Search for time-reversal symmetry breaking in neutron beta decay

emiT Collaboration

NIST, Gaithersburg
P. Mumm, J. Nico, A. K. Thomson

University of Washington
A. Garcia, J.F. Wilkerson(Presently at UNC)

University of Michigan
T. Chupp, R.L. Cooper, K. Coulter

Tulane University
C. Trull, F.E. Wietfeldt

Hamilton College
G.L. Jones

University of California, Berkeley/ LBL
S.J. Freedman, B.K. Fujikawa

CP and T violation are sensitive probes to search for new physics

Can there be additional CP violation to be discovered in beta decay?

Explaining the observed baryon asymmetry of the Universe requires CP violation larger than what is provided by the phase in the CKM matrix. One possibility is that this extra source of CP violation should be observable in nuclear beta decay.

Standard Model Weak Interaction at low energies:

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

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 ~*10^{-3}

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

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

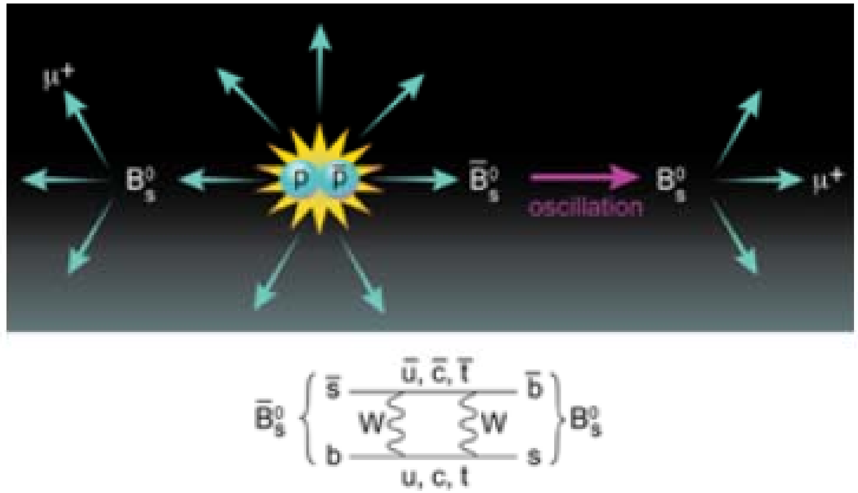
Although we look for a T-odd/P-even signal, people have made connections to EDMs (T-odd/P-odd):

Kurylov, McLaughlin, Ramsey-Musolf PRL **63**, 076007 (2001)
Haxton, Horing, Musolf, PRD **50**, 3422 (1994)
Khriplovich, Pis’ma Zh. Eksp.Teor. Fiz. **52**, 1065 (1990)

These limits are more stringent than the present work, but model dependent.

New results from D0 show unexpected CP-violation in B^0_s B^0_s

A new source of *CP* violation?



Evidence for an Anomalous Like-Sign Dimuon Charge Asymmetry

V. M. Abazov et al. (D0 Collaboration)

Phys. Rev. Lett. **105**, 081801 (2010) – Published August 16, 2010

Download PDF (free)

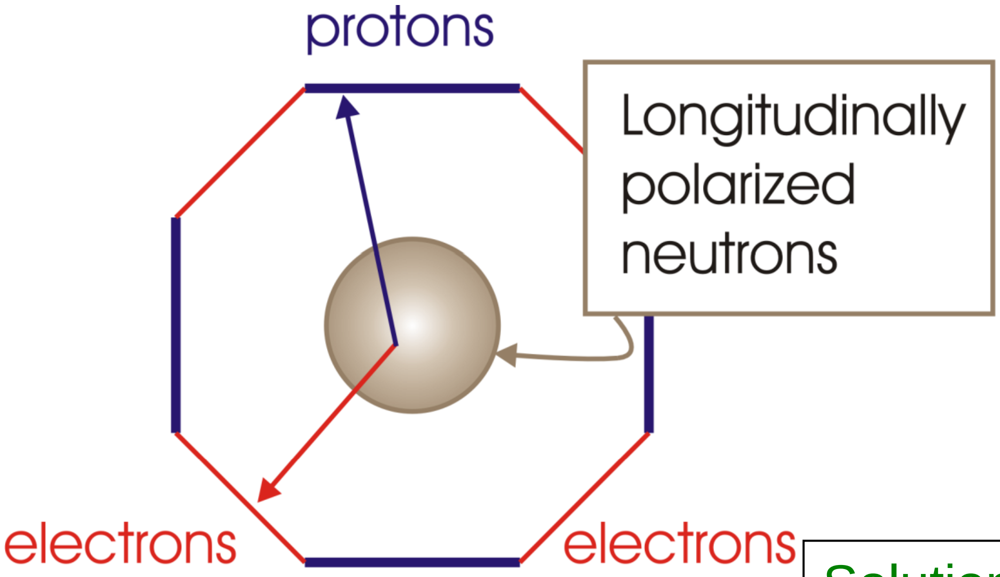
Evidence for an anomalous like-sign dimuon charge asymmetry

V. M. Abazov et al. (D0 Collaboration)

Phys. Rev. D **82**, 032001 (2010) – Published August 16, 2010

emiT's basic sketch:
polarized neutrons;
detect protons and electrons.

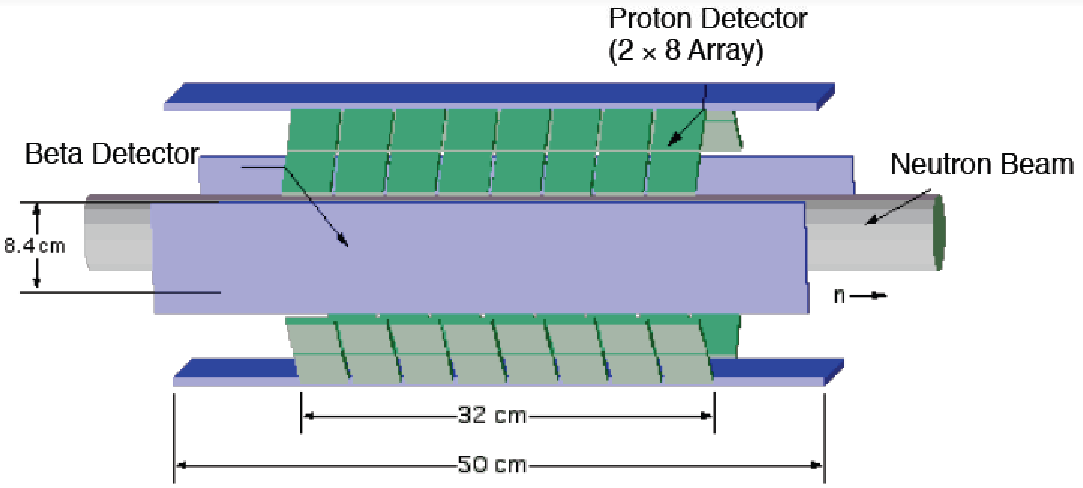
$$dw = dw_0\left[1 + \ldots \frac{\langle \vec{J} \rangle}{J} \bullet \left(D\frac{\vec{p}_e}{E_e} \times \frac{\vec{p}_\nu}{E_\nu} \right)\right]$$

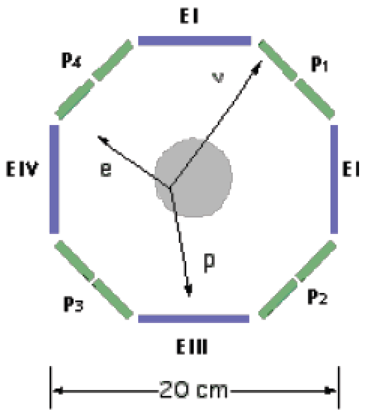


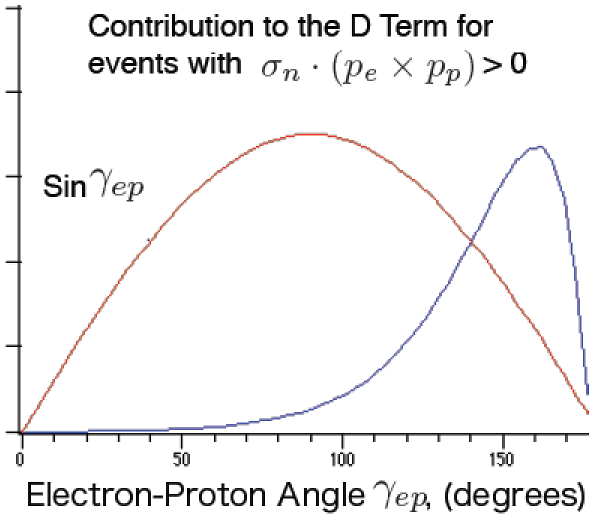
Some challenges:
1) Polarize/flip neutrons;
2) Detect <1 keV protons;
3) Detect electrons down to
90 keV with minimal backscatter;

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



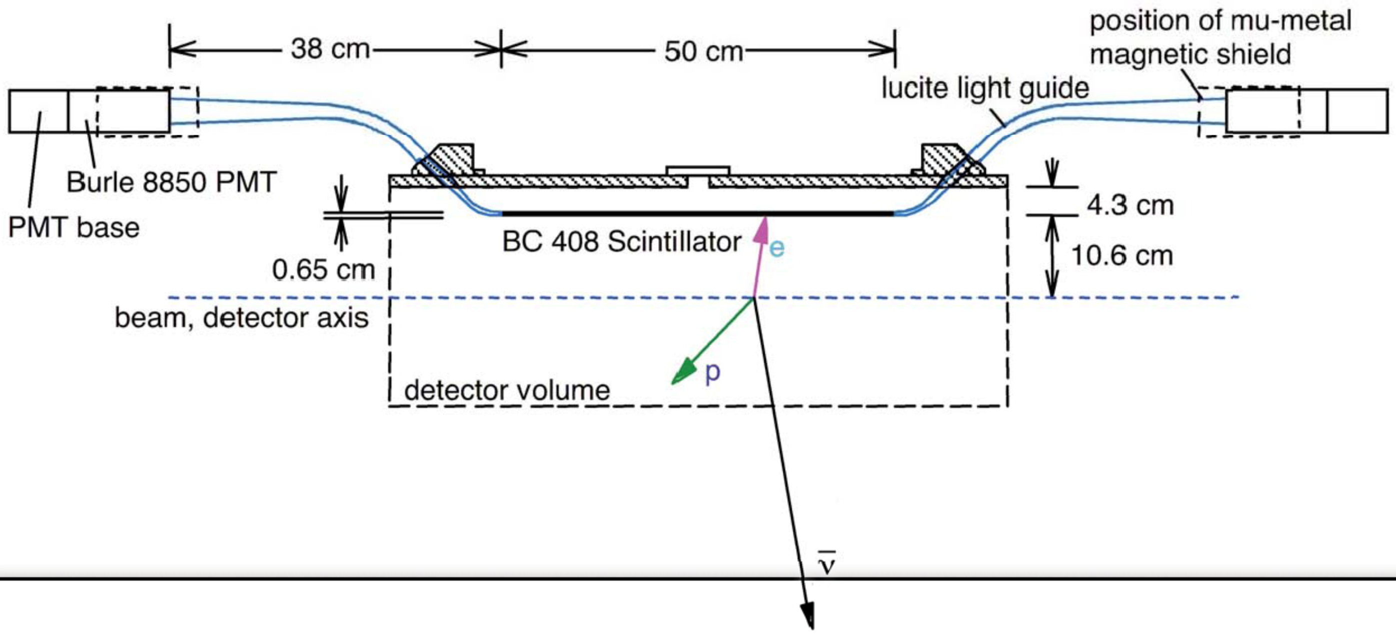




- Statistical precision requires highest possible coincidence rate
- High <u>continuous</u> neutron flux (1.7 x 10^8 cm^{-2} s^{-1} at “C2” collimator)
- Symmetrical, segmented detector to minimize or cancel instrumental asymmetries that could yield false coincidences
- Detector geometry to maximize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

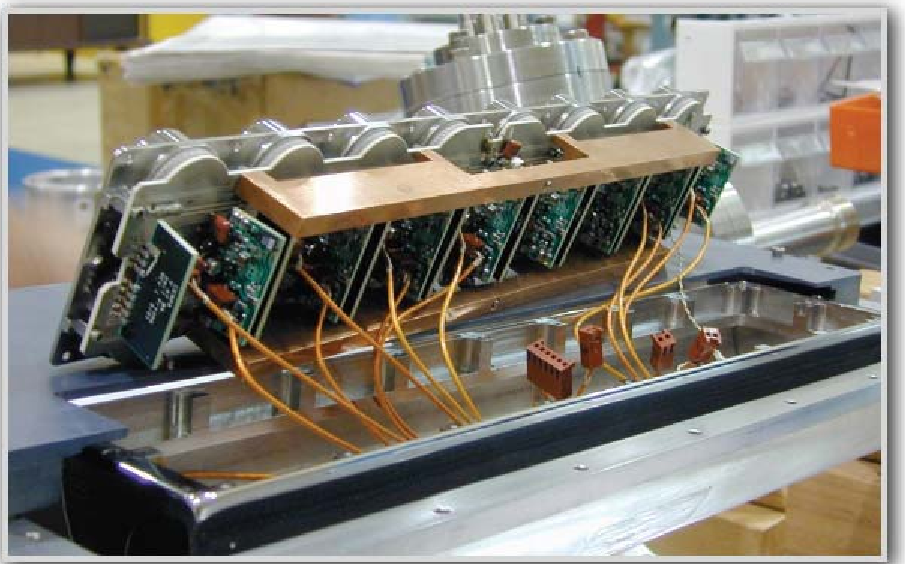
emiT gained a factor of three increase in “effective” beam flux over previous “right angle” geometry beam experiments

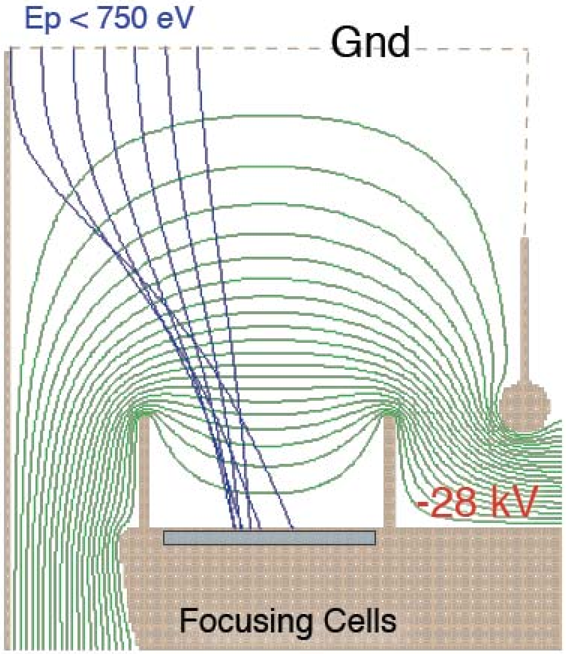
emiT Detector: Beta detectors (4 panels and support hardware)



- 0.1 ns timing resolution (Pulse arrival time may be used to determine position)
- Thresholds (35-50 keV) (Software cut on geometric mean)
- Resolution ~18% at 1 MeV
- Cosmic ray muons deposit ~ 1.42 MeV (well separated)
- Overall rate 300 s^{-1} per paddle (Signal to accidental ~ 1 to 1)

emiT Detector: Proton Paddle Assembly





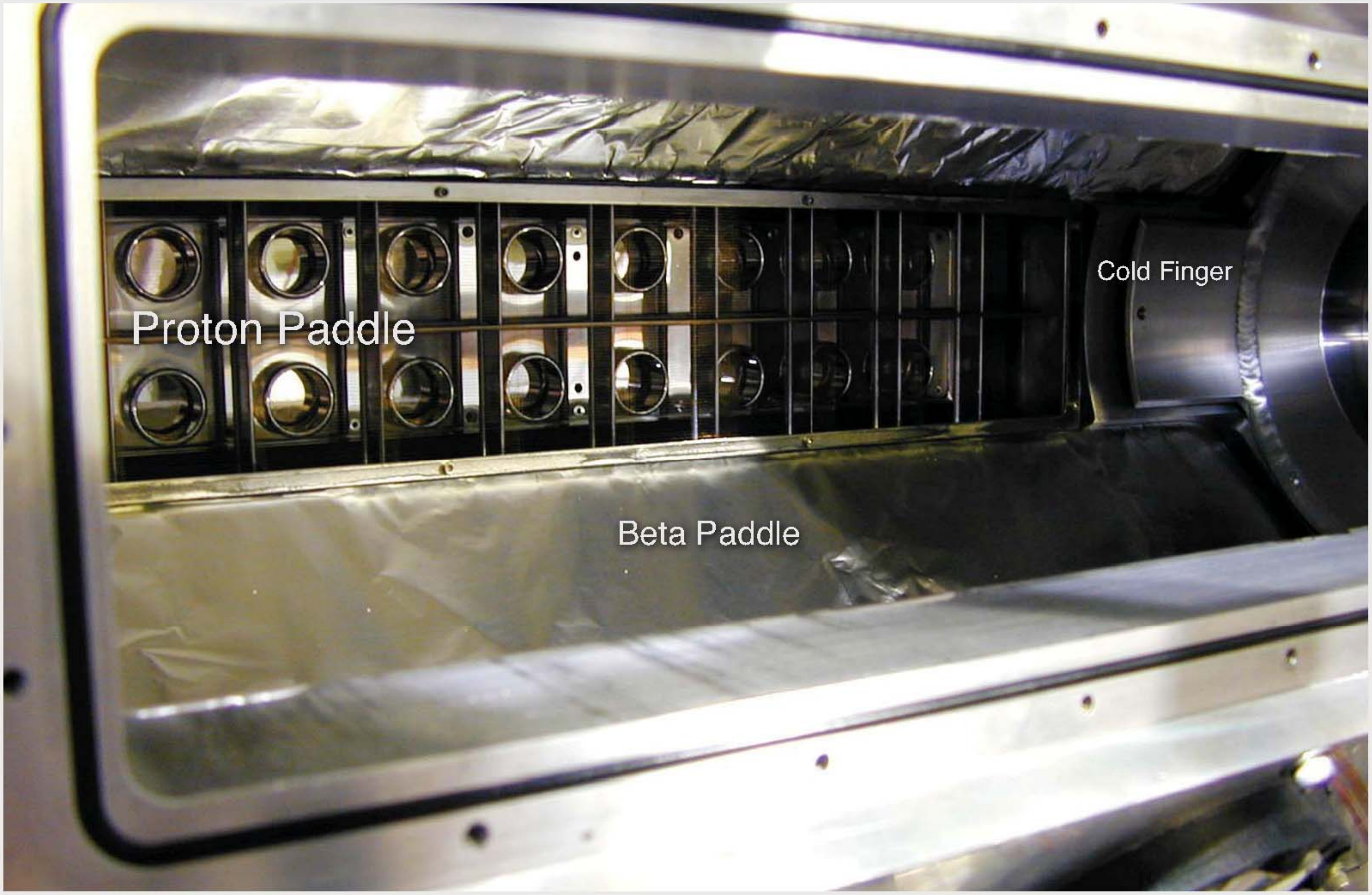
Focusing efficiency reaches 90%
(Voltage Dependent)

Required detector area reduced by ~ 80%

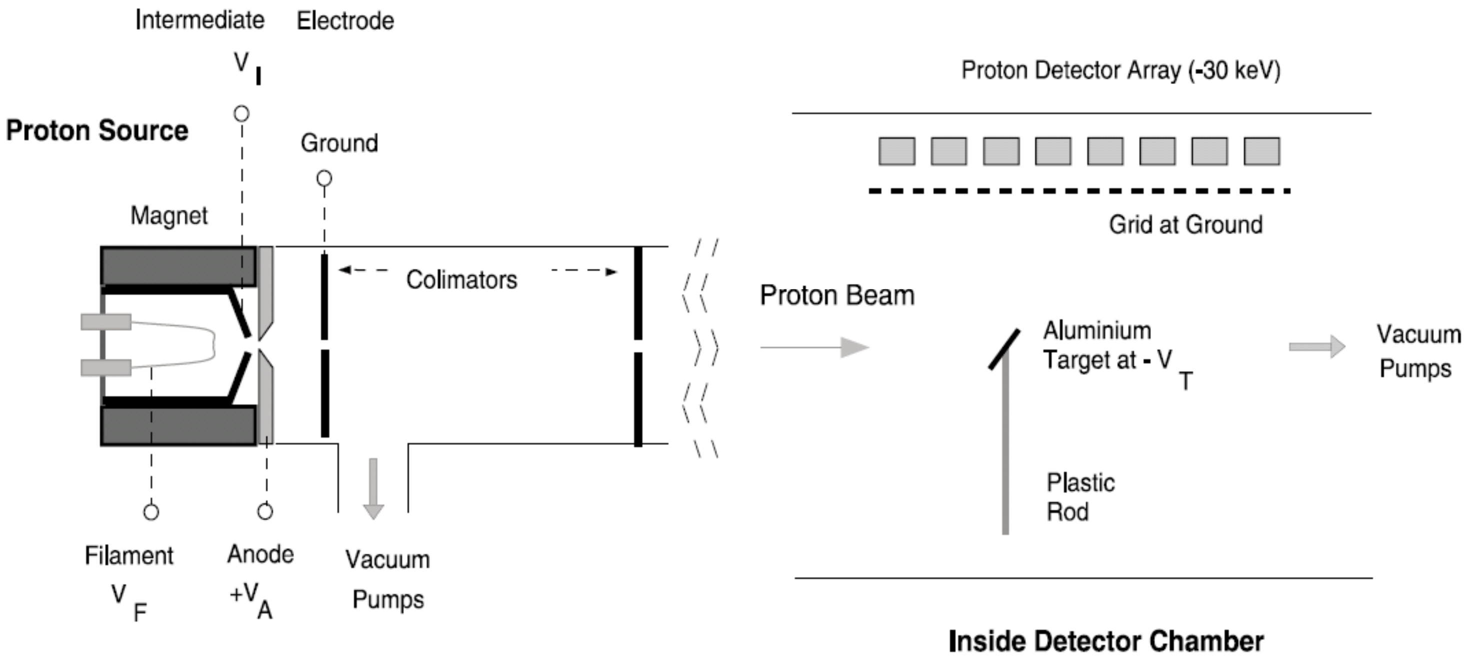
Surface barrier detectors

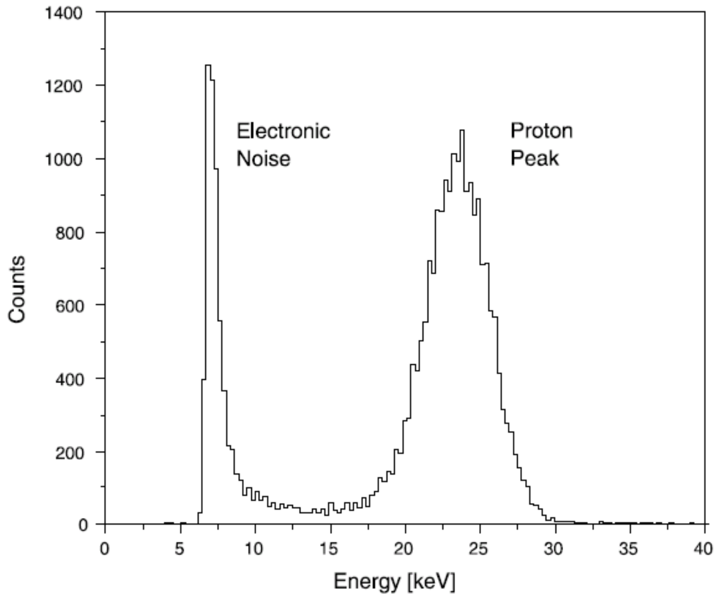
- 20 μg Au (less energy loss)
- 300 mm^2 active area
- 300 μm depletion depth
- Room temperature leakage current ~ μA

emiT Detector: Interior View



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



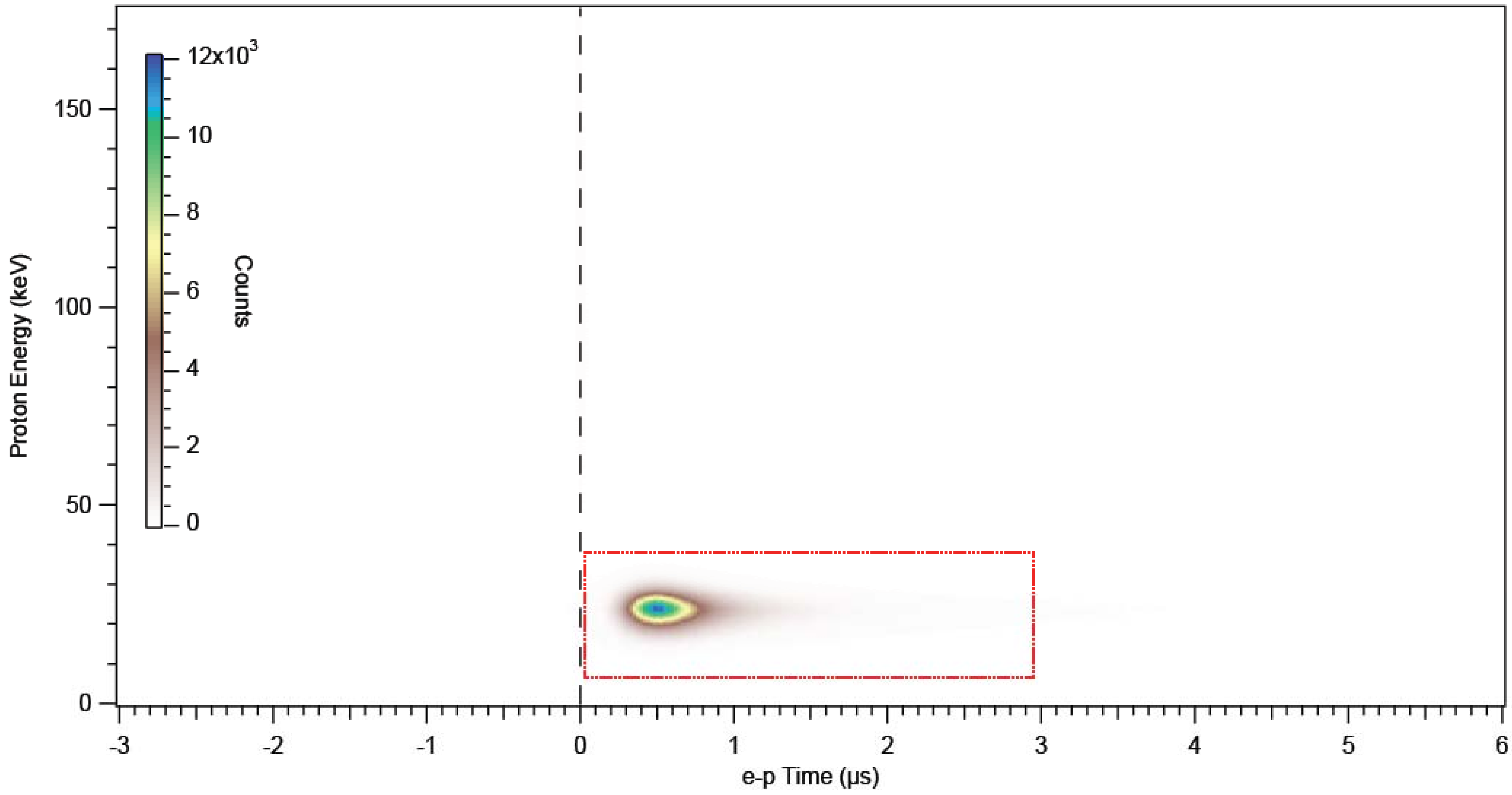


Detector showed good performance and good signal above noise.

F. Naab et al.

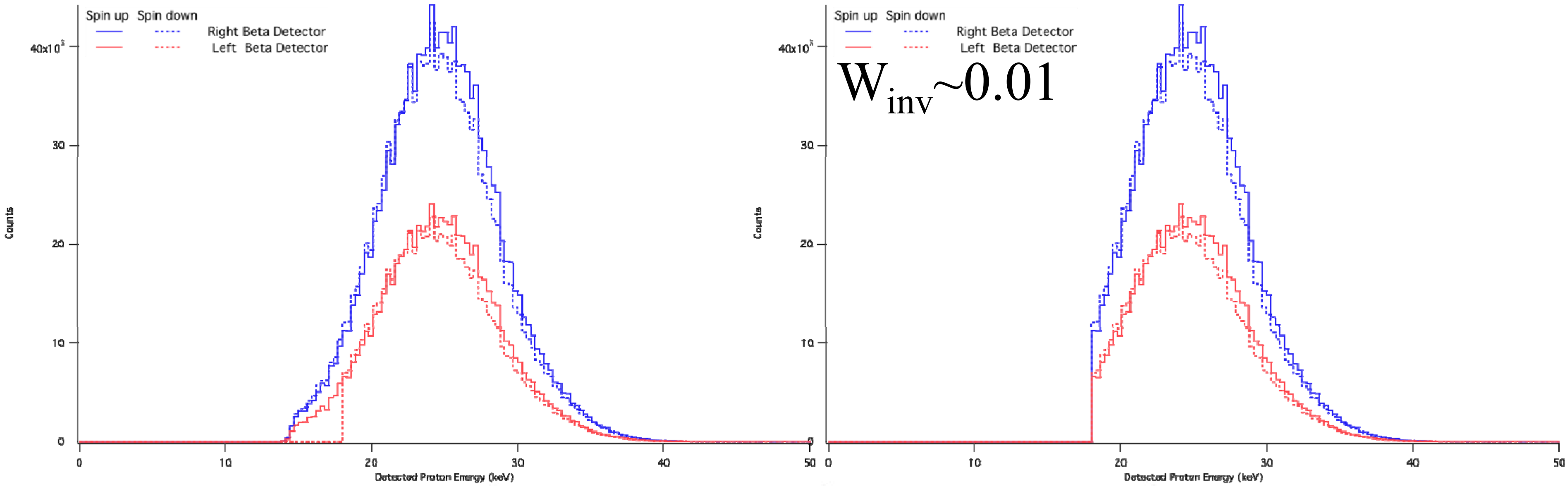
NIM **197**, 278 (2002)

emiT: flitered coincidence data

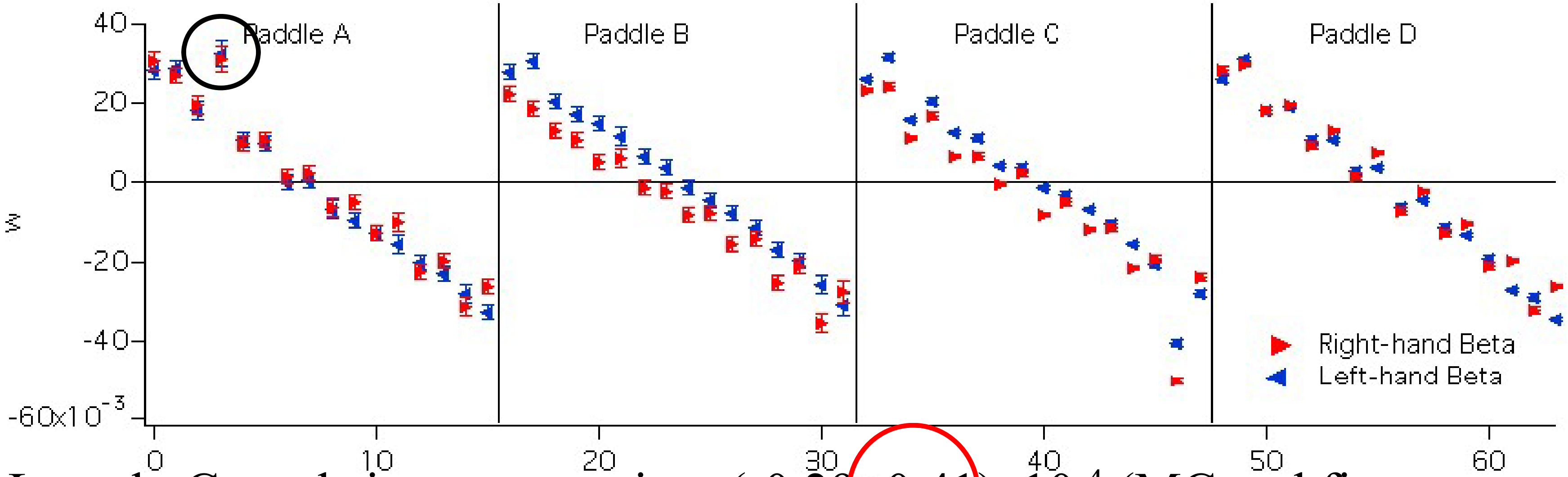


- 3 Hz singles per proton Surface Barrier det
- 0.55 Average coincidence rate per pair
- 25 Hz average coincidence rate
- Essentially no high voltage noise (Modified focusing assembly)
- Signal to noise better than 100/1
- Clear separation of cosmic Landau peak

Proton threshold effect



W_{inv}~0.01

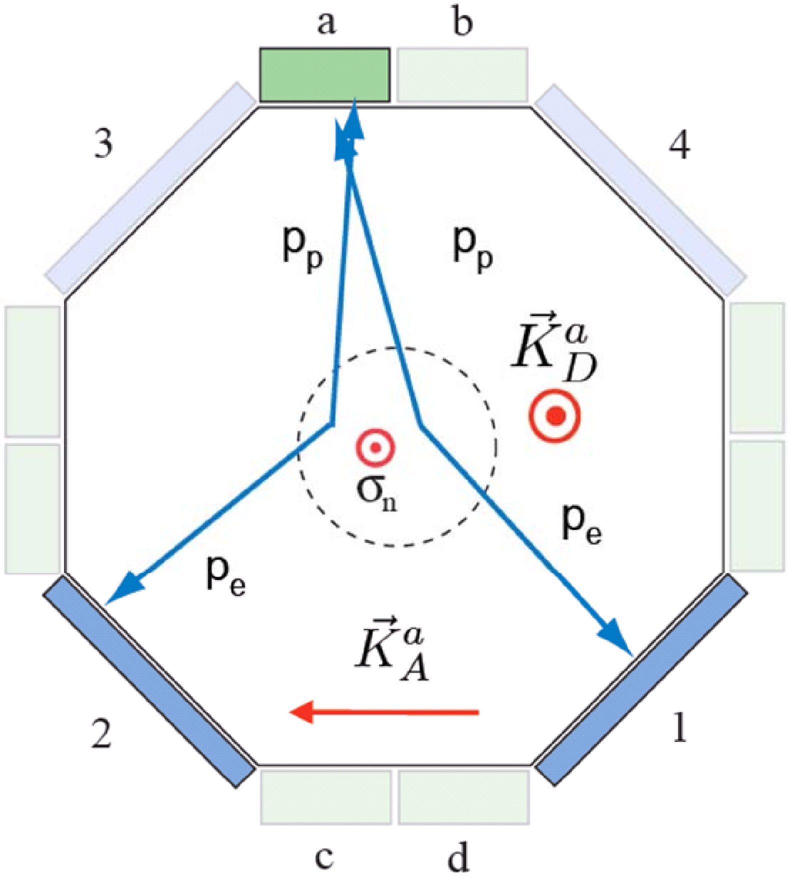


Largely Cancels in *v* - correction: (-0.29±0.41)x10^{-4} (MC and fits to spectra)

threshold variations, etc.

Expect number of coincidences between a proton and beta detector:

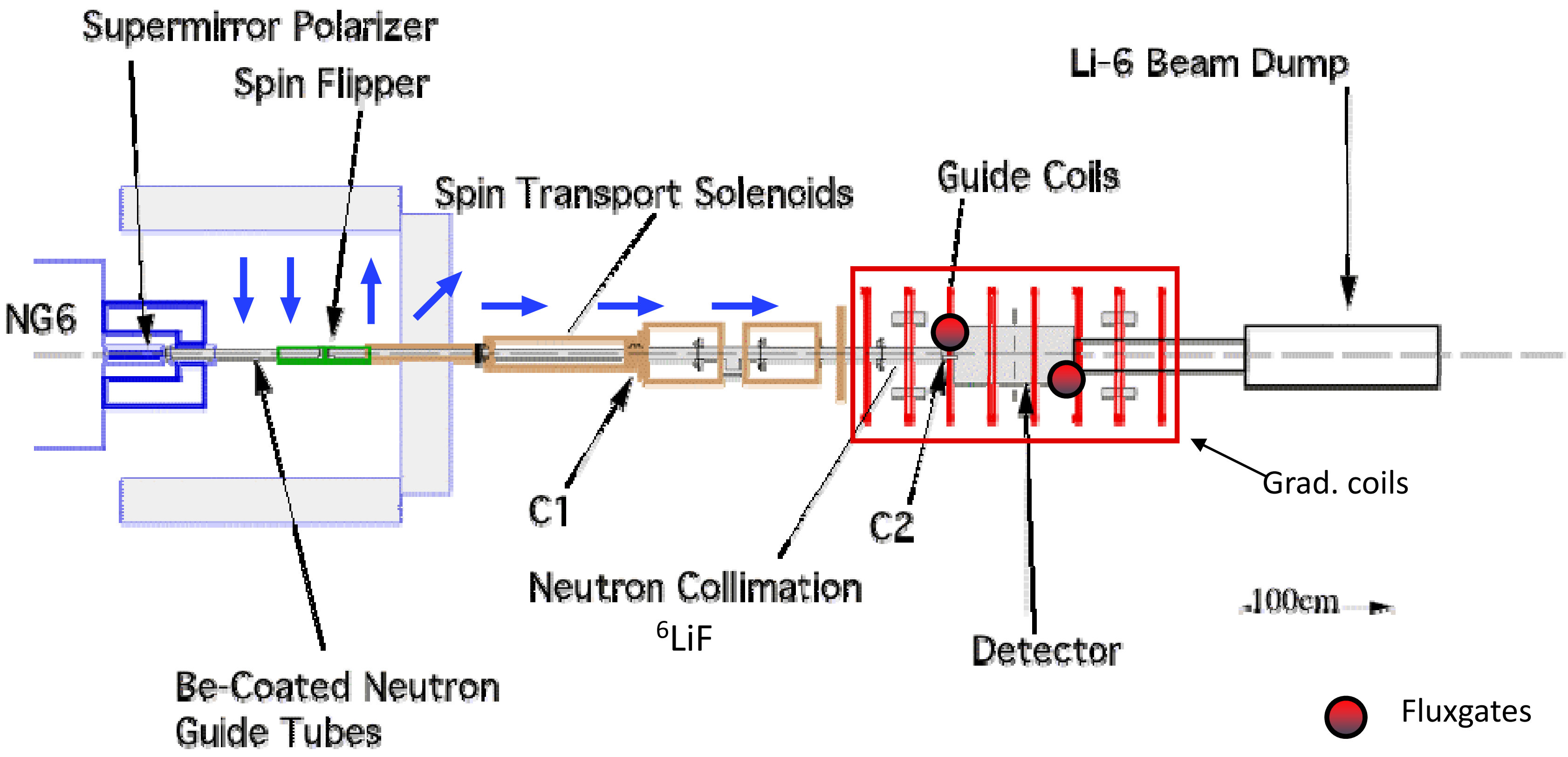
$$N^{\vec{J},R} = N\varepsilon_R\varepsilon_p\left(K_1^{\ R} + aK_a^{\ R}\right)\left\{1+\vec{J}.\left(A\overrightarrow{K_A}^{R} + B\overrightarrow{K_B}^{R} + D\overrightarrow{K_D}^{R}\right)\right\}$$



To extract signal

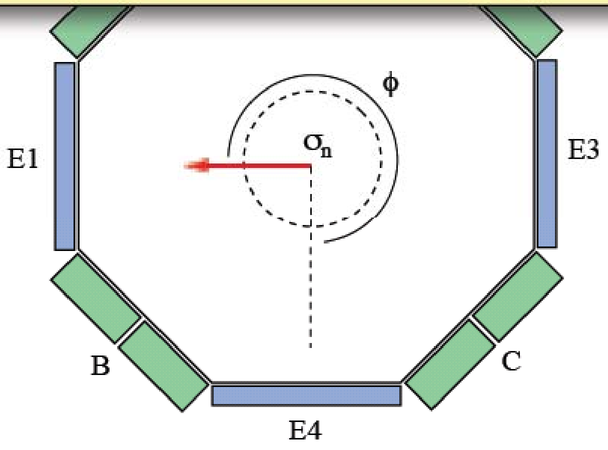
$$v_a = R - 1 = \frac{N_{1,a}^{\uparrow}\ N_{2,a}^{\downarrow}}{N_{1,a}^{\downarrow}\ N_{2,a}^{\uparrow}} - 1$$

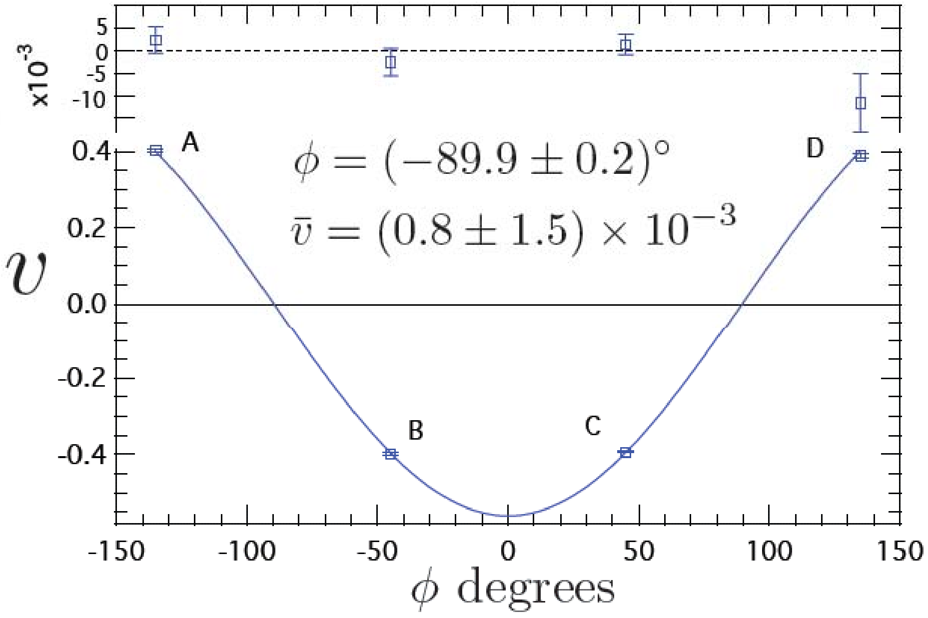
Spin transport

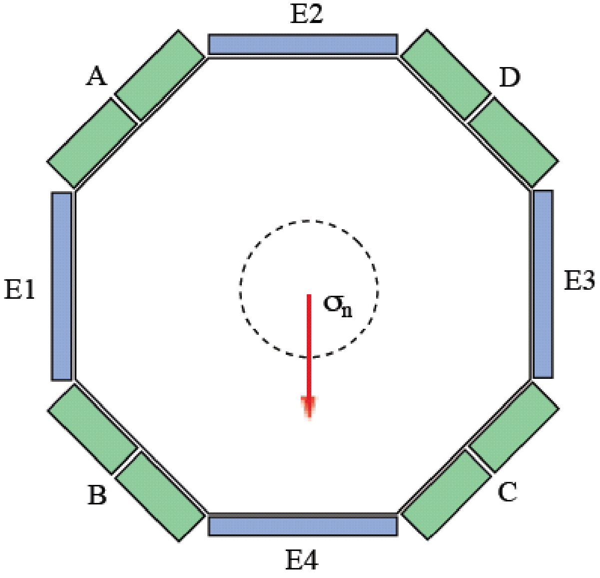


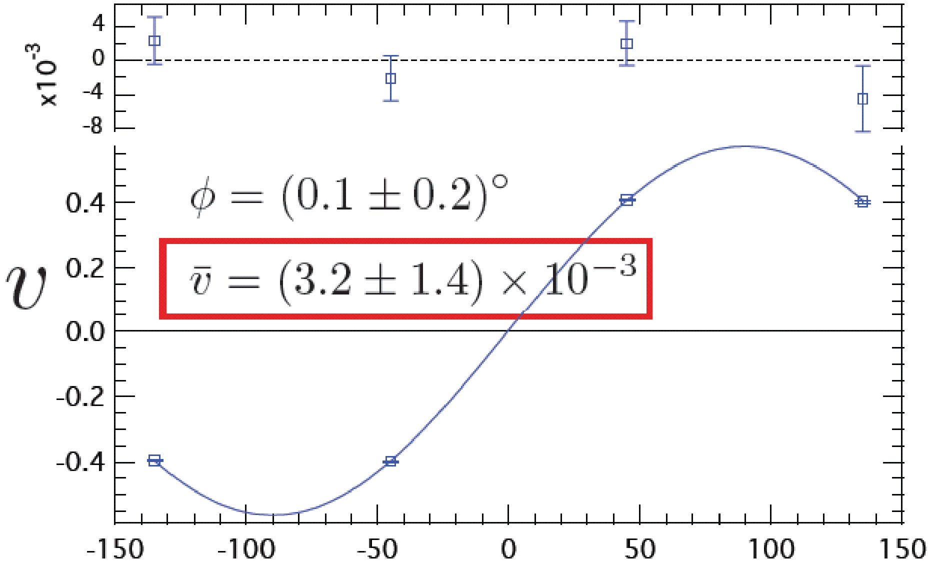
- High neutron flux (1.7 x 10^8 cm^{-2} s^{-1} at “C2”)
- 560 μT guide field, monitored during run
- Beam profile at 3 positions via Dysprosium foil activation
- Polarization measured with supermirror analyzer flipping ratio measurement

Intentional field rotation (Maximal polarization misalignment)





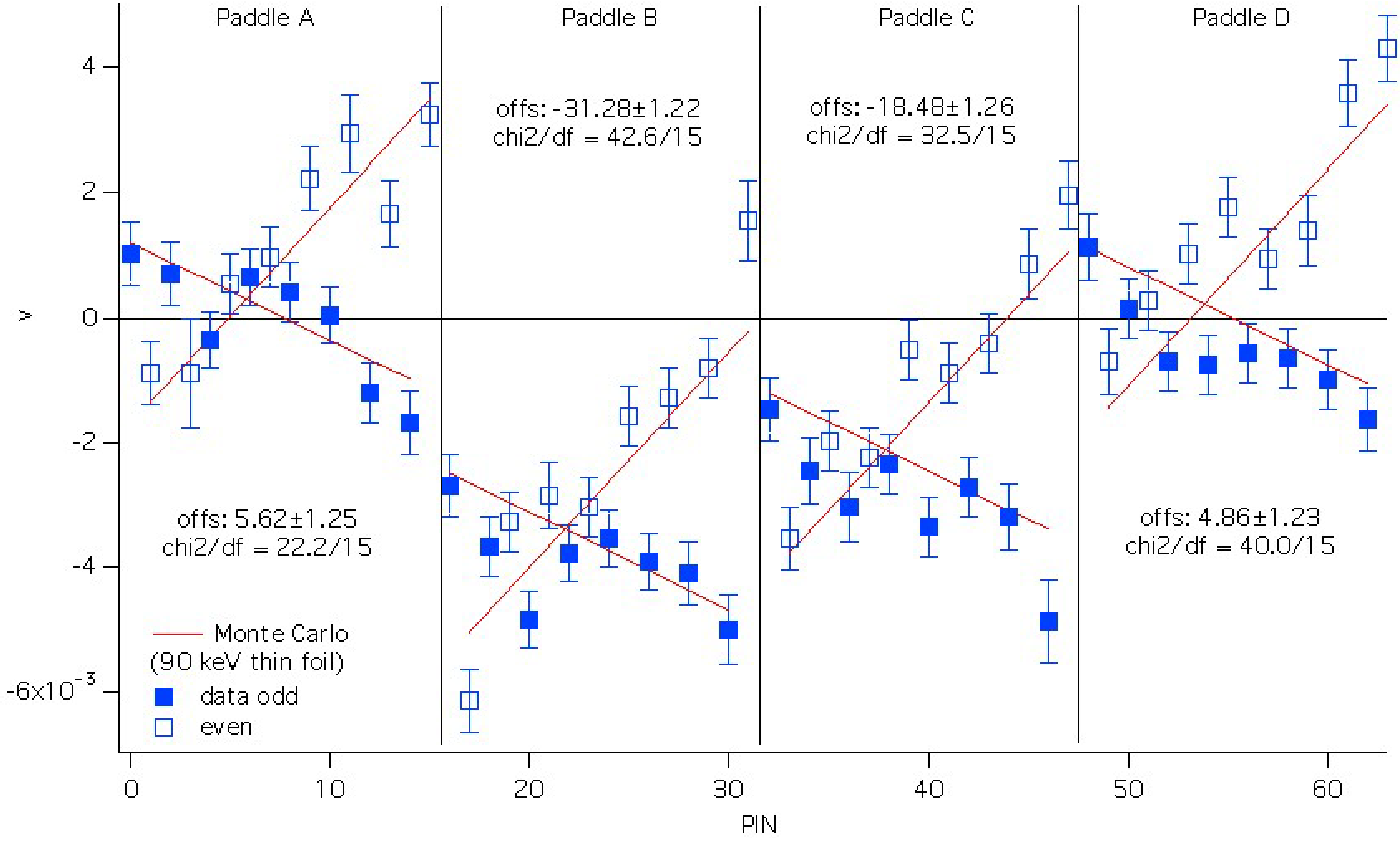




$$\boxed{\bar{v} = (3.2 \pm 1.4) \times 10^{-3}}$$

Comparison between data and expectations look good

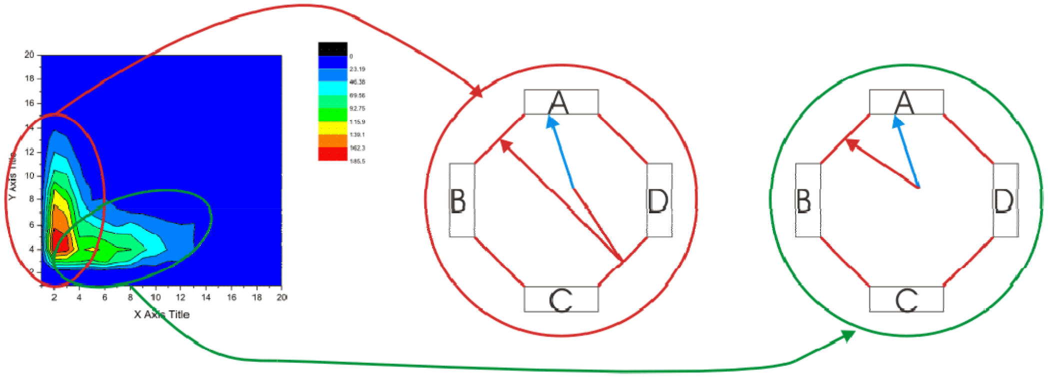
V factors

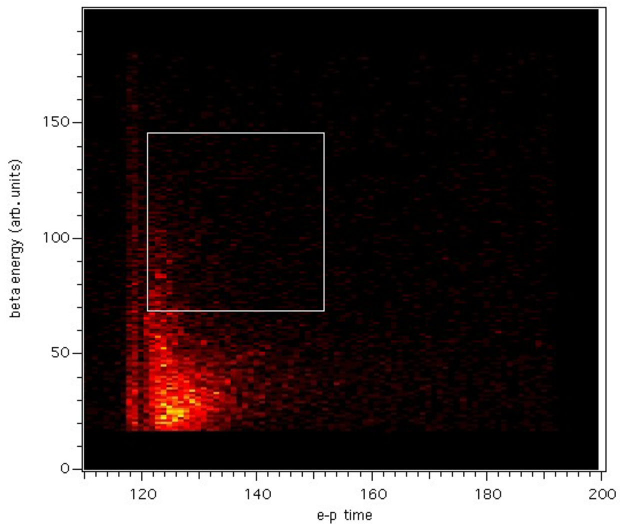


Another subtle issue: beta and proton backscattering

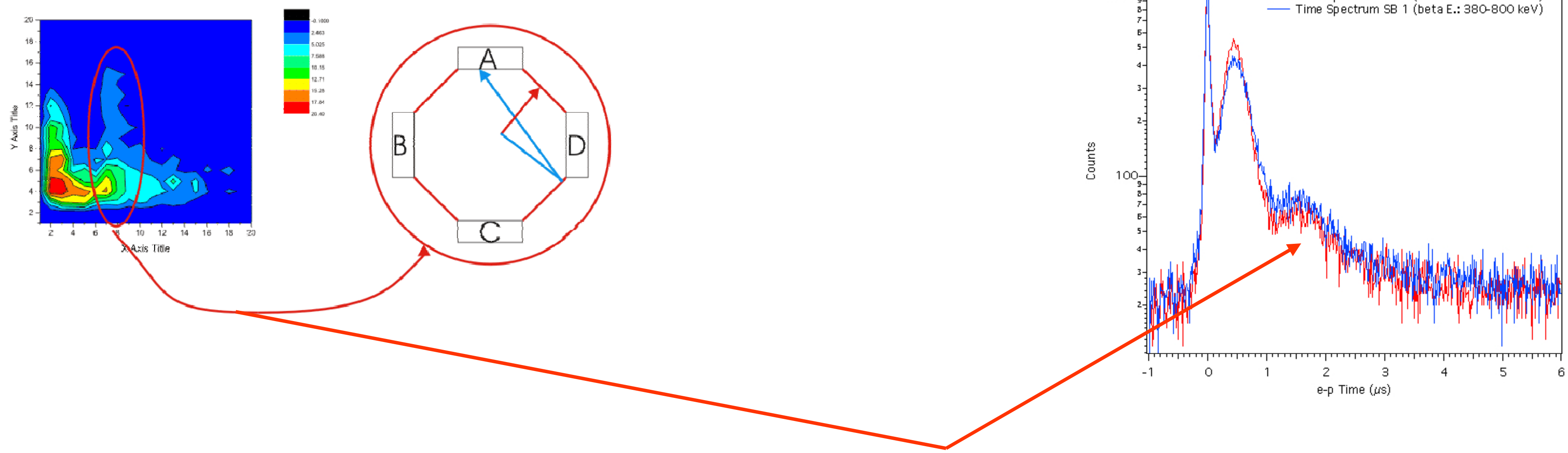
Data at 45 degrees

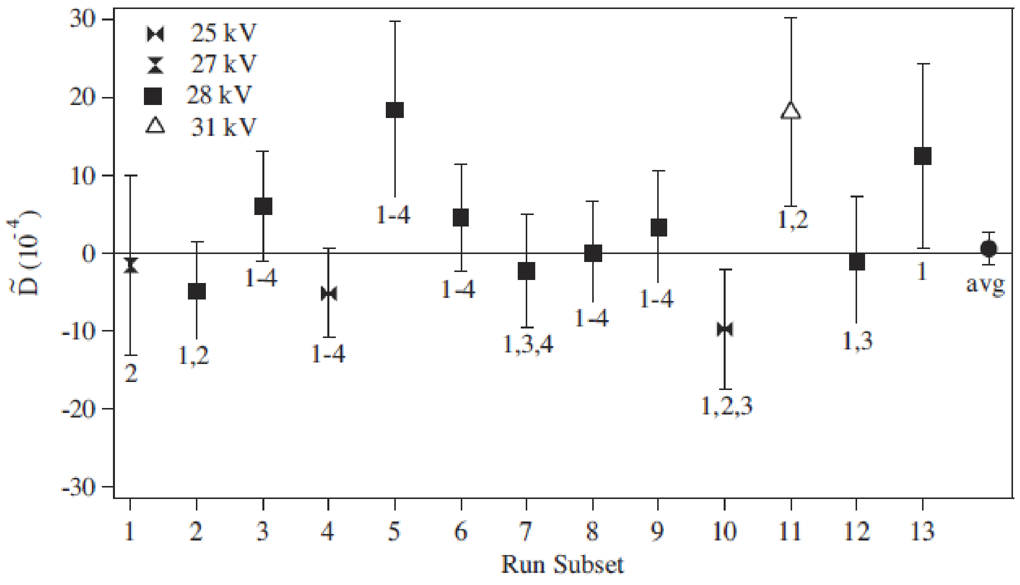
Only beta bksct





Beta AND proton bksct





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

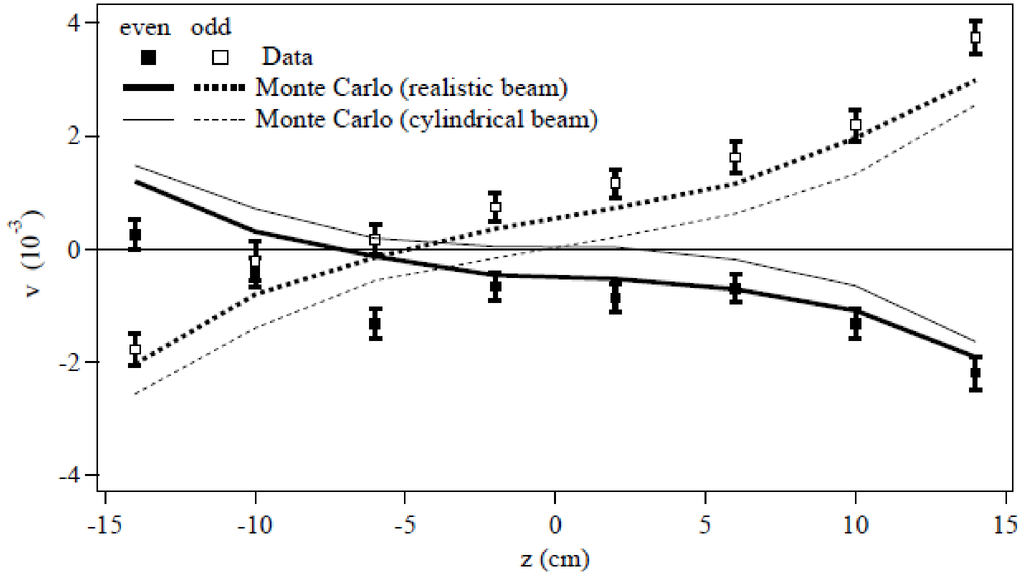


FIG. 3: Solid (open) squares show the values of v averaged

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

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. **107**, 102301 (2011).

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 ~*10^{-3}

The End