

Neutron β -Decay Measurements with a Pulsed Cold Neutron Beam

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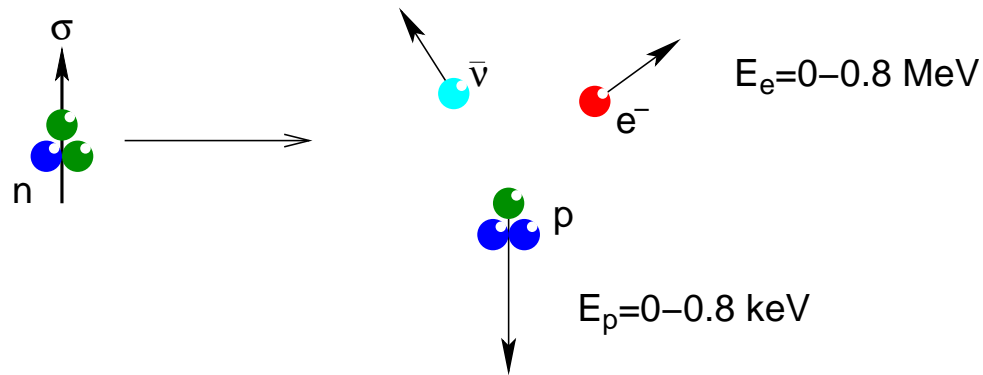
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Overview

- Program of measurements in neutron β -decay
- Candidate for first experiment at SNS
- Propose making first measurements at LANSCE FP12
 - First measurements in 2007
 - Important physics results
 - Apparatus tested and ready for SNS

Neutron β -Decay



$$\rho(E_e) \approx \rho_s(E_e) \left\{ 1 + \beta a \cos \theta_{e\nu} + P_n [\beta A \cos \theta_{e\sigma} + B \cos \theta_{\nu\sigma}] + b \frac{m_e}{E_e} \right\}$$

$$a \sim -0.1 \quad A \sim -0.1 \quad B \sim 1 \quad b \sim 0$$

A and *B* require precision neutron polarimetry

Goals

- Determine $\lambda = G_A/G_V$ redundantly
Measure both a and A (first precision measurement of a)
Determine A from e^- and p asymmetries
 3σ deviation from value required for CKM unitarity
- Search for Fierz interference term b
Sensitive to scalar and tensor couplings
Non-zero value suggested by π^+ β -decay results
Never measured
- Measure B precisely
Sensitive to deviations from $V - A$ theory
e.g. Mass of right-hand boson

Measuring V_{ud} with Neutron Decay

$$V_{ud}^2 = \frac{K/\ln 2}{G_F^2 (1 + \Delta_R^V) (1 + 3\lambda^2) f(1 + \delta_R) \tau_n}, \quad \lambda = G'_A/G'_V \approx -1.265$$

$$\begin{aligned} 1 - V^2 &= 0.0047 \pm 0.0051 \\ &= 0.0047 \pm \underset{\lambda}{0.0049} \pm \underset{\tau_n}{0.0010} \pm \underset{V_{us}}{0.0010} \pm \underset{RC}{0.0007} \end{aligned}$$

$$\frac{d\lambda}{da} = 3.3$$

$$\frac{d\lambda}{dA} = 2.6$$

$$\frac{d\lambda}{dB} = 13.4$$

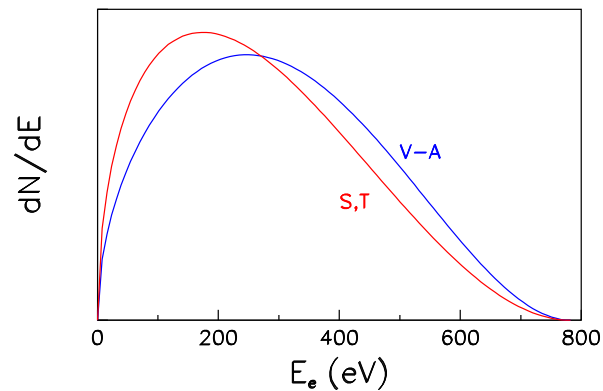
$$\Delta a = 2.3 \times 10^{-4}$$

$$\Delta A = 3.0 \times 10^{-4}$$

$$\Delta B = 0.6 \times 10^{-4}$$

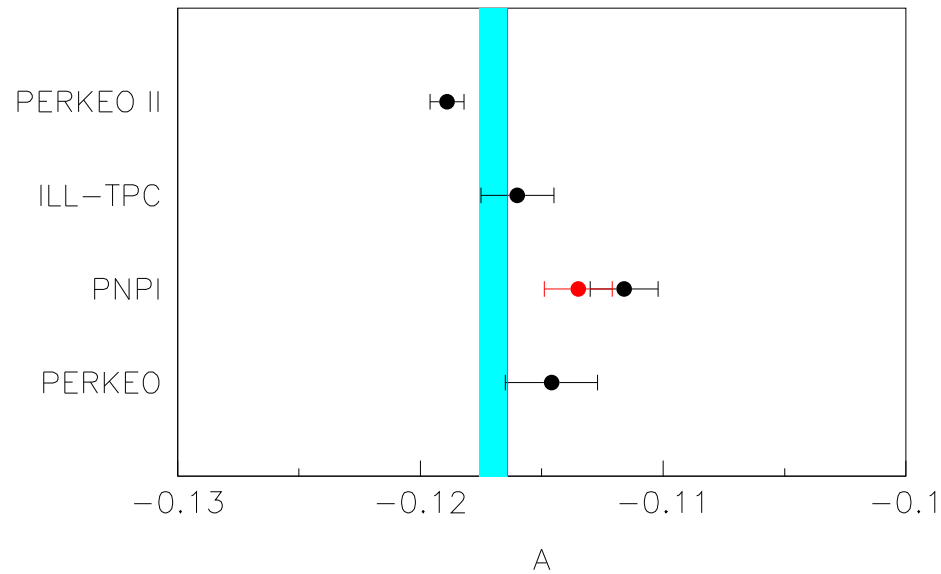
$$\longrightarrow \Delta V_{\lambda}^2 = 0.0010$$

Measurement of b Coefficient



- Important physics measurement
 - $b = 0$ in standard model
 - $b \neq 0$ for scalar or tensor couplings
 - Never determined from neutron β -decay
 - Results of π^+ β -decay suggest $b \neq 0$
- $\Delta b = 0.001$ (statistics)
- Needed to extract V_{ud} from λ , τ_n

Consistency of Existing Measurements of A



$$A = -0.1170 \pm 0.0006 \text{ (0.0015)} \quad \chi^2 = 24.2 \quad P = 8 \times 10^{-5}$$

$$A = -0.1173 \pm 0.0006 \text{ (0.0012)} \quad \chi^2 = 15.3 \quad P = 4 \times 10^{-3}$$

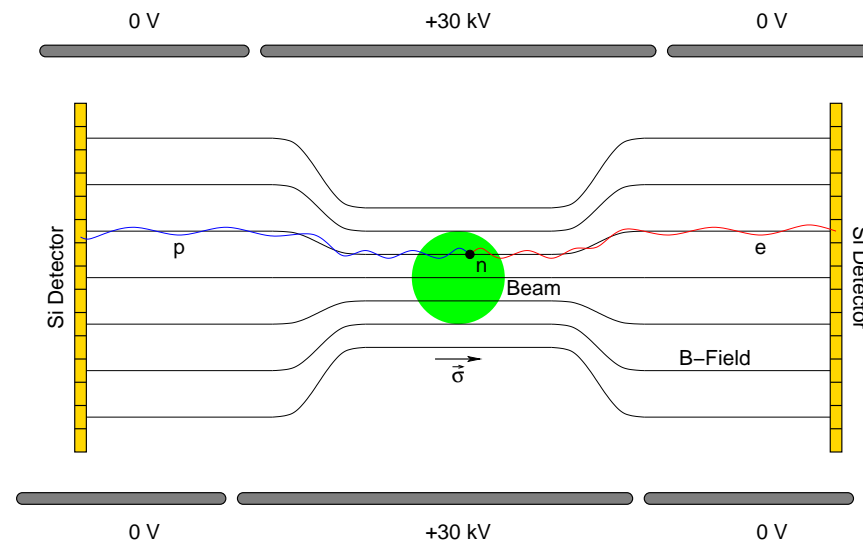
Sources of Systematic Error in Previous Experiments

1. Neutron polarization determined in auxiliary experiments
2. Detector properties
Resolution, efficiency, stability, homogeneity
3. Background subtraction: singles measurements needed
4. Fiducial volume defined by material apertures
Energy loss, scattering
5. Magnetic field pinch reverses particle trajectories
6. Electron back-scattering from detectors

New Techniques to Address Systematic Errors

1. *In situ*, absolute neutron polarization established
2. Large-area segmented silicon detectors
3. Detect e and p in coincidence
4. Segmented detectors image decay volume
5. All decays in homogeneous B region
No material apertures or grids
6. Transient digitize events for reconstruction of backscattering events

Neutron β -Decay Spectrometer



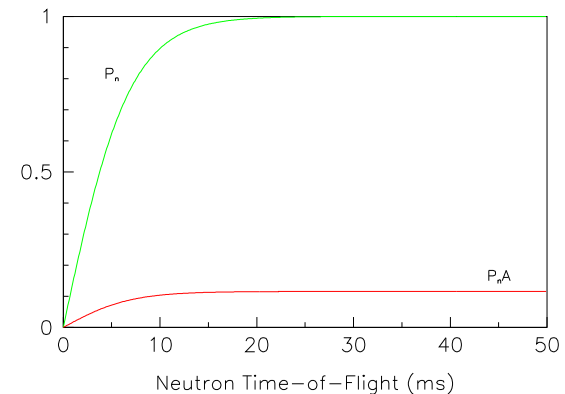
- Two 2π detectors
- e backscattering monitored
- $\Delta t \sim 1$ ns
- $\Delta E \leq 5$ keV
- $e - p$ coincidence
- Beam imaged by detectors
- *In situ* background measurement
- No material apertures

In Situ Polarization Measurement

- Neutrons polarized by transmission through polarized ^3He
- Measure asymmetries as a function of TOF
- Exact relation between neutron polarization and TOF
- *In situ* determination of P_n to $< 0.1\%$

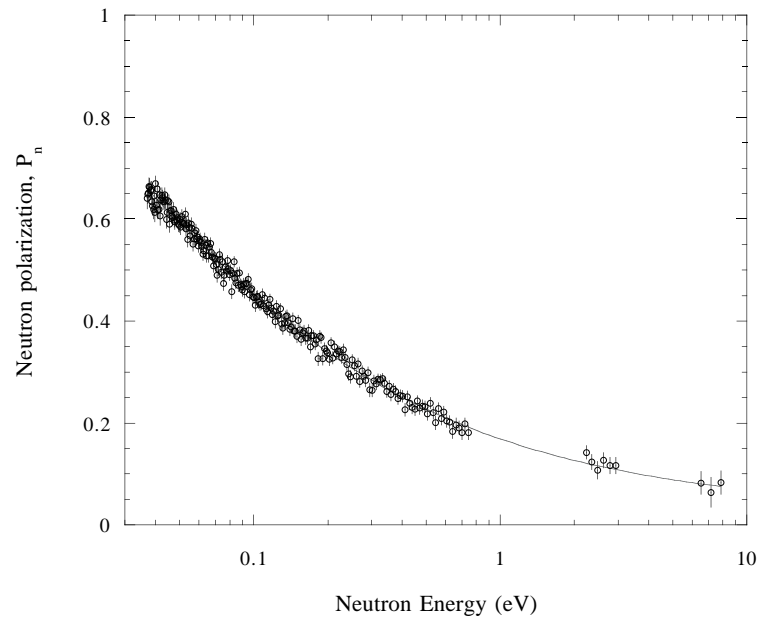
$$P_n = \tanh(-t/\tau)$$

$$AP_n = A \tanh(-t/\tau)$$



Extract A and B from two-parameter fits to decay data

Absolute Neutron Polarimetry at LANSCE



$$\Delta P_n \leq 0.3\%$$

S.I. Penttilä, *et al.*



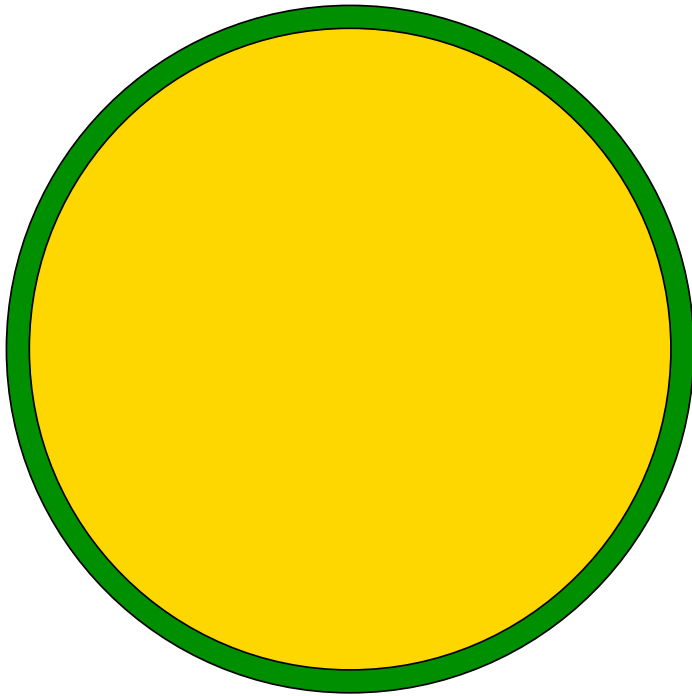
Constructed for $\vec{n} + p \rightarrow d + \gamma$

Straight forward extension of polarimetry method to $\sim 10^{-4}$

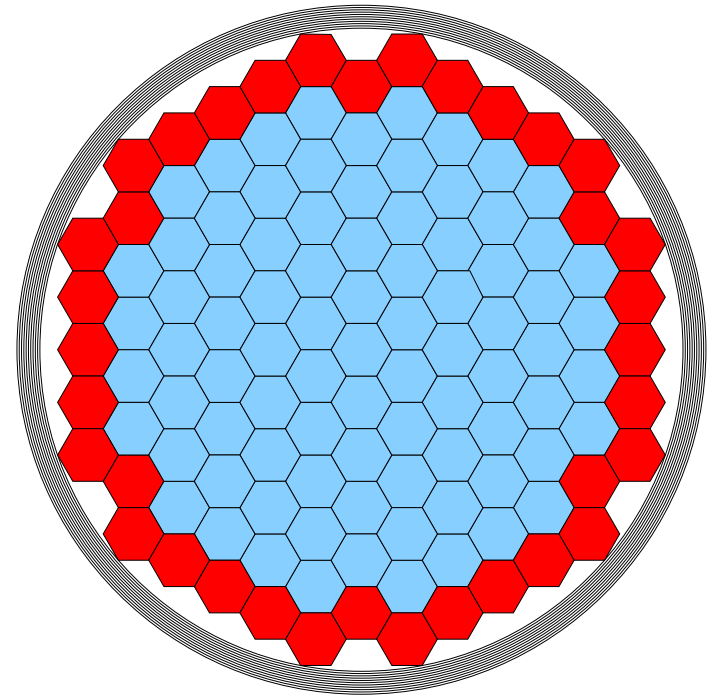
Advantages of Silicon Detectors

- Thin dead layer: $\Delta E_e \leq 5$ eV, $\Delta E_p \leq 5$ keV measured
- Almost unity efficiency: small well-understood corrections
- Extremely uniform dead layer: no wires, foils, supports, etc.
- 4π detection of electrons and protons: coincidence
- Imaging: defines fiducial volume without material apertures, provides *in situ* background measurement

Preliminary Detector Design



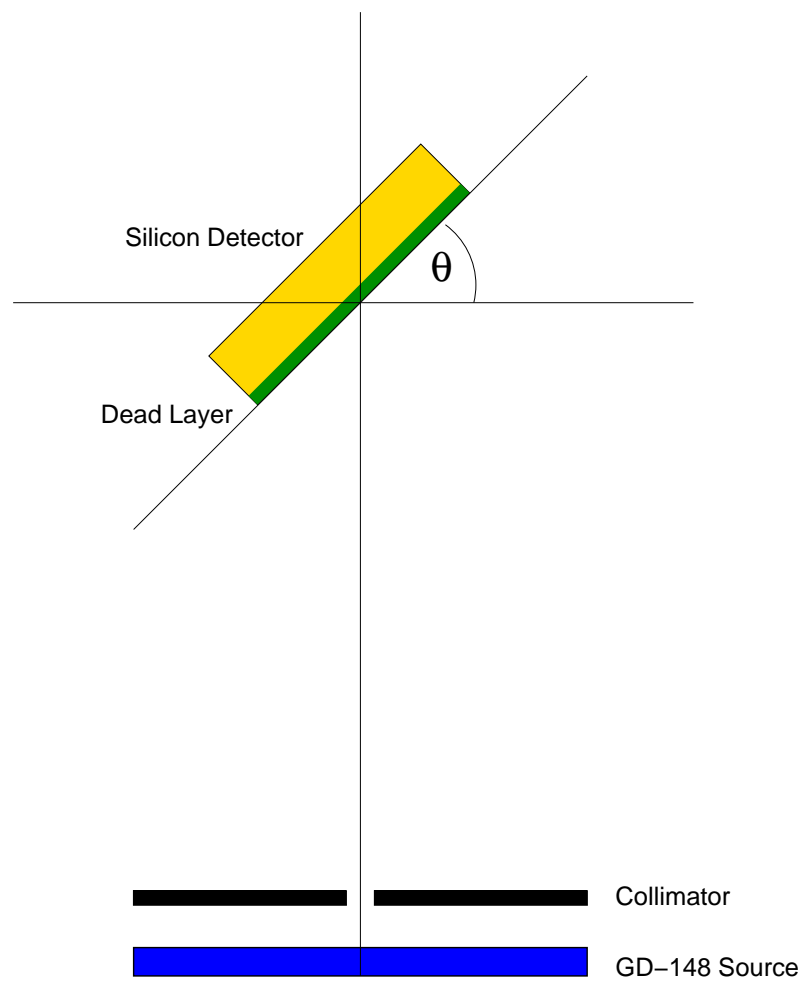
Junction Side
(Particles Incident)



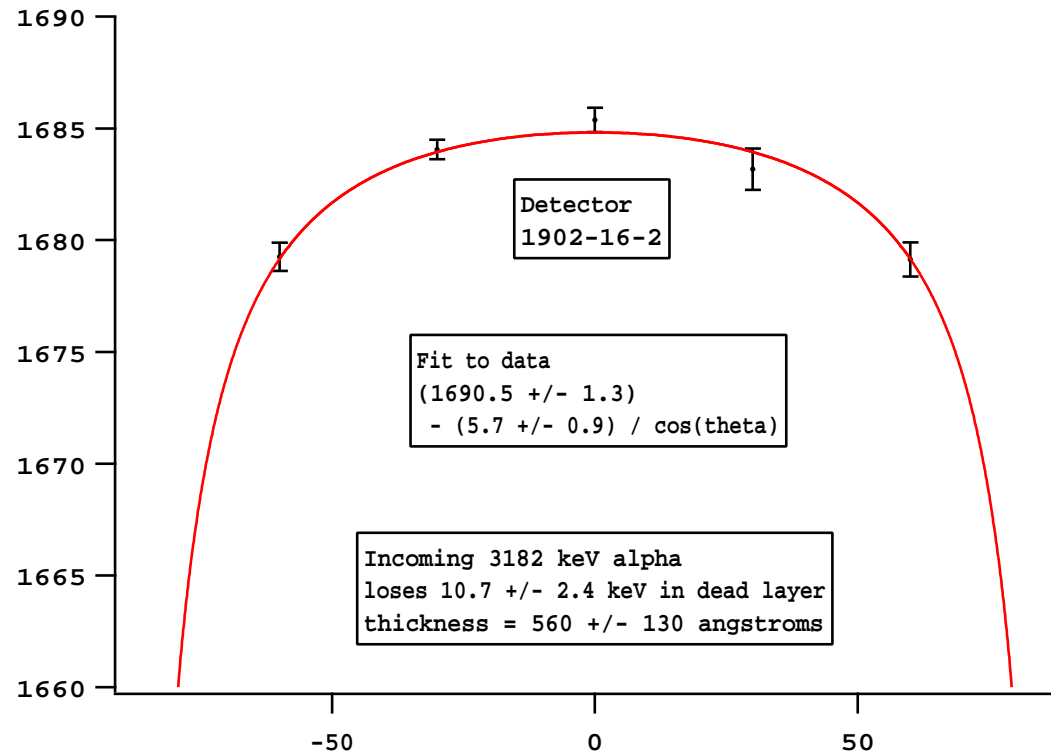
Ohmic Side
(Readout)

15 cm Diameter, 2 mm Thick, 127 Channel

Dead Layer Measurements



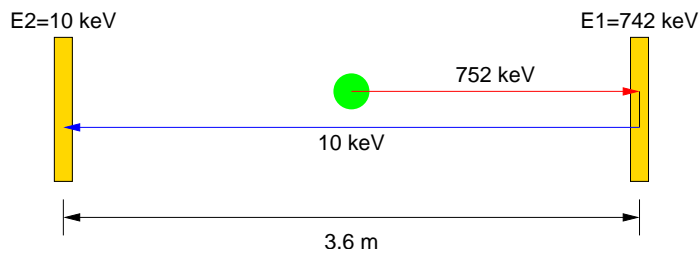
Thin Dead Layer Silicon Detector



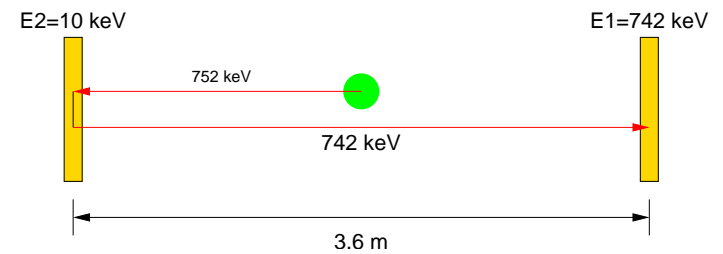
56 nm Dead Layer

$$E_{\text{loss}} = 5 \text{ keV for } E_p = 30 \text{ keV}$$

Detector Timing Resolution



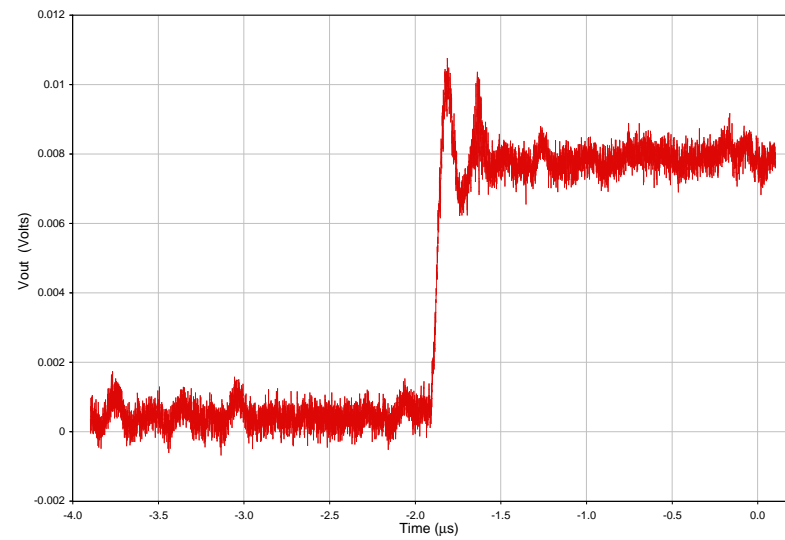
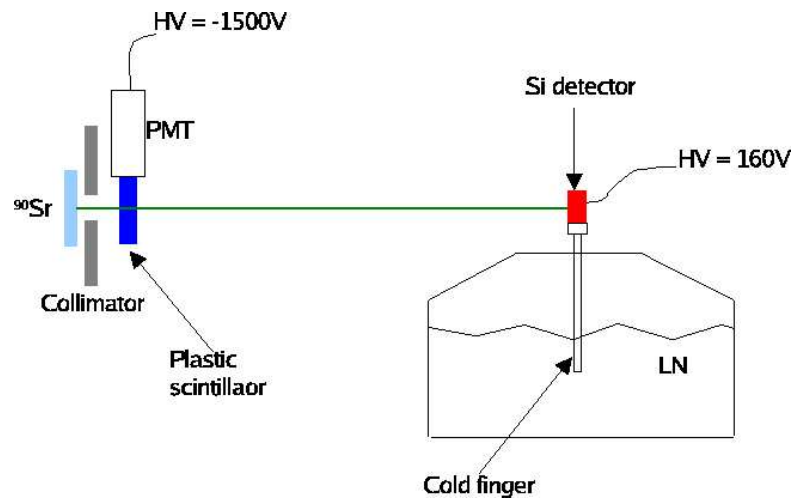
$$t_2 - t_1 = 50.2 \text{ ns}$$



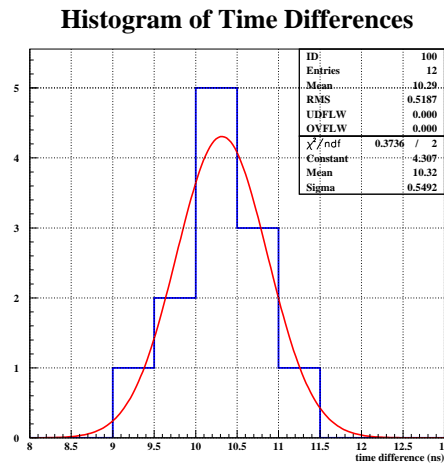
$$t_2 - t_1 = -13.1 \text{ ns}$$

- Timing information needed for e^- backscatter events
- Worst-case events have low E in one detector
- Must achieve timing resolution $\sim 20 \text{ ns}$ for 10 keV
- Figure-of-merit $E \cdot \Delta t \sim 200 \text{ keV}\cdot\text{ns}$

Silicon Detector Timing Measurement

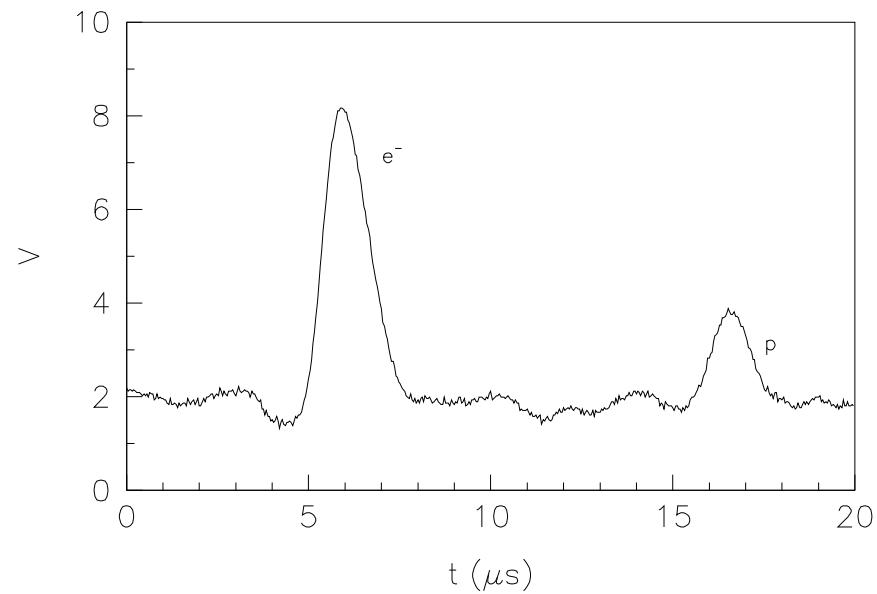


Silicon Detector Timing Results



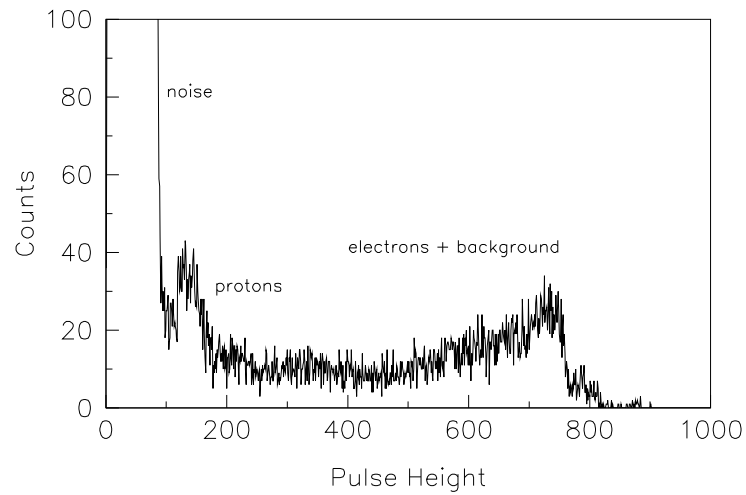
- Preliminary $\Delta t = 1.39 \pm 0.40$ ns for 170 keV (1.02 ns theoretical limit)
- Figure-of-merit 236 ± 68 keV·ns
- Sufficient for proposed spectrometer
- Expect $\times 3.3$ improvement (cooled FET, increased detector bias)

Electron-Proton Coincidence in Neutron Decay

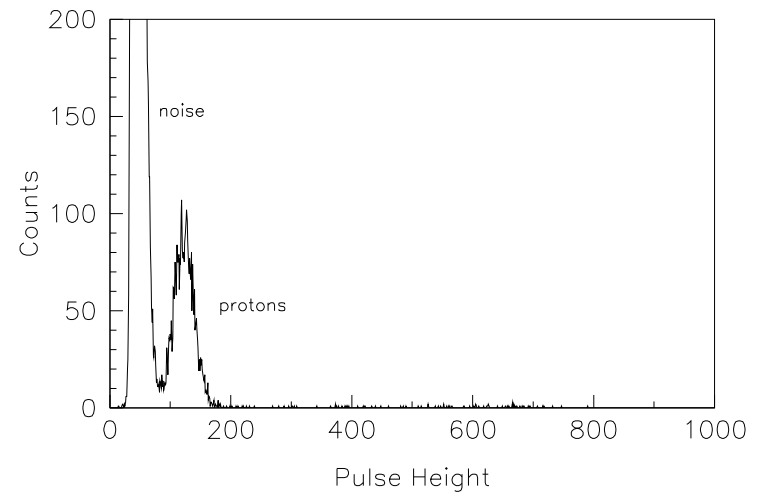


- Cold neutron beam
(NIST Penning trap neutron lifetime apparatus)
- Silicon detector

Singles vs. Coincidence Spectrum



No Coincidence



Coincidence

Detector Development Status

- All properties proven in individual detectors
- Quote from vendor on developing 10 cm diameter, 2 mm thick detector (12 month delivery)
- No known problems scaling to 15 cm diameter, 2 mm thick detector

Anticipated Statistical Uncertainty at SNS

Parameter	Rate (Hz)	Uncertainty	PDG Uncertainty
b	800	1.1×10^{-4}	—
a	800	1.4×10^{-4}	50×10^{-4}
A	160	0.9×10^{-4}	13×10^{-4}
B	160	1.5×10^{-4}	40×10^{-4}

Assume two runs of 1×10^7 s (polarized, unpolarized)

Anticipated Statistical Uncertainty at LANSCE

Parameter	Rate (Hz)	Uncertainty	PDG Uncertainty
b	40	5×10^{-4}	—
a	40	6×10^{-4}	50×10^{-4}

Assume two runs of 5×10^6 s

Systematic Errors Analyzed

- Electron backscattering
- Proton backscattering
- Neutron depolarization effects
 - Depolarization in glass window
 - Finite neutron pulse width
 - $1/v$ n - ^3He cross section dependence
- Magnetic field inhomogeneities
- Proton arrival time

All systematics $\sim 10^{-4}$

Status

- ^3He polarizer exists
In situ polarimetry technique demonstrated
- Detector technology proven
Deadlayer measured
Timing resolution measured
10 cm diameter, 2 mm thick detector under development
- Preliminary spectrometer design
Magnet design and cost study complete
HV electrode structure designed by UTenn/ORNL
- ADC/DSP design and cost study in progress
100 MHz 12 bit prototype tested by ORNL
- LANSCE FP12 under construction
Neutron guide in place
Shielding being installed
Flux measured

Status

- Strong collaboration formed
- Several institutions express strong interest in joining
- Presented at Chapel Hill Workshop, LRP Town Meeting
- Endorsed by NSAC Long Range Plan
- Favorably reviewed by Peoples committee for SNS project
- Draft proposal

Preliminary Cost Estimate

WBS	Task	Cost	
		<i>a,b</i>	<i>A,B</i>
1	Beam Line Modifications	\$160k	\$160k
2	Spectrometer	\$1658k	
3	Detectors	\$170k	
4	Detector Electronics	\$717k	
5	Polarizer		\$111k
6	Spin Flipper		\$45k
7	Beam Monitors	\$15k	
8	Transverse Field		\$192k

Total Capital \$3.2M (DOE, NSF, and Institutional)
Includes contingency and overhead

Proposed Schedule

Milestone	Date
Final Proposal	Jun 2003
Begin Construction	Jan 2005
Commissioning (LANSCE)	Jan 2007
Commissioning (SNS)	Jan 2009

- Physics Results before SNS
- Tested apparatus when SNS turns on