High Energy Physics with Ultra Cold Neutrons

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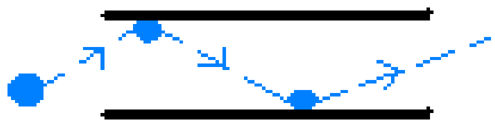
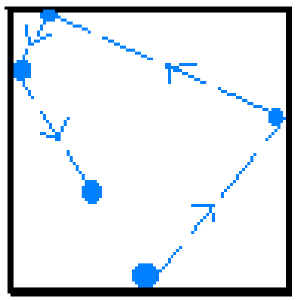
- Advantageous properties of Ultra Cold Neutrons (UCN).
- A few possible experiments with UCN and current/future UCN sources.
- Focus: Measurements of angular correlations.
- Recent progress on understanding and measuring UCN depolarization.

UCN Are very Slow

$$E \le 10^{-7} eV, \quad v \le 8m/s, \quad t \le 1mK$$





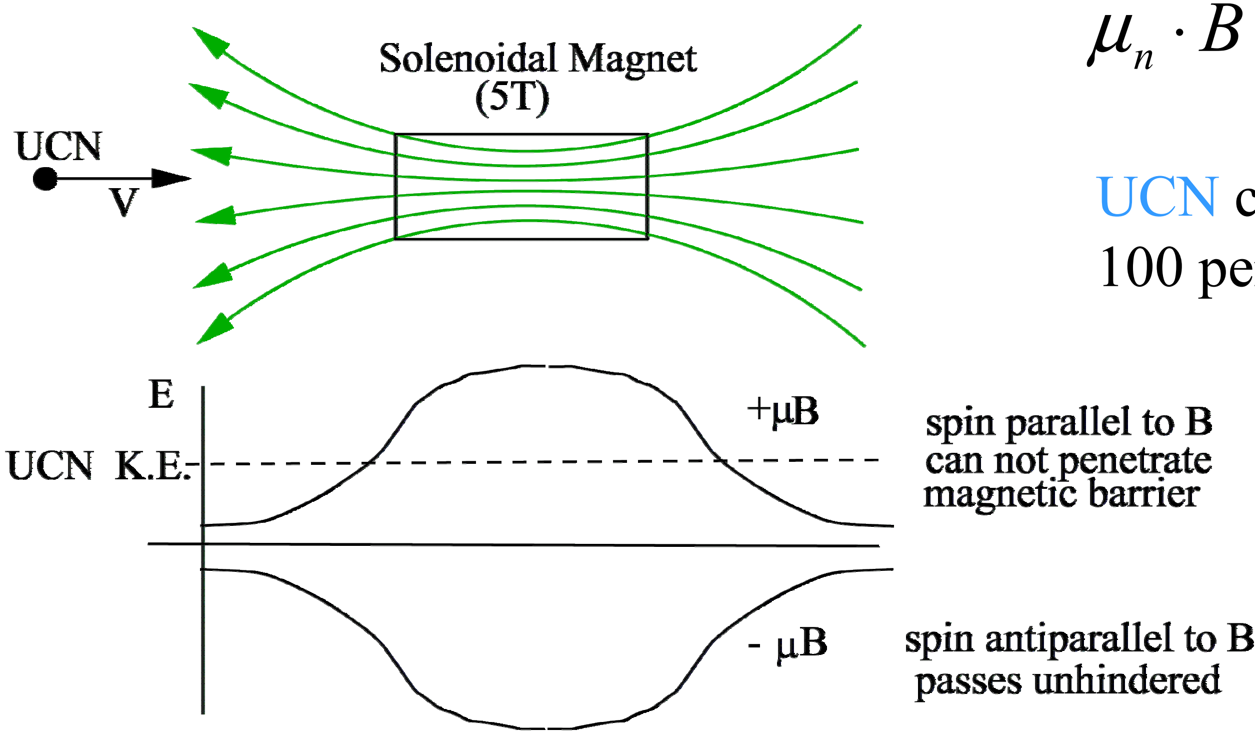
- Their wavelength is long (~500Å), thus, they totally internally reflect from many surfaces. (Ex: ^{58}Ni, Diamond,…).
  - They can be guided long distances or stored in bottles for long times.
  - Neutron experiments can be undertaken in a well shielded, low radiation background environment at reactors or (especially) spallation sources.
  - The UCN activation of an experimental apparatus is negligible.

UCN are Easy to Polarize

UCN kinetic energy is less than their potential energy in a strong magnetic field.

$$\mu_n \cdot B \approx 3\times10^{-7}\,eV$$

UCN can be essentially 100 percent polarized.



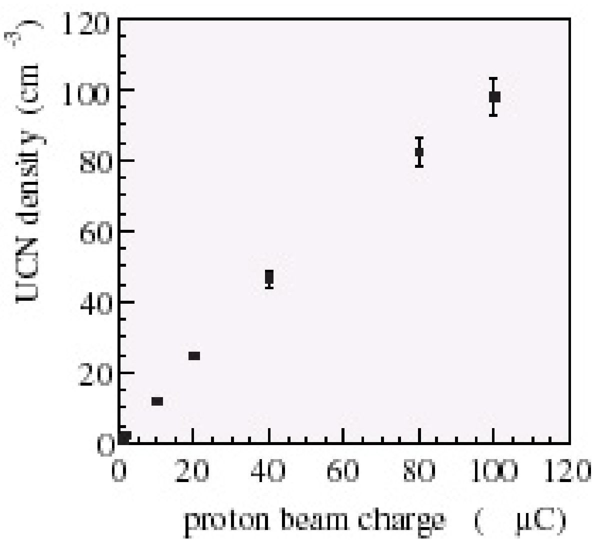
(note: neutron magnetic moment is negative)

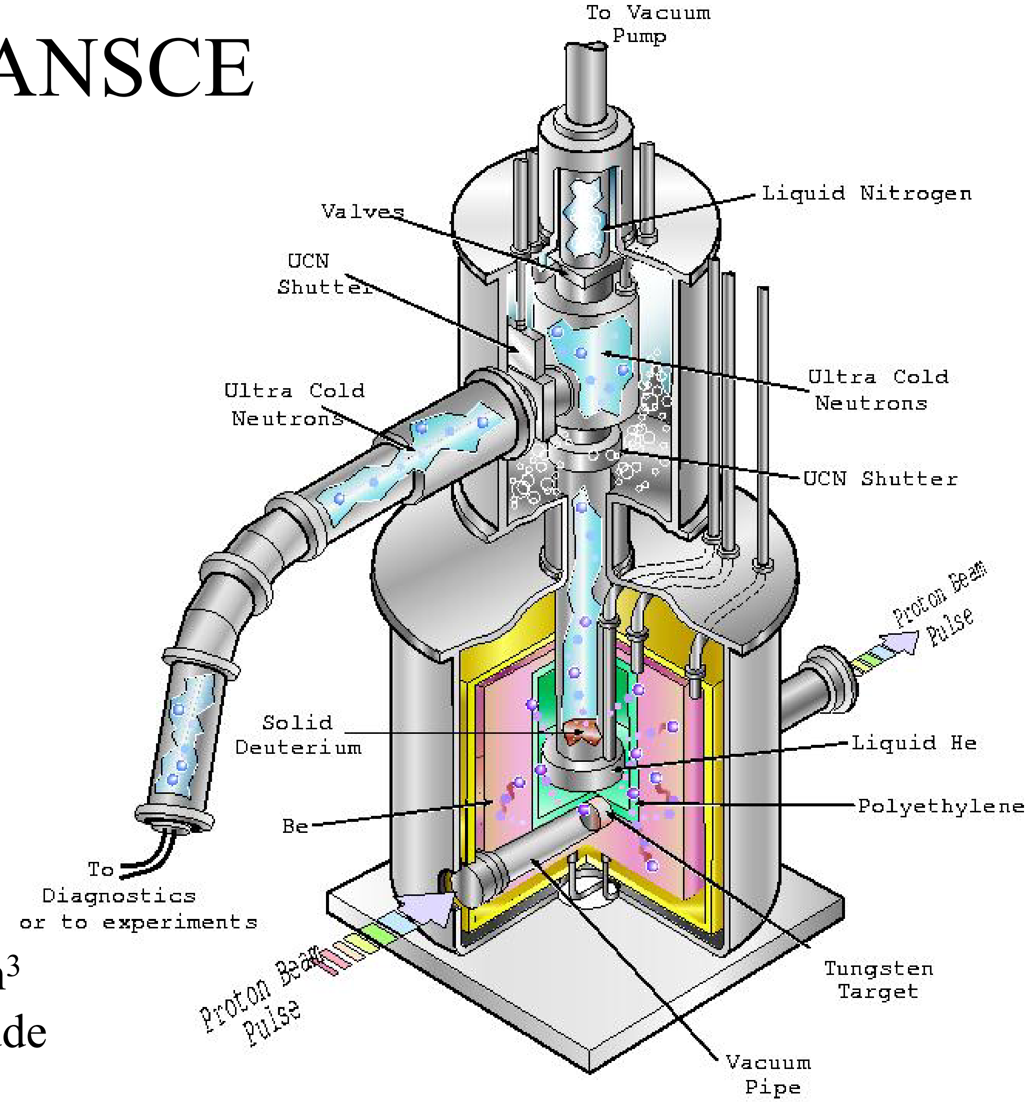
Experiments with UCN

- High polarization, low radiation background and long storage time facilitate many high precision measurements of neutron properties.
- For example:
  - The neutron lifetime.
  - The neutron electric dipole moment.
  - Neutron-antineutron oscillation.
  - The beta energy spectrum.
  - The recoil proton energy spectrum.
  - The angular correlations between neutron decay products (electron, proton and neutron spin).
- These quantities are interesting in themselves. Perhaps more intriguing, they are also probes of "new" physics.
- Recent advances in UCN production make efforts feasible.

A Superthermal Solid Deuterium UCN Source at LANSCE

World record densities achieved





Compare to previous record of 41 UCN/cm^3 (at ILL). Note: over two orders of magnitude improvement may ultimately be possible.

Current and Future World Wide UCN Sources

Operational for experiment, Fall 2003. (→ LANL)

Institution	Source Type	Density (UCN/cc)
ILL	Reactor	40
LANL	Spallation	400-800
FRMII	Reactor	10^4
PSI	Spallation	2.5×10^3
NCSU	Reactor	1.5×10^3

Angular Correlations of Neutron Decay: The Current Situation

$$W dE_e d\Omega_e d\Omega_\upsilon \propto p_e E_e (E_0 - E_e)^2 \left(1 + a \frac{\vec{p}_e}{E_e} \cdot \hat{p}_\upsilon + b \frac{m_e}{E_e} + A \vec{\sigma} \cdot \frac{\vec{p}_e}{E_e} + B \vec{\sigma} \cdot \hat{p}_\upsilon + D \vec{\sigma} \cdot \frac{\vec{p}_e \times \hat{p}_\upsilon}{E_e} \right)$$

To first order in the SM:

$$a = \frac{1-\lambda^2}{1+3\lambda^2}$$

$$A = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$

$$B = 2\frac{\lambda(\lambda-1)}{1+3\lambda^2}$$

$$\lambda = g_a / g_v$$

	PDG 2000
a	-0.102±0.005
A	-0.1162±0.0013
B	0.983±0.004
D	(-0.5 ±1.4)×10^{-3}
λ	-1.2670±.0035

Note: A UCN measurement of D may have less systematic error than a CN measurement.

Physics motivation for measuring λ with UCN

- There is a 2-σ discrepancy between V_{ud} determined from $0^+ \rightarrow 0^+$ nuclear beta decay (most precise measurement to date) and CKM unitarity.
- Neutron decays are amenable to a straightforward theoretical treatment because they are a single nucleon, (as opposed to $0^+ \rightarrow 0^+$ decays), and thus, the best way to learn more.
- Given λ, the neutron lifetime and the muon lifetime, one can determine V_{ud}.
- A is the most sensitive of the three correlations to λ:

$$\frac{d\lambda}{dA} = 2.6, \quad \frac{d\lambda}{da} = 3.3, \quad \frac{d\lambda}{dB} = 13.4$$

- Measuring B with the same experimental apparatus provides a polarization independent determination of λ. (I.A. Kuznetsov et al. NIM A 440 (2000) 539-542).

Additional Motivations for a and B

- A, a and B are sensitive to different recoil order corrections. (Example: a is most sensitive to weak magnetism and induced tensor form factors).
- A precise measurements of A and a at the 0.1% level permits a test of the conserved-vector current hypothesis (CVC) and a search for second class currents (SCC). (S. Gardner and C. Zhang PRL 86(2001) p.5666).
- A precise measurement constrains both the minimally super symmetric model (MSSM) and the R-violating extension to MSSM. (Ramsey-Musolf PRL 88(2002) 071804, PRD 62(2000) 056009).
- A precise measurement of B constrains $\left(M_L/M_R\right)^2$ in manifest left-right symmetric models. (Kuznetsov et al. PRL 75(1995) p. 794).

The UCN A Collaboration

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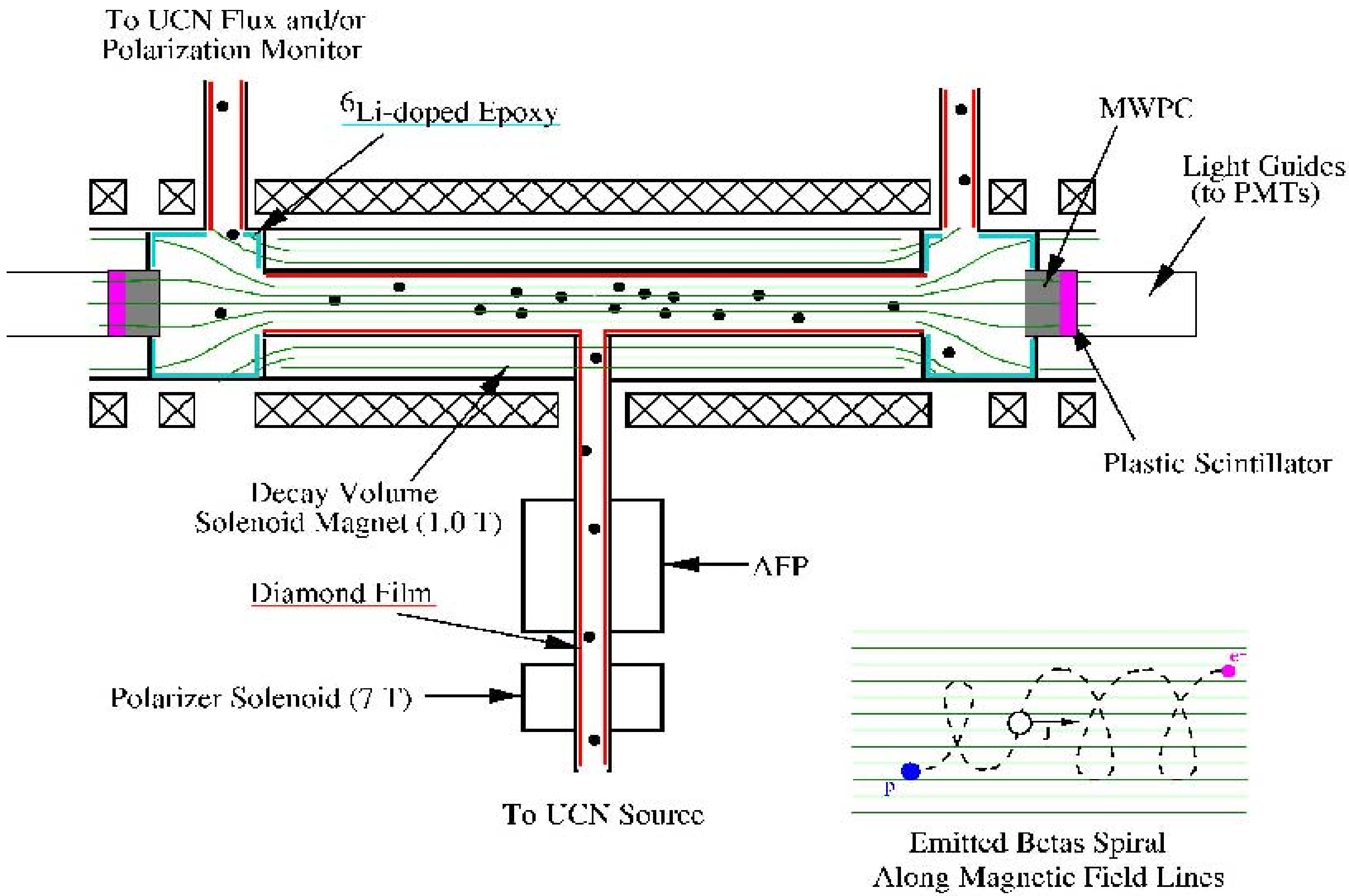
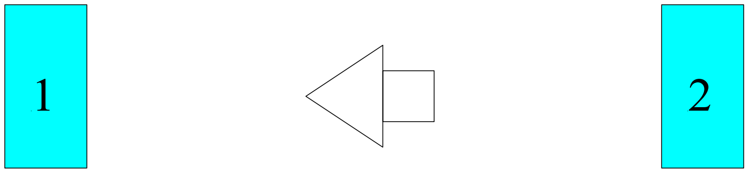
Initial goal: $\Delta A/A = 0.2\%$

A Spectrometer for Angular Correlation Studies

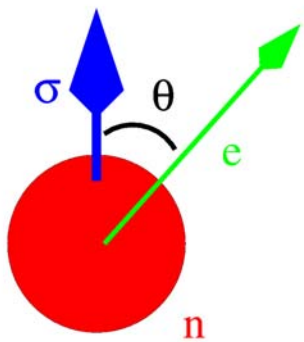


How to Measure A: The Electron Asymmetry



$$dW = \left[1 + \beta P A(E) \cos\theta\right] d\Gamma(E)$$

$$A_{\exp}(E) \propto \frac{N^{\uparrow}(E) - N^{\downarrow}(E)}{N^{\uparrow}(E) + N^{\downarrow}(E)} \approx \frac{1}{2} A(E) \beta P$$

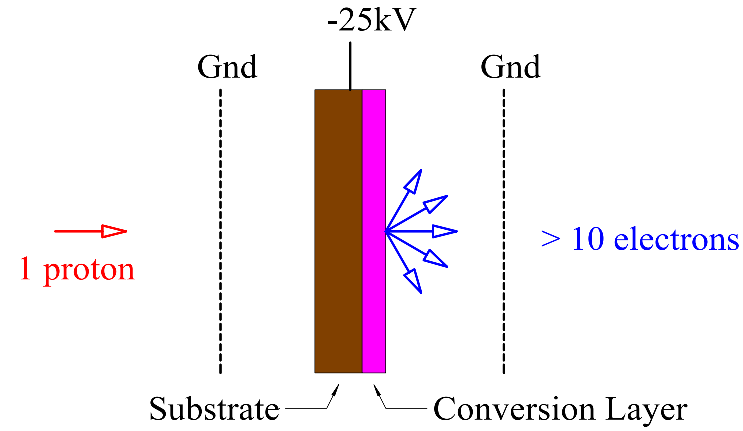


- Measure electron energy, electron direction, neutron polarization.
- Controlling systematic errors is critical:
  - Background subtraction.
  - Polarization (0.1%)
  - Detector Response (backscatter, linearity etc.) (0.1%)

We are undertaking a thorough study to understand and control systematic errors associated with beta detectors (MWPC, Scin., Si.).

Electron Transparent Proton Detectors

- The Strategy: Convert protons into electrons in an electron transparent foil which has no impact on A. Use the planned electron detectors to see these electrons.
- Advantages:
  - Should be easy to install, easy to operate, robust proton identification.
  - Minimal impact on systematic errors of A measurement (electron backscatter and energy loss).
  - Measure B concurrently with A.



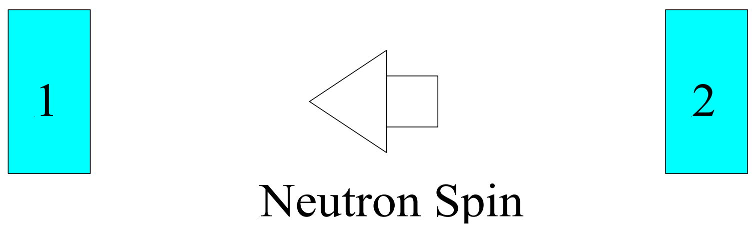
•PERKEO colleagues tried C-foils (25µg/cm^2) with MgO.

•We are investigating fluorinated polyimide (0.1 µm) with CsI or diamond (200Å).

•Should be stronger, larger, with a higher electron yield.

How to Measure B: The Proton Asymmetry

- The proton asymmetry is the best method in our geometry.
- Measure emission direction of protons only (electron coincidence not required).



$$\alpha_p = \frac{p_+ - p_-}{p_+ + p_-} = PC_p(A+B), \qquad C_p = 0.27484$$

Polarization uncertainty limited measurement with 10^7 decays (36hrs).

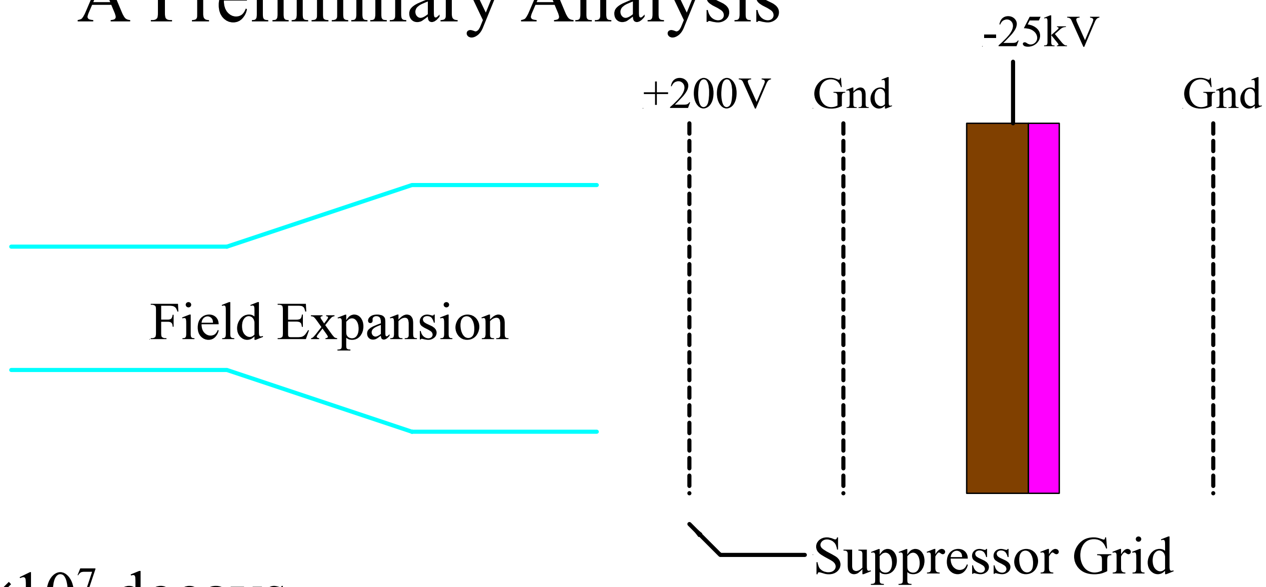
$\Delta B/B = 0.2\%$

Gluck et al. *Nuclear Physics A* 593 (1995) pg. 125

How to Measure a: The 1-d Integration Method

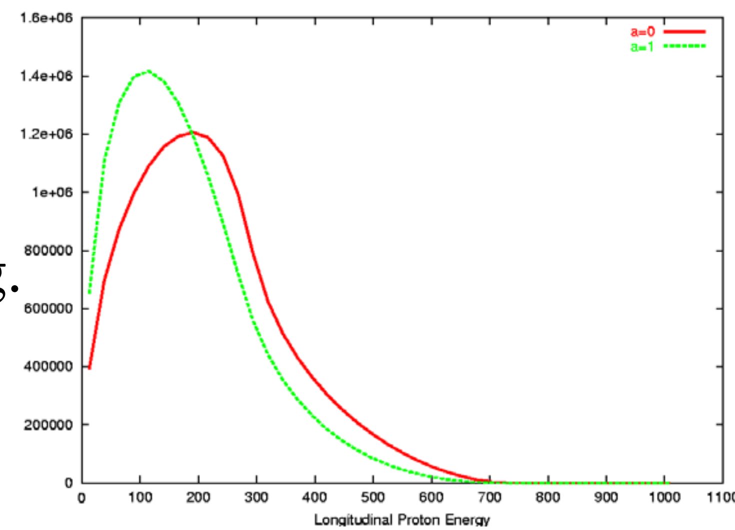
A Preliminary Analysis

1) Fill trap and count protons higher than E_{cut}.
2) Empty trap and count protons lower than E_{cut}.



$\Delta a/a=0.5\%$

5×10^7 decays (8 days)



Very preliminary investigation.
Systematic errors are very challenging.
Field uniformity, unpolarization, etc.

J. Byrne et al. NIMA 349(1994) pg. 454

Polarization Progress

Polarization Level

- Goal for the first experiments: less than 1×10^{-3} depolarization error (we should do significantly better).

Sources of Depolarization

- Material depolarization – Benchmarked at the ILL (fall 2001,spring 2002).
  - less than 2×10^{-6} per bounce
  - 8×10^{-5} per sec
- Majorana transitions – Monte Carlo treatment complete.
  - less than 2×10^{-4} per pass (holding fields <= 200G)
  - in field reversal region
- Wall collisions in gradient fields - Monte Carlo exists.
  - less than 1×10^{-4} per pass in field reversal region and AFP region
- AFP performance – Monte Carlo exists, partially benchmarked at the ILL.
  - less than 1×10^{-4} per pass