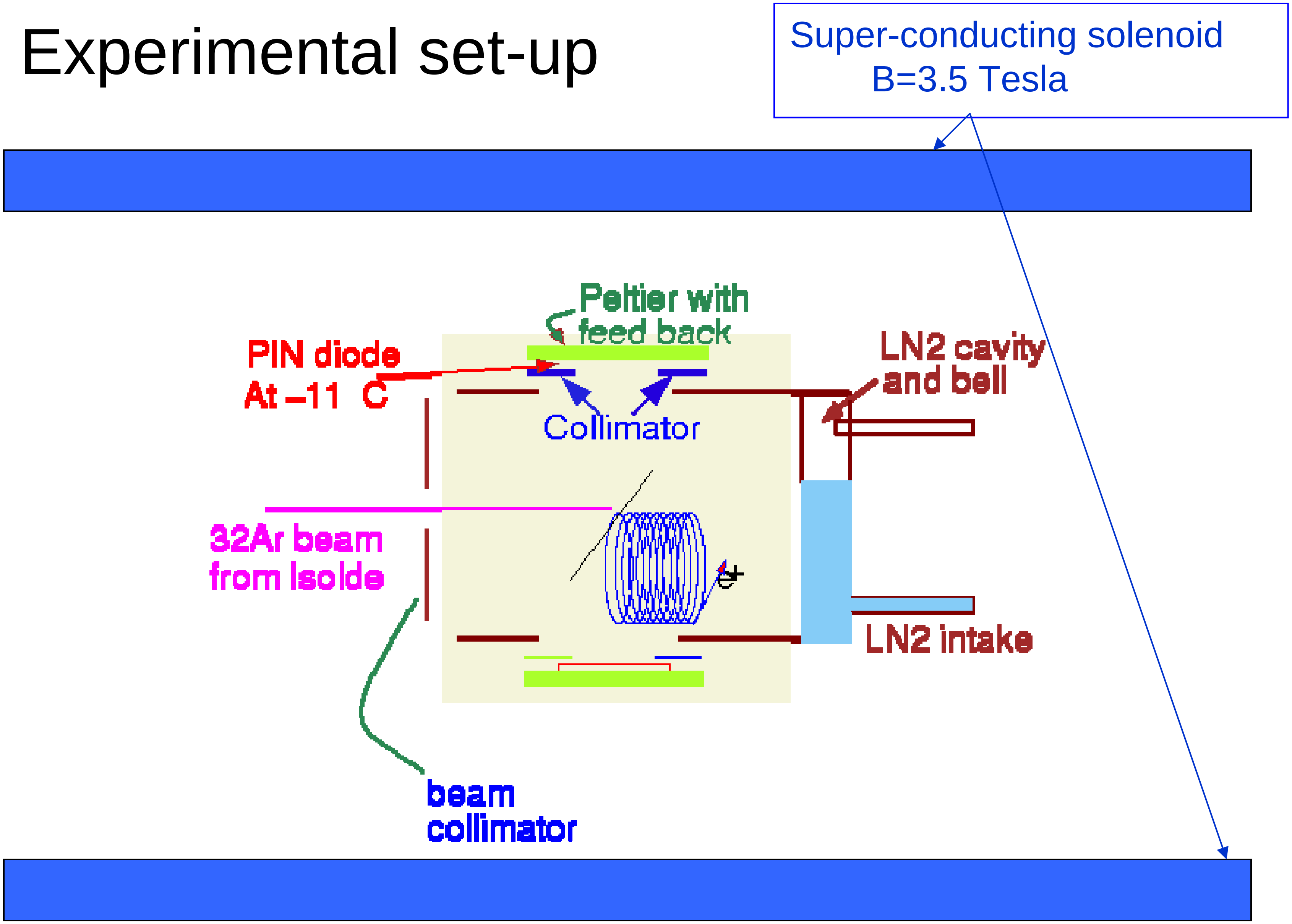






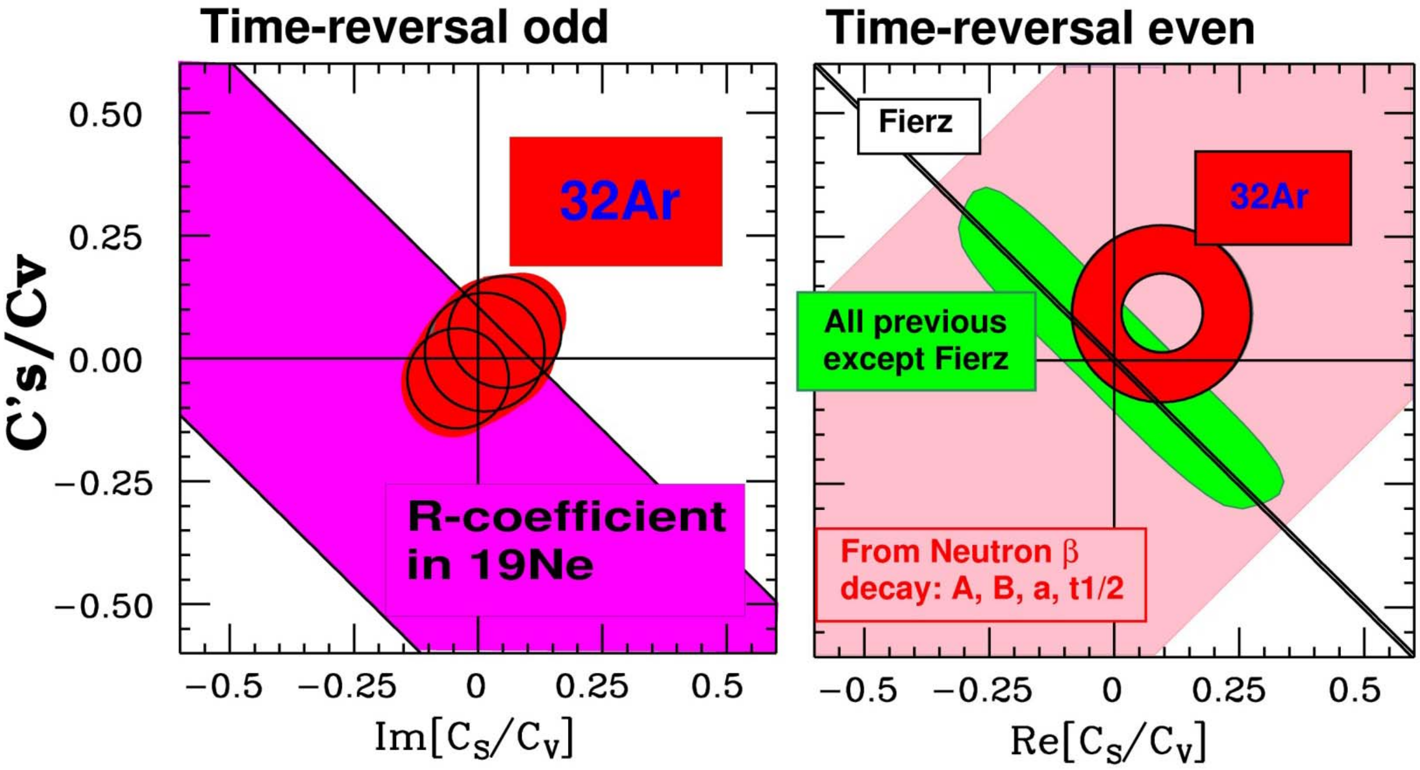
These events belong here

Experimental set-up



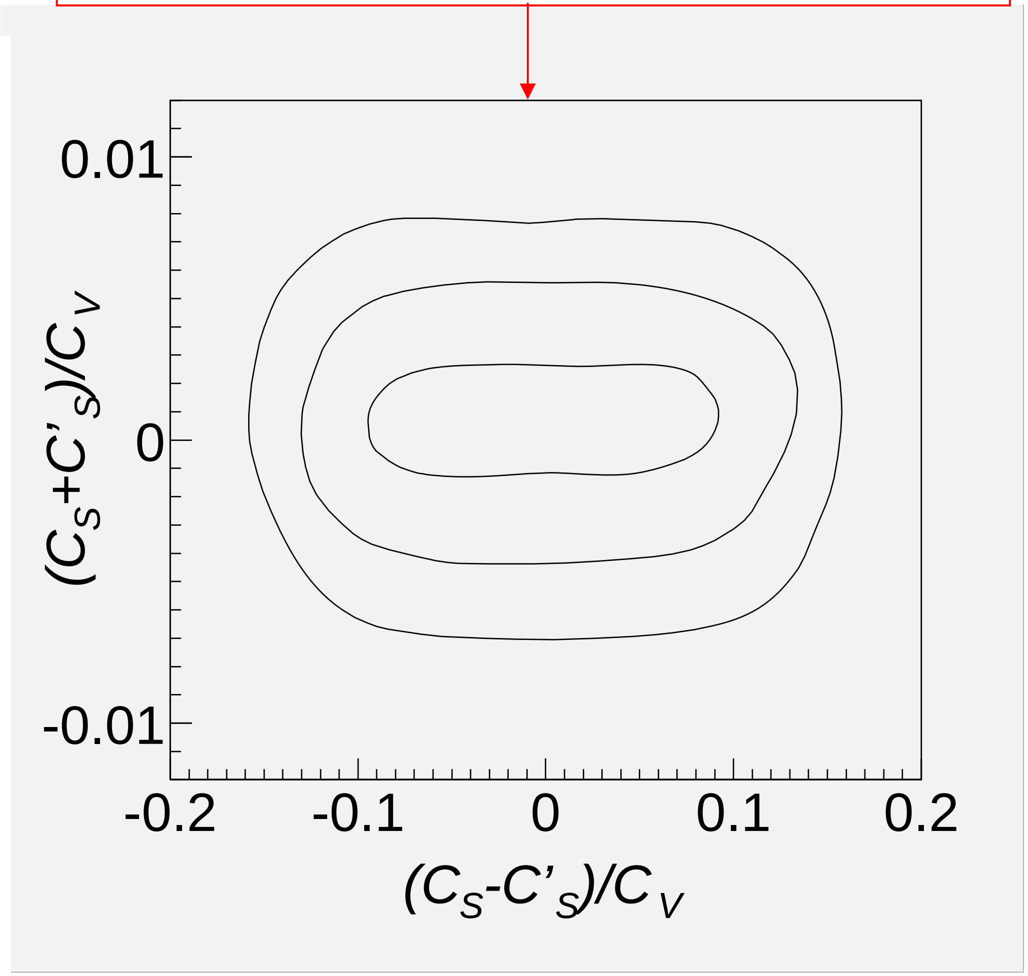
Super-conducting solenoid
B=3.5 Tesla

Consequences for couplings



Searches for scalar currents:
still looking.

From Severinjns et al. RMP **78**, 991 (2006)



Energy calibration with ^{33}Ar lines known from ^{32}S(p, γ)

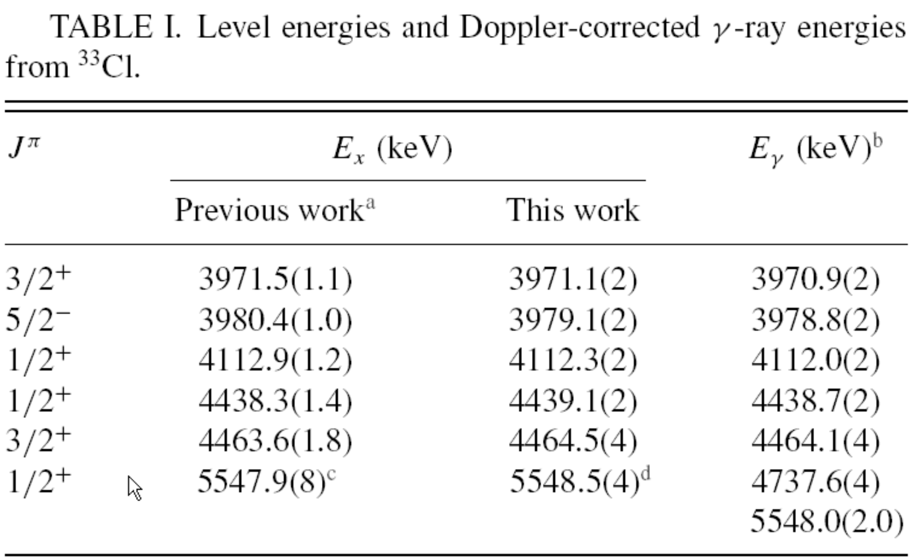
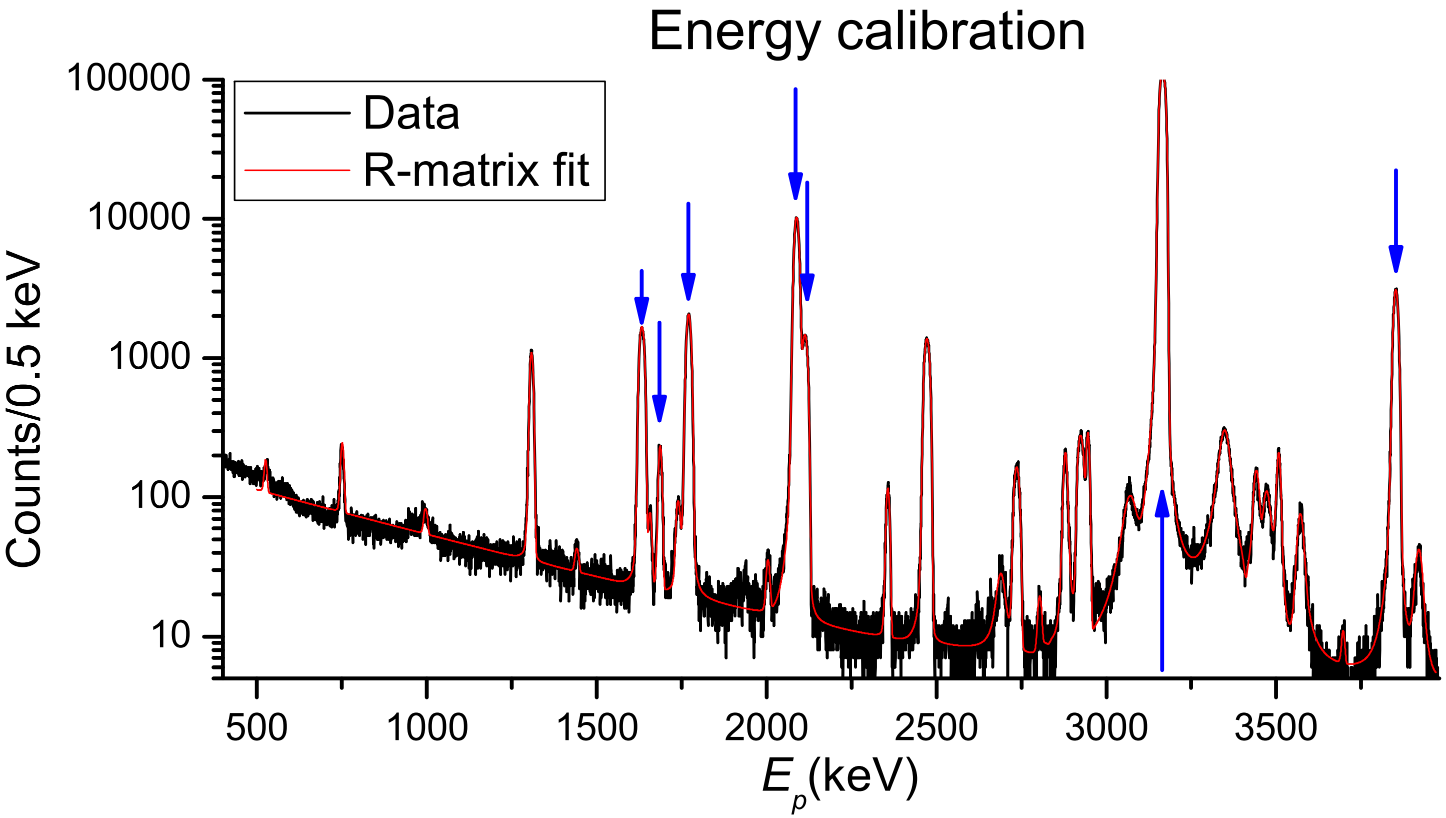
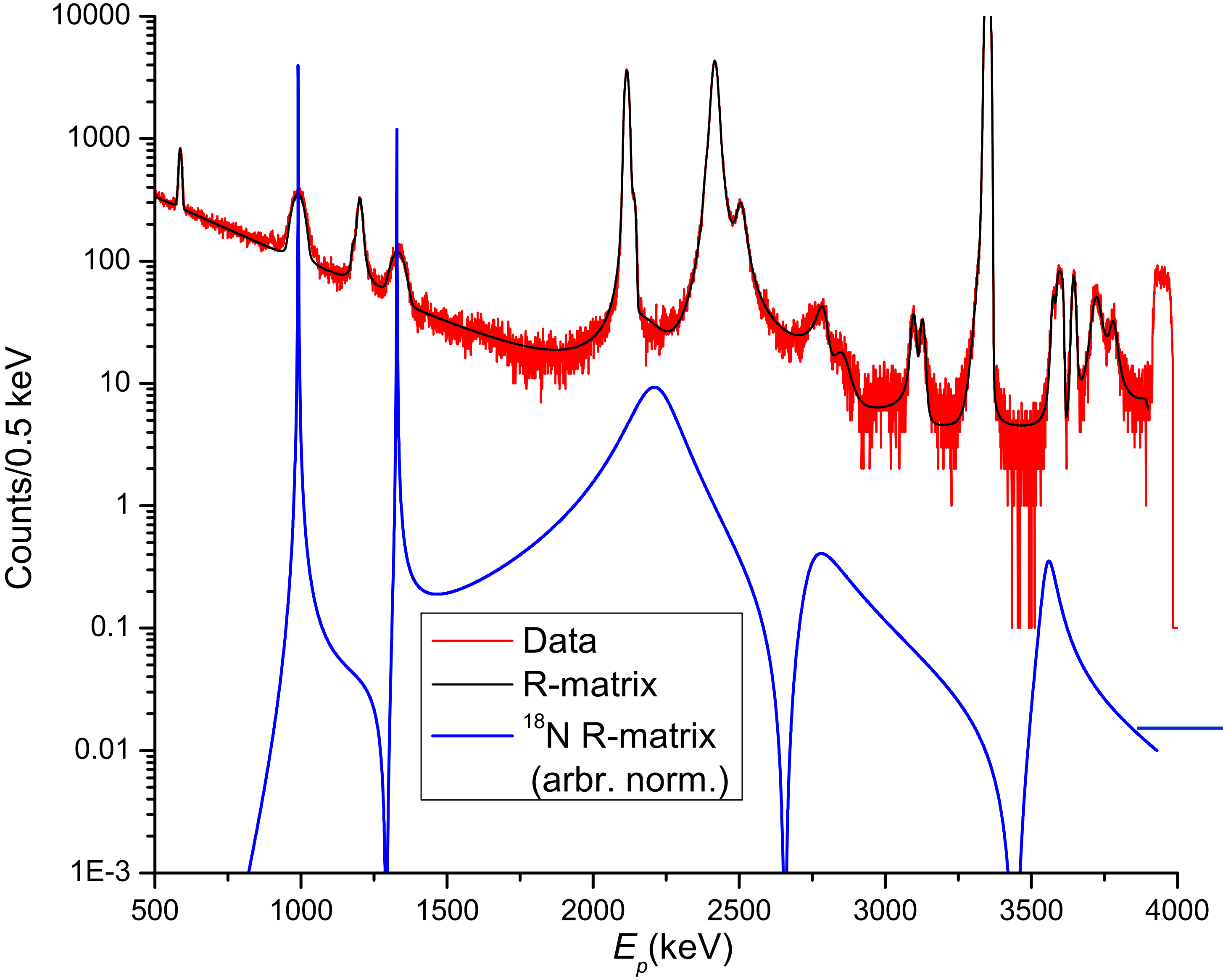


TABLE I. Level energies and Doppler-corrected γ-ray energies from ^{33}Cl.

J^π	E_x (keV)		E_γ (keV)[b]
	Previous work[a]	This work	
$3/2^+$	3971.5(1.1)	3971.1(2)	3970.9(2)
$5/2^-$	3980.4(1.0)	3979.1(2)	3978.8(2)
$1/2^+$	4112.9(1.2)	4112.3(2)	4112.0(2)
$1/2^+$	4438.3(1.4)	4439.1(2)	4438.7(2)
$3/2^+$	4463.6(1.8)	4464.5(4)	4464.1(4)
$1/2^+$	5547.9(8)[c]	5548.5(4)[d]	4737.6(4) 5548.0(2.0)

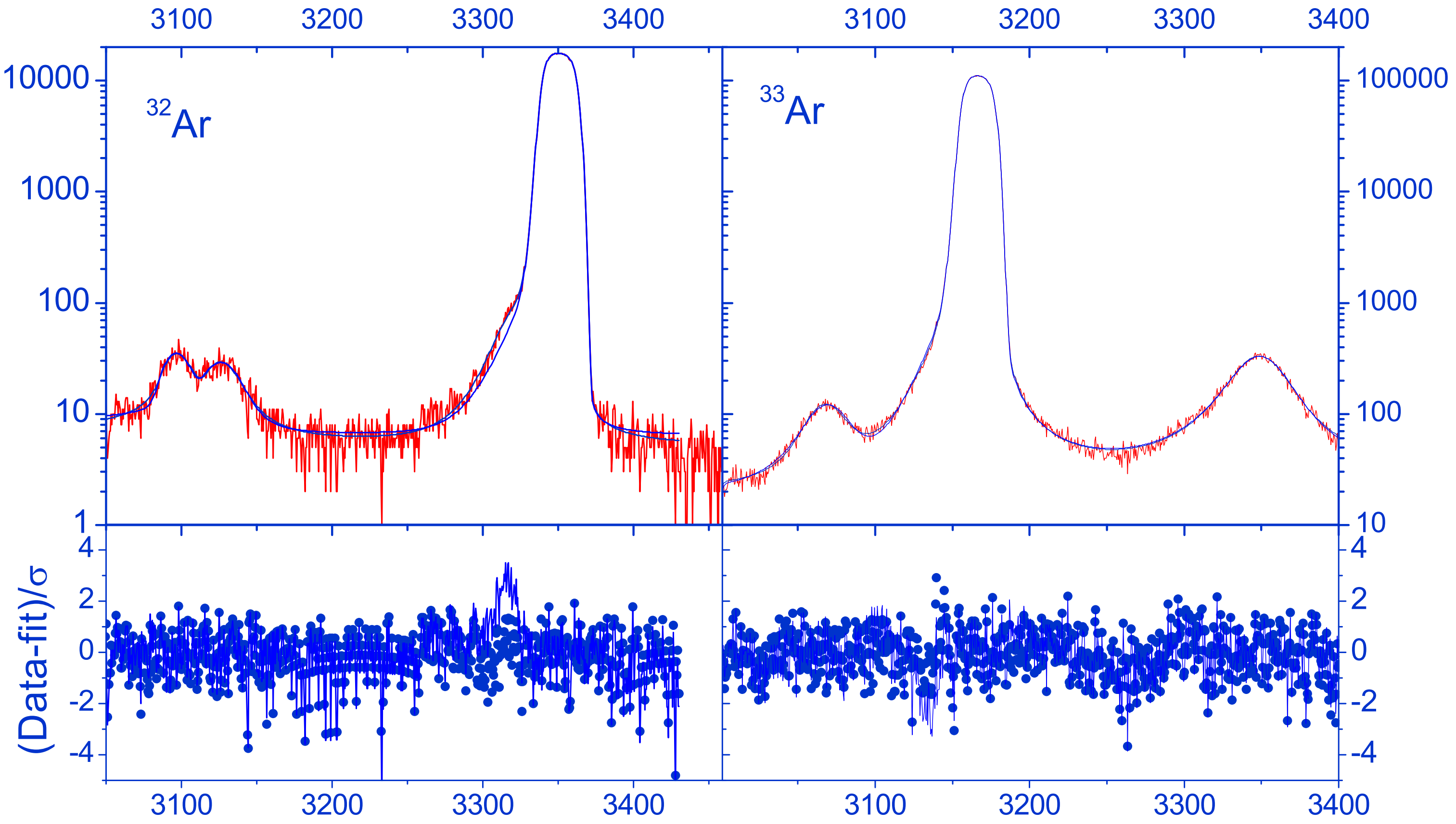


Energy calibration



Thanks to Lothar Buchmann

Simultaneous fit requiring ^{33}Ar to yield width in agreement with ^{32}S(*p*,*p*) measurements

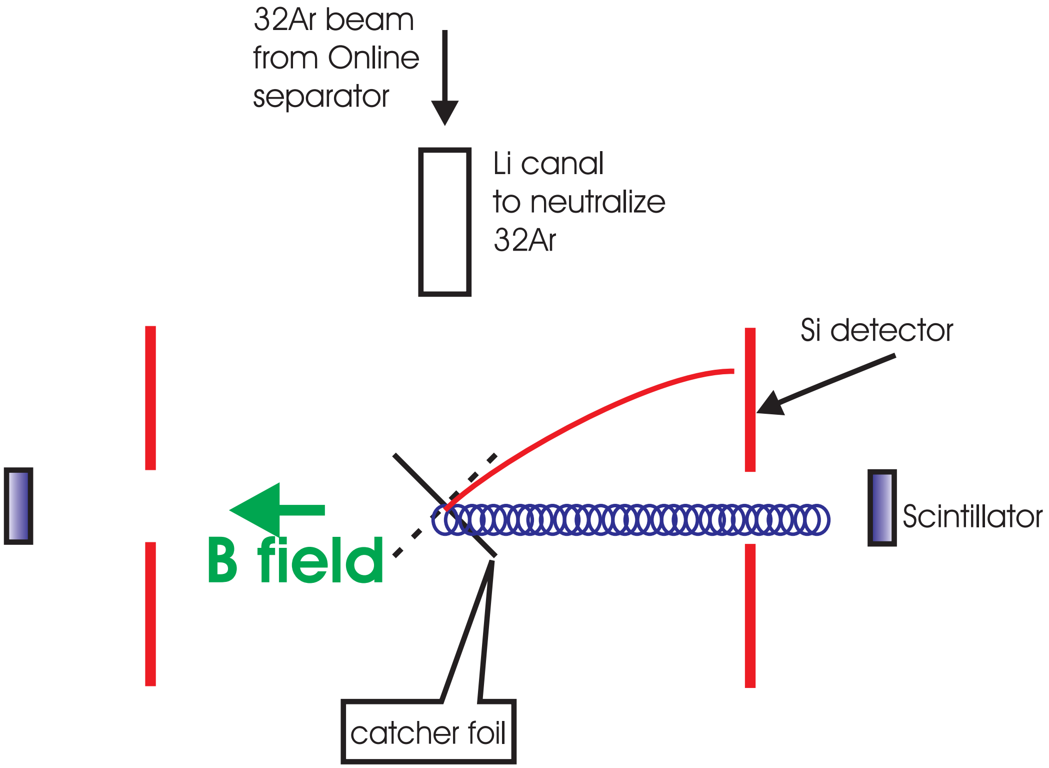


Preliminary result: ã=0.9980(51)

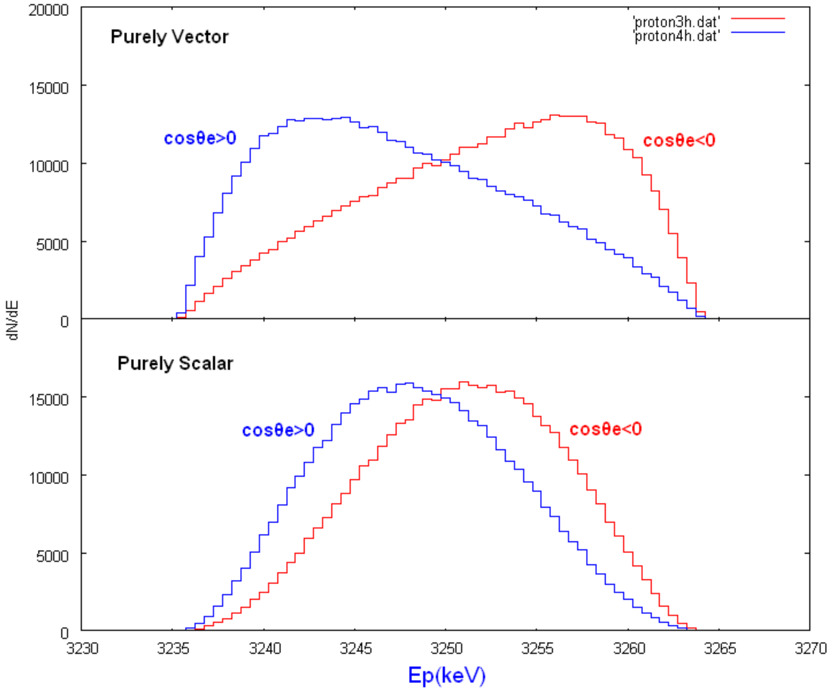
Spectroscopic data that affected the extraction of $\tilde{a}$

Data	Precision	Publication
Width of ^{33}Cl(T=3/2) state	9 eV	P.G. Ikossi et al., Phys. Rev. Lett. **36**, 1357 (1976); J.F. Wilkerson et al. Nucl. Phys. **A549**, 223 (1992);
Mass of ^{32}Ar	1.8 keV	K. Blaum et al., Phys. Rev. Lett. **91**, 260801 (2003).
Mass of resonances in ^{33}Cl	0.2-0.4 keV	M.C. Pyle et al. Phys. Rev. Lett. **88**, 122501 (2002); S. Triambak et al., Phys. Rev. C **74**, 054306 (2006).
Mass of ^{31}S	0.65 keV	Wrede et al. Phys. Rev. C **81**, 055503 (2010); A. Kankainen et al. Phys. Rev. C **82**, 052501 (2010);

Future plans: Melconian et al.



In the short term we can improve determination of *a* in 32Ar by a factor of 5!



This device can be used in FRIB as a spectroscopic tool to determine particle branches with high precision.

Interaction for GT transitions

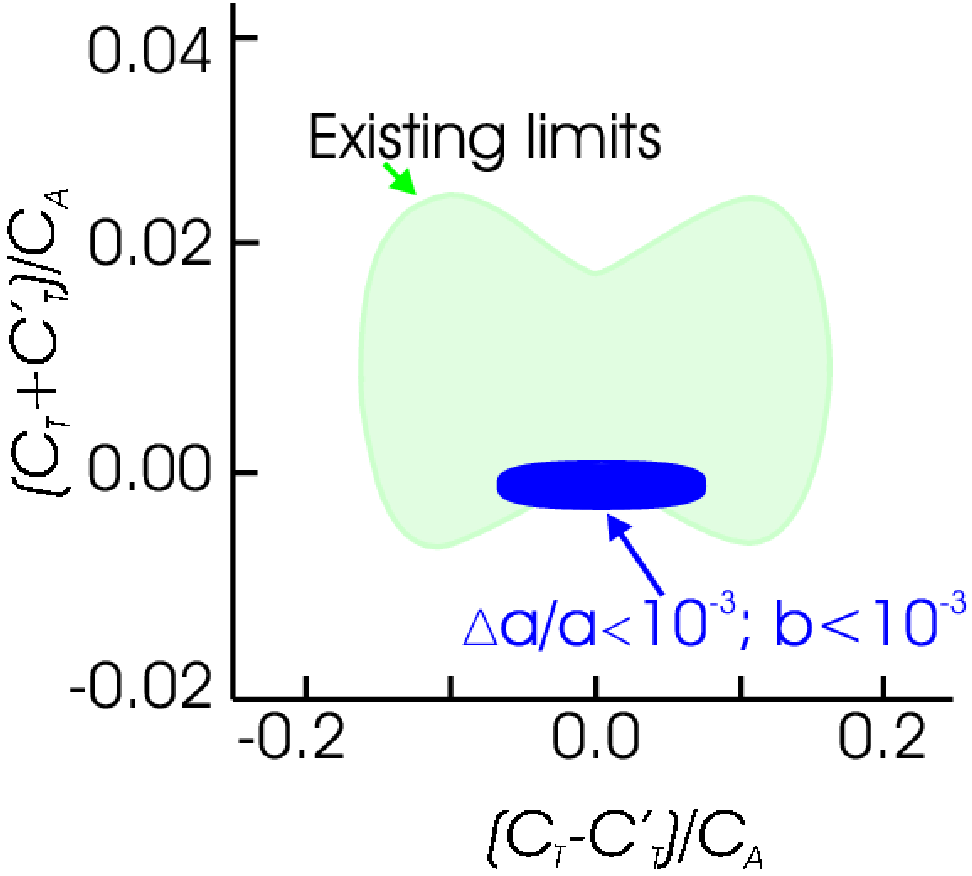
$$H = \overline{\Psi}_f \gamma^{\mu}\gamma_5 \Psi_i \quad 2C_A \overline{e}^{L} \gamma_{\mu}\gamma_5 \nu_e^{L} +$$
$$\overline{\Psi}_f \gamma^{\mu}\gamma^{\nu} \Psi_i \quad \left[(C_T - C_T^{'}) \overline{e}^{L} \gamma_{\mu}\gamma_{\nu} \nu_e^{R} + (C_T + C_T^{'}) \overline{e}^{R} \gamma_{\mu}\gamma_{\nu} \nu_e^{L} \right]$$

Decay rate:

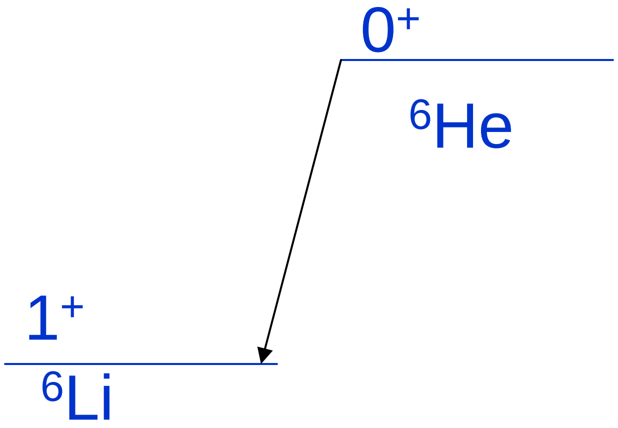
$$dw = dw_0 \left[1 + a \frac{\overrightarrow{p_e}}{E_e} \cdot \frac{\overrightarrow{p_\nu}}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

$$b \approx \frac{\mathrm{Re}\left[2C_A \left(C_T + C_T^{'} \right) \right]}{2|C_A|^2 + |C_T|^2 + |C_T^{'}|^2}$$

$$a \approx -\frac{1}{3} \frac{2|C_A|^2 - |C_T|^2 + |C_T^{'}|^2}{2|C_A|^2 + |C_T|^2 + |C_T^{'}|^2}$$



Searching for tensor currents in ^{6}He: Little a



0^+

^{6}He

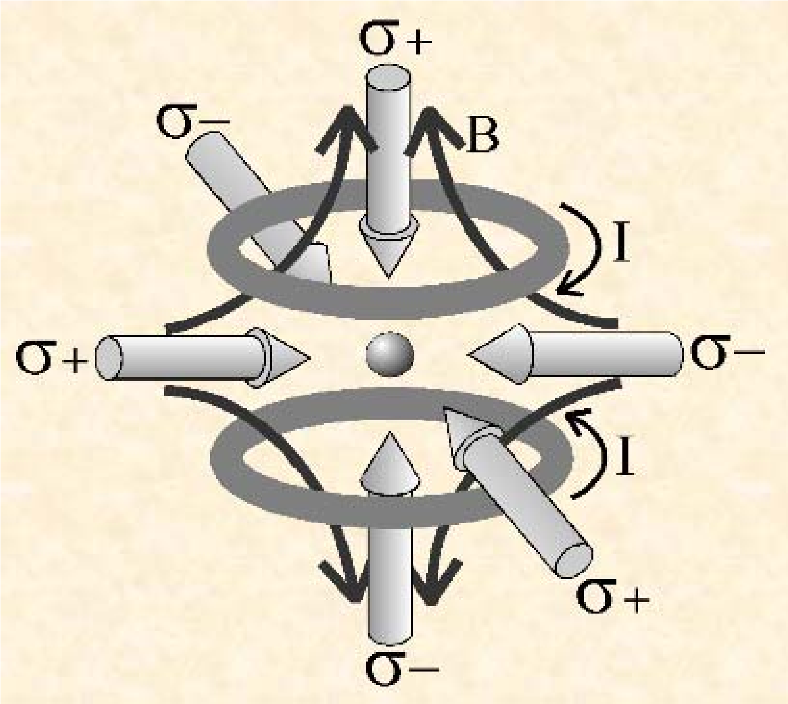
1^+

^{6}Li

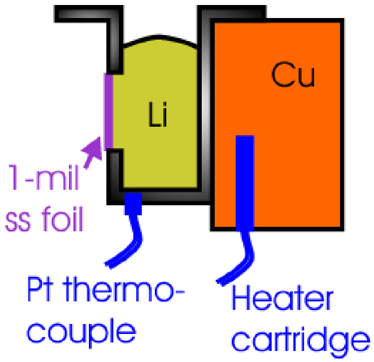
- Intense & stable source
- Simple decay
- Light nucleus
- Large endpoint (3.5 MeV)

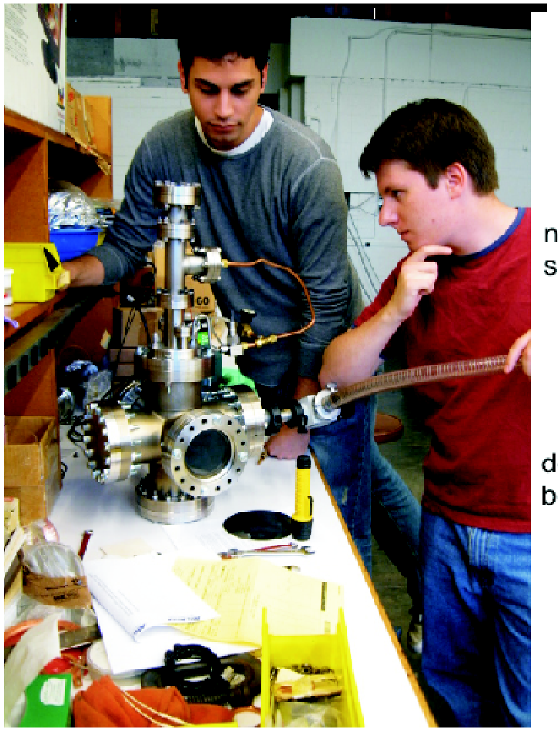
Need to detect ^{6}Li recoil with kinetic E=1-2 keV. Not possible by implantation…

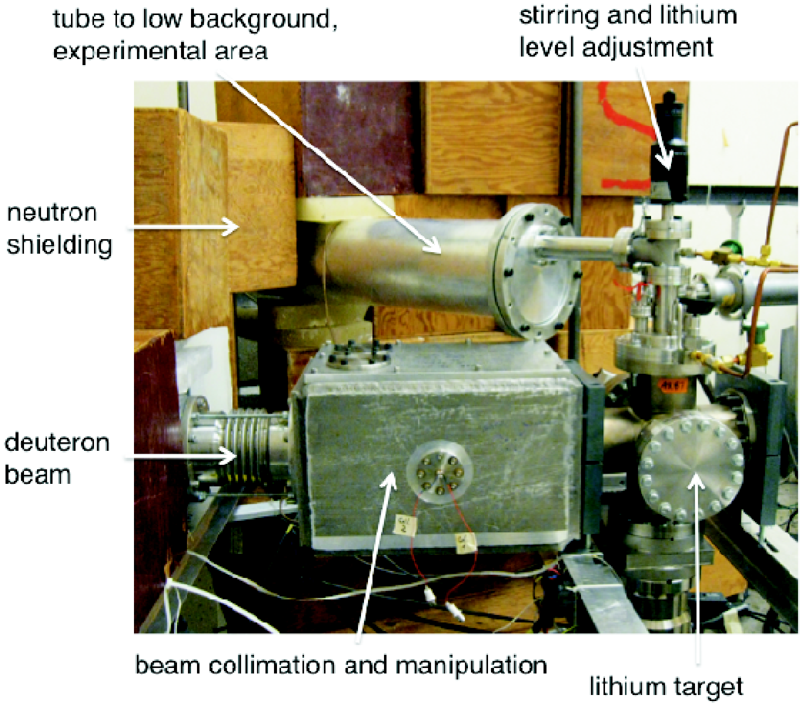
Solution: can use optical (MOT, dipole) traps.



Production of ^{6}He at CENPA



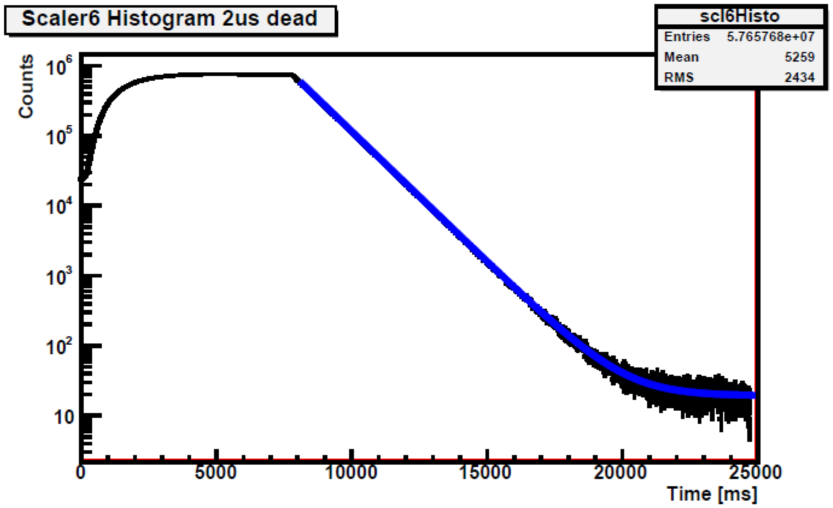


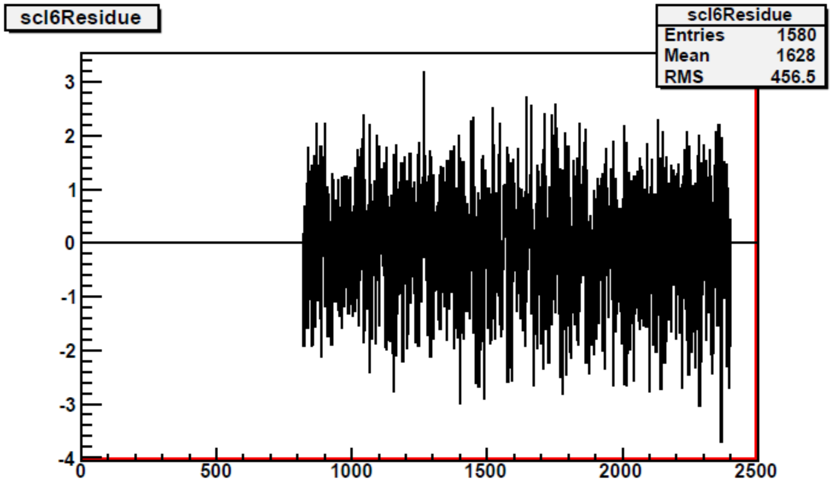


Now have a reliable source of ^{6}He yielding 10^9 atoms/s in a clean room!
A. Knecht et al. submitted to NIM.

Lifetime of ^{6}He and gA

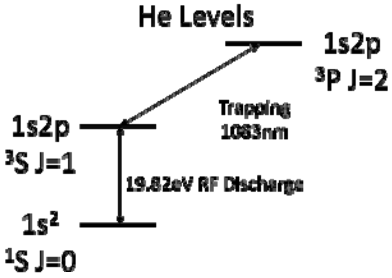
- Two previous experiments disagree by 9 ms
- Together with neutron and ^{3}H shed light on g_A renormalization by using *ab initio* (Wiringa et al.'s) calculations.
- Good grounds for beginning students to train on data analysis issues.
- Have already taken data that narrow statistical uncertainty to better than 0.1 ms!



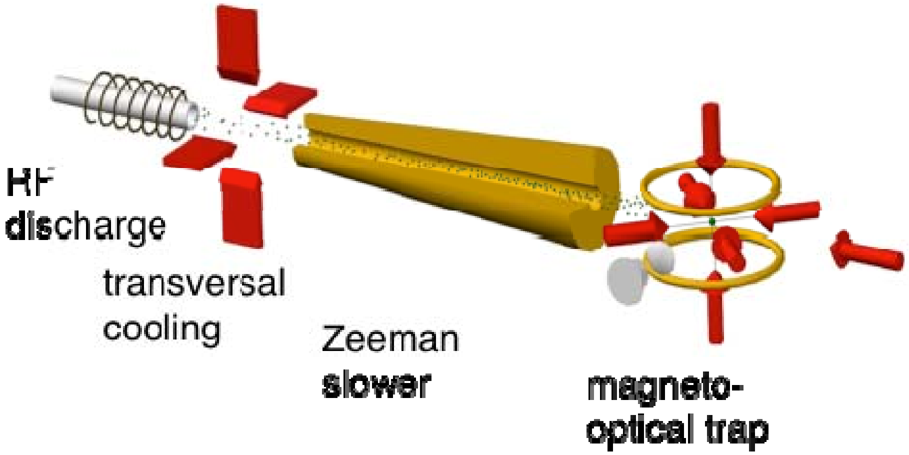


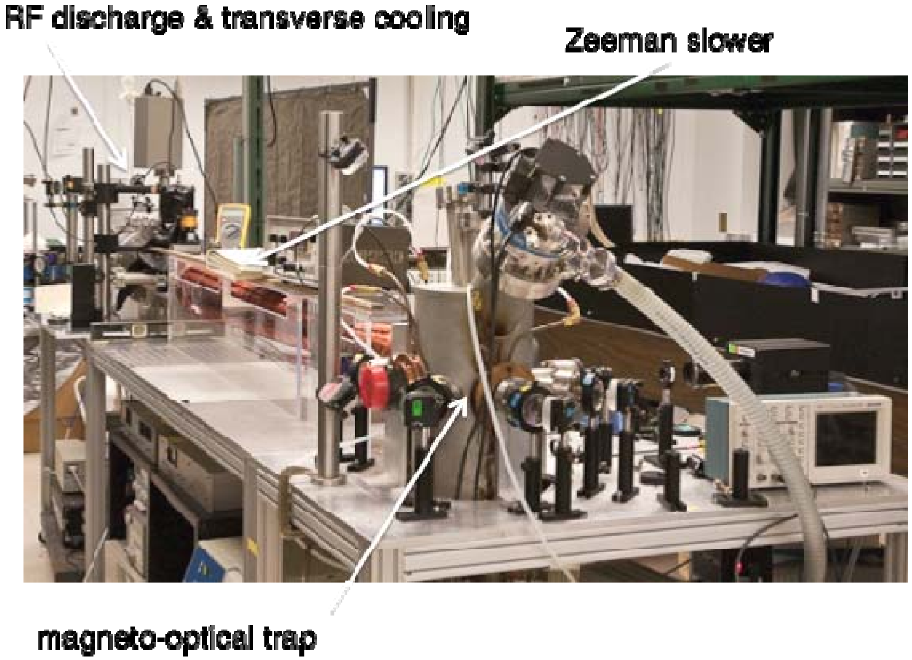
Trapping of ^{6}He

- RF discharge in xenon/krypton to excite into metastable state
- Cycling on 1083 nm transition to transversely cool, slow down and trap magneto-optically



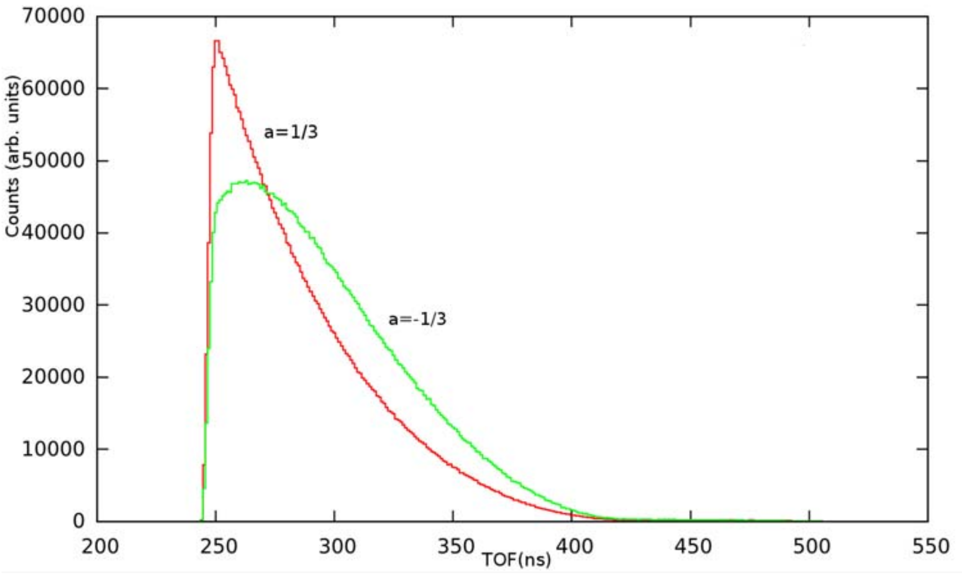
- Trapped atoms transferred to detection chamber with dipole trap
- Based on experience from ^{6}He, ^{8}He charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL **93**, 142501 (2004)
  P. Mueller et al., PRL **99**, 252501 (2007)

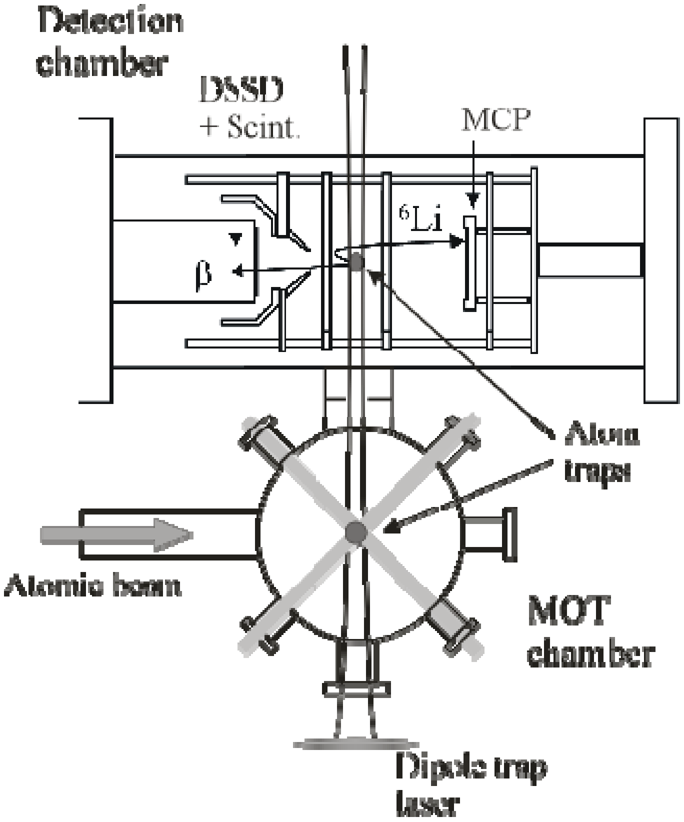




^{6}He Little a, detection

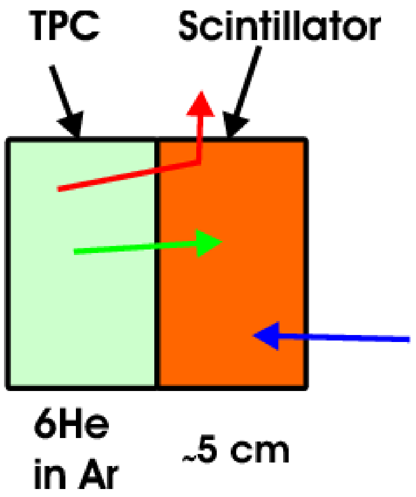
- Electron and ^{6}Li recoil nucleus detected in coincidence
- ΔE-E scintillator system for electron detection (energy, start of time-of-flight)
- Micro-channel plate detector for detection of recoil nucleus (position, time-of-flight)





6He: measuring the spectrum in search of the `Fierz interference’

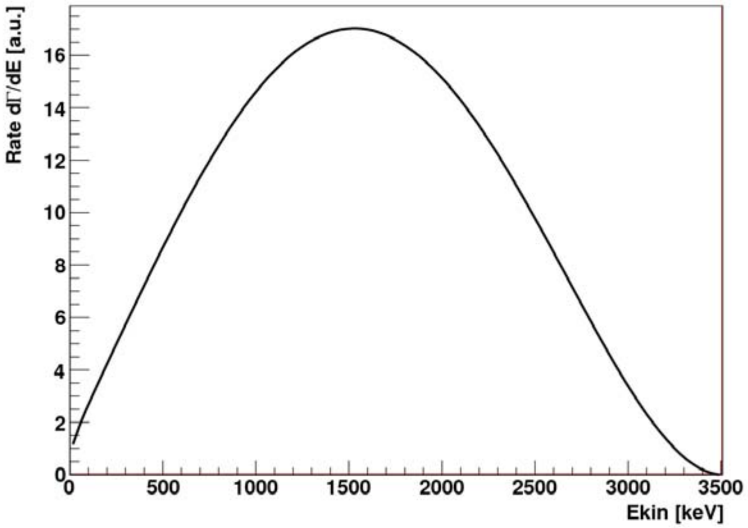
Use TPC to
- Identify backscattering
- Veto non-contained events, backgrounds,
- Oblique-incidence events

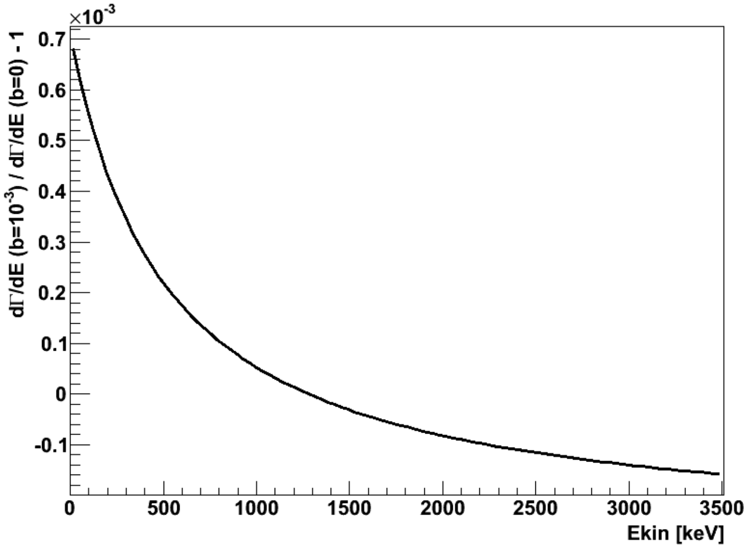


Calibration of line shapes very important.

Follow Tseung, Kaspar, Tolich, arXiv:1105.2100v1:

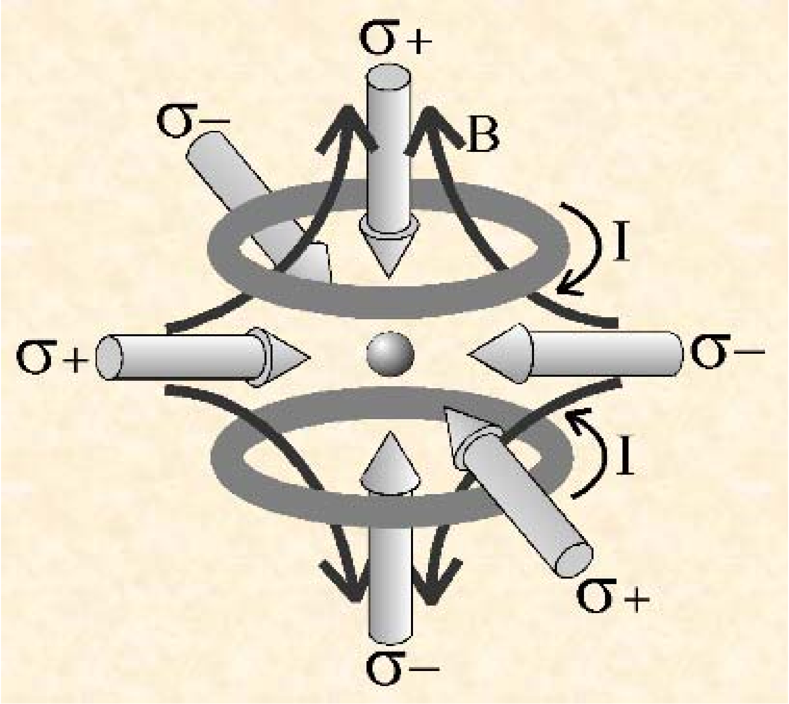
Use ^{12}C(p,p’) to generate 4.4 MeV photons an then scatter in TPC to generate Compton electrons.

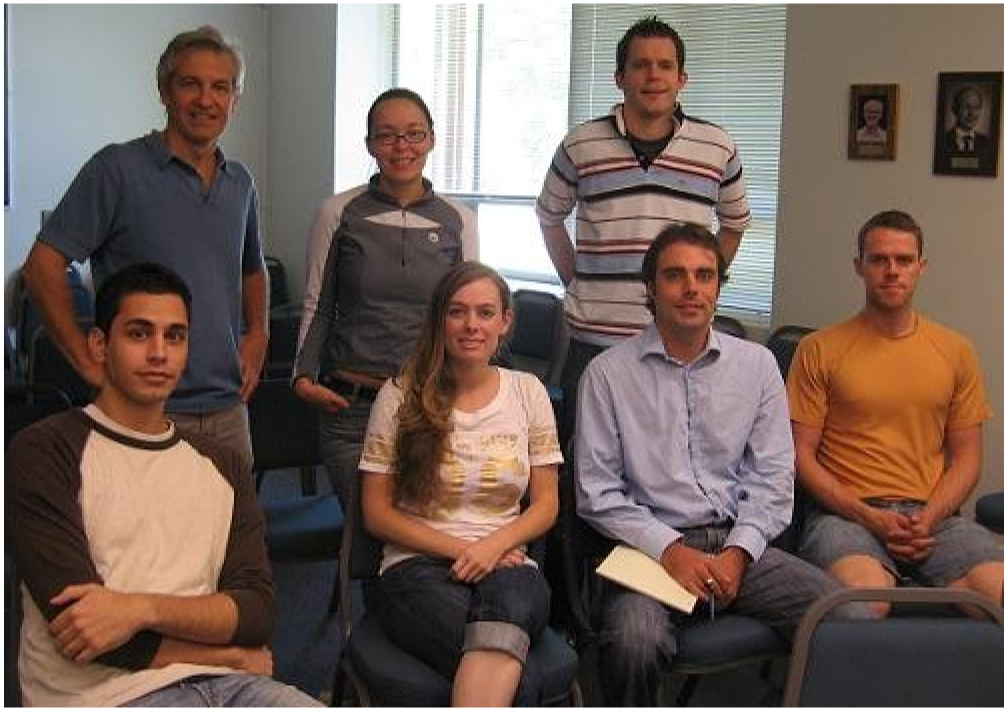




Ongoing simulations to understand the limits of our methods

Laser trapping of 6He at CENPA should start this year!





The End