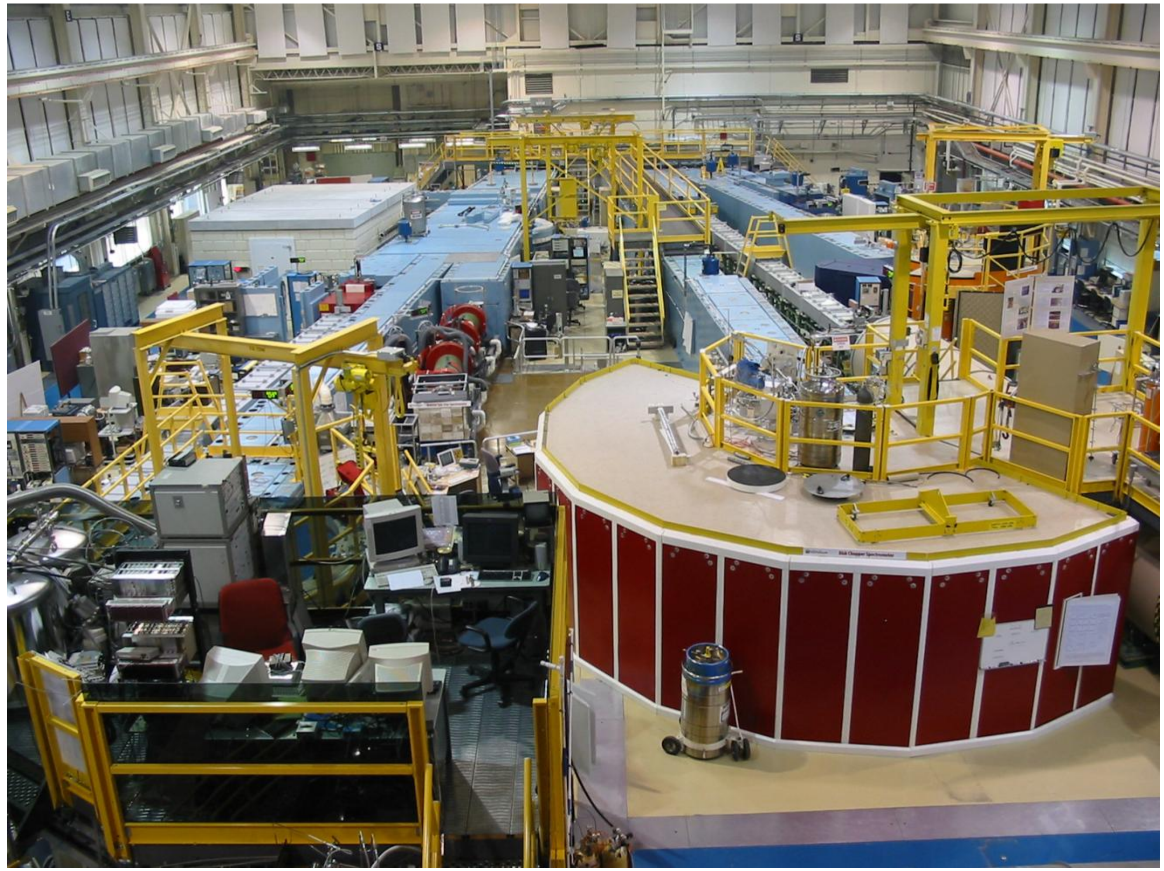
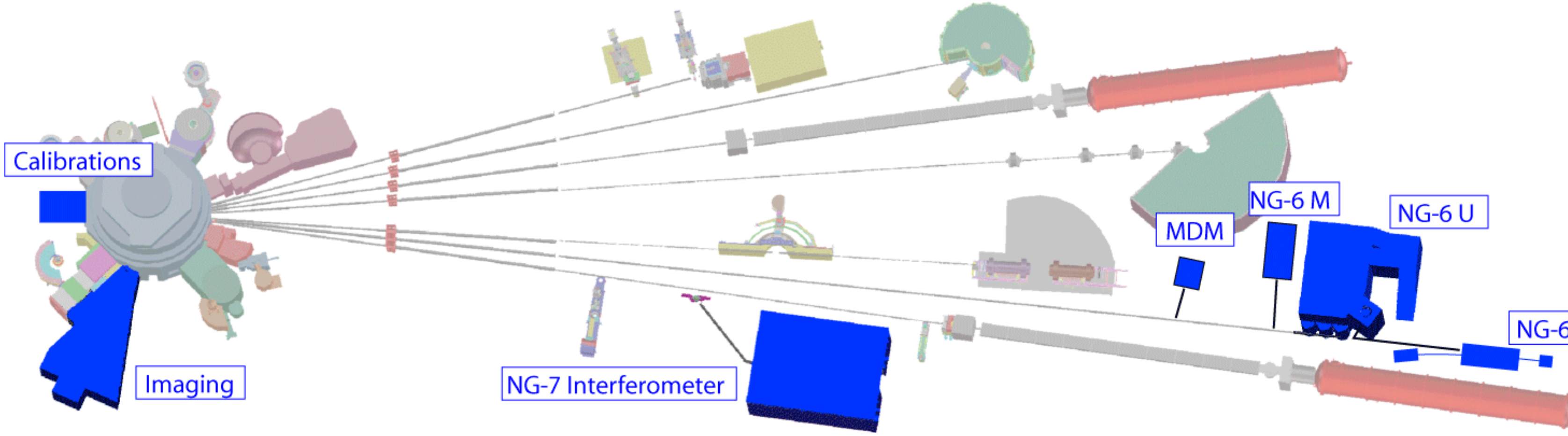
Fundamental Physics with Neutrons at NIST



M. Scott Dewey
Physics Laboratory, NIST

Physics with Secondary Hadron Beams in the 21st Century, April 7th, 2012, Ashburn, VA

Neutron Physics Stations at NCNR



Current Facilities (9 Neutron Beam lines)

NG-6U	UCN neutron lifetime
NG-6	Radiative decay of Neutrons
NG-6M	Absolute neutron fluence (τ_n)
	n-Beam for ^{3}He polarization
NG-6A	Magnetic dipole moment
	LAND Detector
NG-7	Neutron charge radius
	n-^{3}He scattering length
	QIP
Laser Labs	^{3}He Research and Cell Fabrication (2)
BT-2	Neutron Imaging (Thermal)
TC3	Device calibrations (3 Thermal Beams)
^{252}Cf	Homeland Security
Mn Bath	n-Source Calibrations

Current and Recent Programs/Experiments

- **Radiative Decay of Neutrons (RDK):** *NIST, Tulane University, University of Maryland, University of Michigan, Arizona State University and University of Sussex*

- **UCN Lifetime:** *NC State, NIST, Harvard and Yale*

- **Parity Violating Spin Rotation:** *Indiana University, Gettysburg College, George Washington University, University of Washington, NC Central University. NIST, JINR and Kazakh University*

- **‘a’ Correlation in Neutron Decay (aCORN):** *Tulane University, NIST, Indiana University, DePAW University, Hamilton College, Harvard and University of Sussex*

- **<u>Time Reversal Asymmetry (emiT):</u>** *University of North Carolina, NIST, University of Washington, Tulane University, Hamilton College and LBNL*

- **<u>Neutron Interferometry:</u>** Tulane University, MIT, NIST, NCSU, NCSU_WIL, Yale and Indiana University

- **<u>Magnetic Dipole Moment:</u>** University of Hawaii, ANL, Valparaiso University, NIST, Indiana University and Tulane University

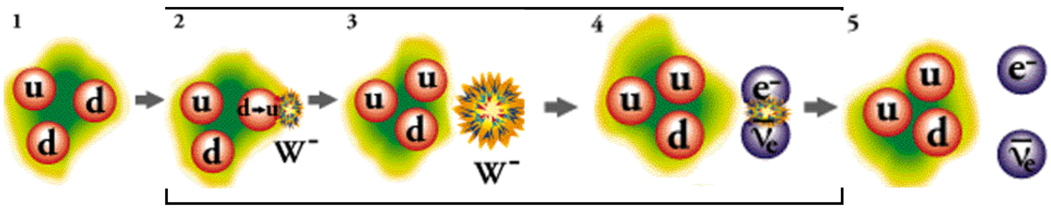
- **<u>He-3 Polarization:</u>** NIST, Indiana University, Hamilton College and Wisconsin University

- **<u>Absolute Neutron Counting:</u>** NIST and University of Tennessee/ORNL

SUPPORT

NSF, DOE and NIST

Neutron in the Standard Model



$$n \to p + e^- + \bar{\nu}_e \; (+\gamma)$$

$$dW \propto (g_V^2 + 3g_A^2)F(E_e)[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_eE_\nu} + \vec{\sigma_n}\cdot(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_eE_\nu})]$$

Jackson, Treiman, Wyld, *Nucl. Phys.* **4**, 206 (1957)

Lifetime

$$\tau = \frac{1}{f(1+\delta_R)}\frac{K/ln2}{(1+\Delta_R^V)(g_V^2+3g_A^2)} = (885.7 \pm 0.8)\,\mathrm{s}$$

Coupling ratio

$$\lambda = \frac{|g_A|}{|g_V|}e^{i\phi} = (-1.2695 \pm 0.0029)$$

Electron-antineutrino asymmetry

$$a = \frac{1-|\lambda|^2}{1+3|\lambda|^2} = (-0.103 \pm 0.004)$$

Spin-antineutrino asymmetry

$$B = 2\frac{|\lambda|^2 - |\lambda|cos\phi}{1+3|\lambda|^2} = (0.981 \pm 0.004)$$

Spin-electron asymmetry

$$A = -2\frac{|\lambda|^2 - |\lambda|cos\phi}{1+3|\lambda|^2} = (-0.1173 \pm 0.0013)$$

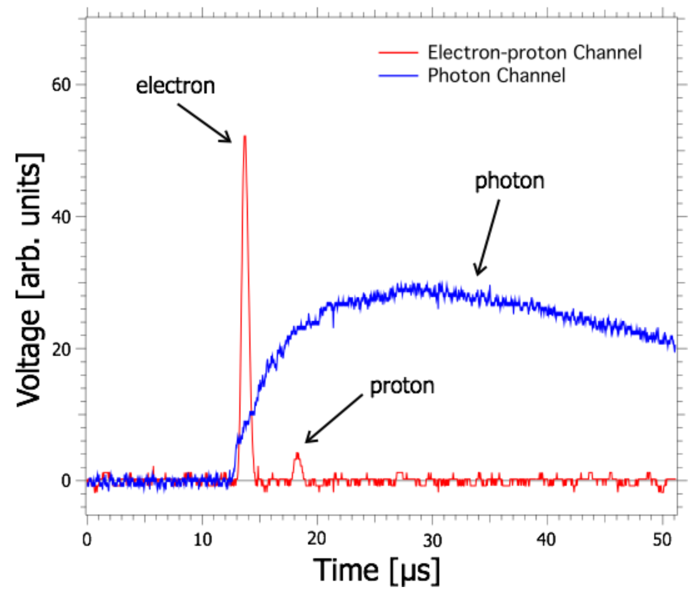
Triple correlation

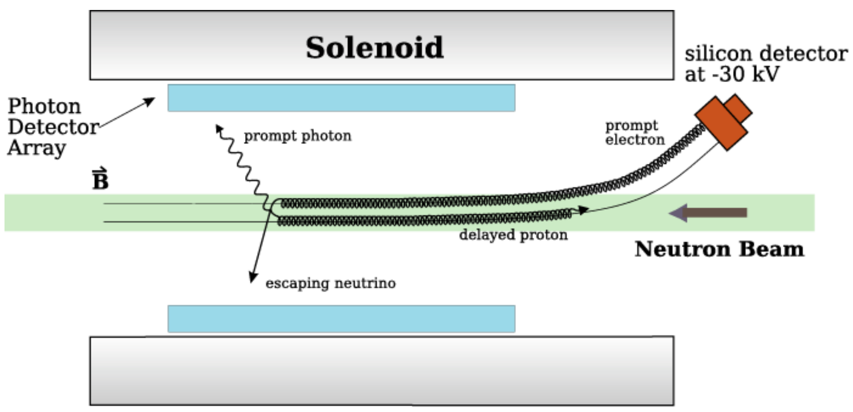
$$D = 2\frac{|\lambda|sin\phi}{1+3|\lambda|^2} = (-4 \pm 6)\times 10^{-4}$$

Radiative Neutron Decay (RDK)

$$n \rightarrow p + e^{-} + \bar{\nu}_e + \gamma$$

- Previously unmeasured process in a fundamental semileptonic decay. Testing QED in a weak process.
- Groundwork for other investigations: new correlations for Standard Model tests, photon polarization, testing radiative corrections O(0.5%).



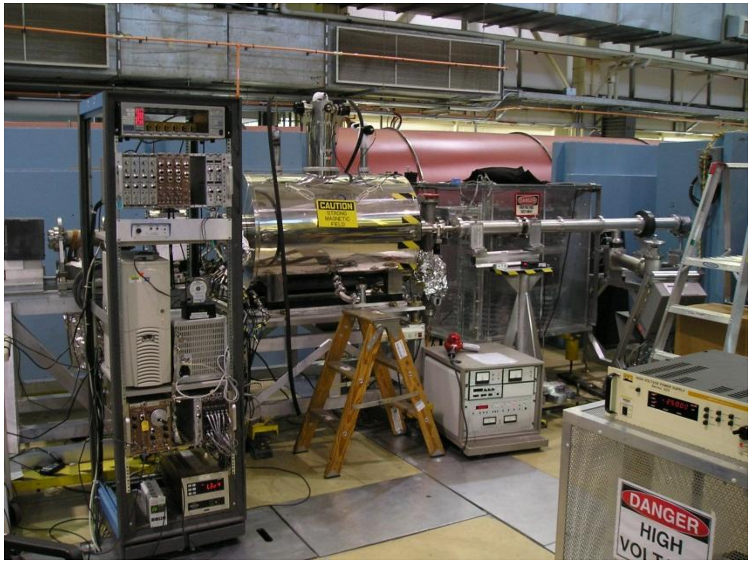


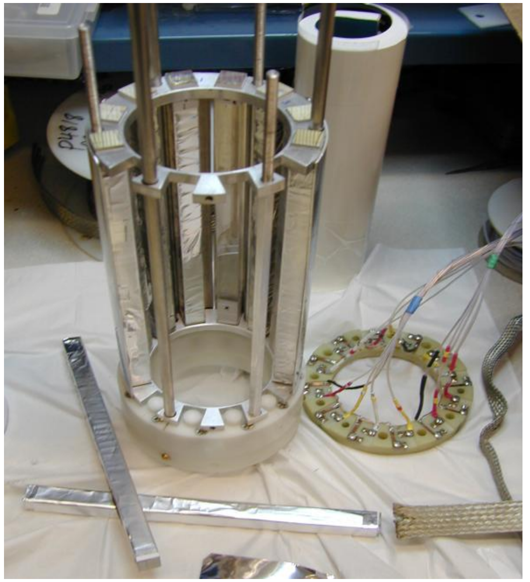
Measured branching ratio:

$BR_{\mathrm{RDK\ I}} = (3.13 \pm 0.34)\ \mathrm{x}10^{-3}$
$BR_{\mathrm{QED}} = 2.81\ \mathrm{x}10^{-3}$

J.S. Nico *et al*, *Nature* **444**, 1059 (2006)

RDK II





- Measurement of the branching ratio from threshold to the endpoint. Statistics and systematic uncertainties ~ 1%.

- Measurement of the energy spectrum of photons from radiative neutron decay from ~5 keV to 753 keV endpoint using 12-element BGO

- Extend low-energy region with bare avalanche photodiodes to ~100 eV)

Data collection will end in October, 2009

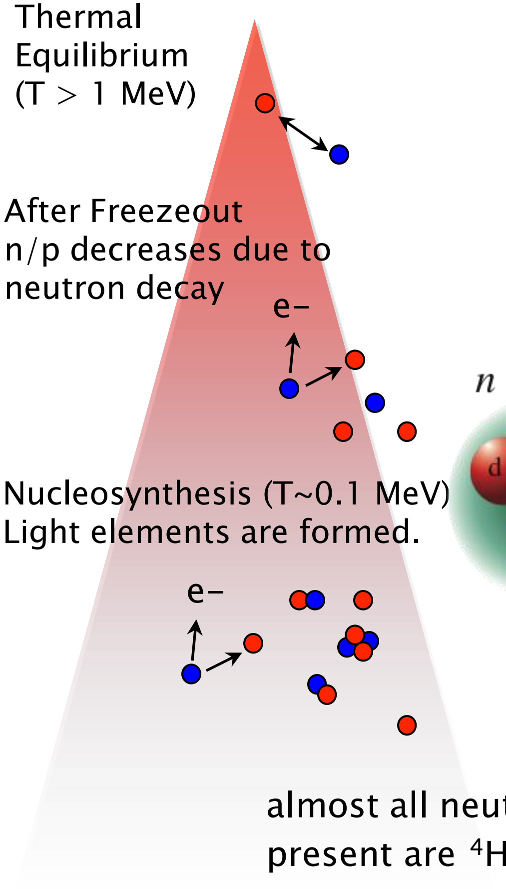
Neutron Lifetime Measurement

Big Bang Nucleosynthesis

Thermal Equilibrium (T > 1 MeV)

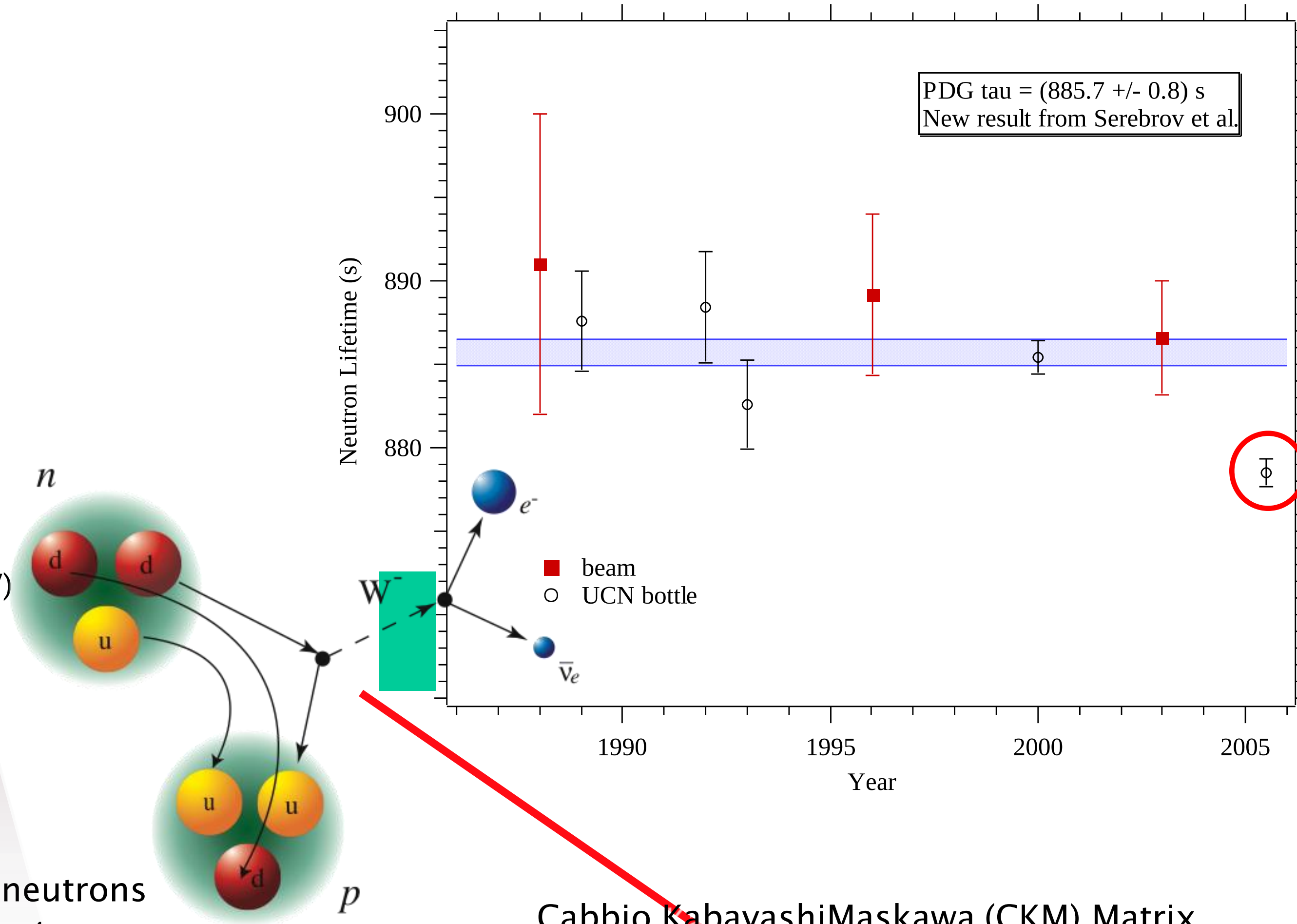
After Freezeout n/p decreases due to neutron decay

Nucleosynthesis (T~0.1 MeV) Light elements are formed.



almost all neutrons present are ^{4}He

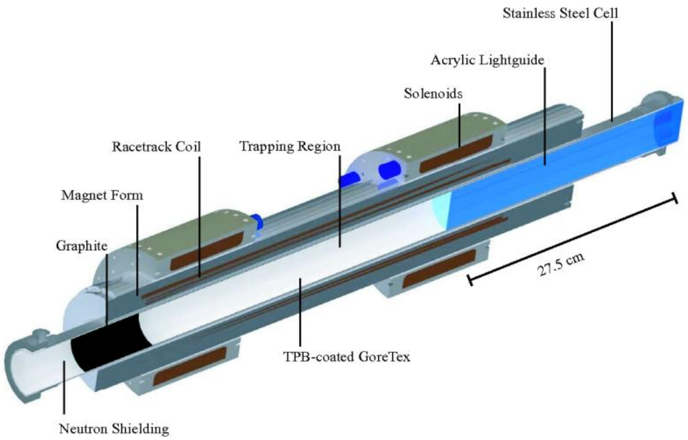
Neutron lifetime dominates the theoretical uncertainty of ^{4}He abundance.

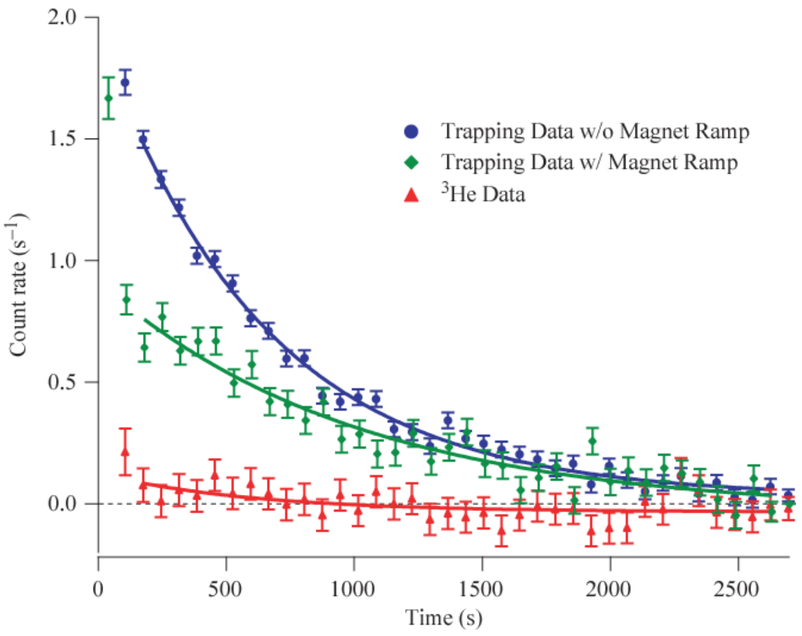


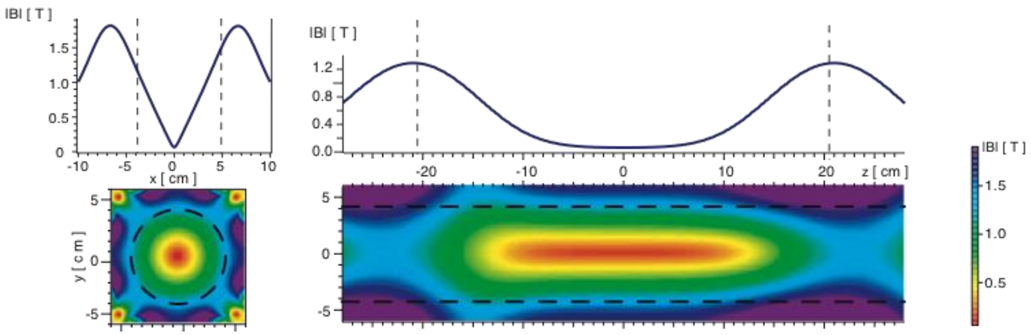
Cabbio KabayashiMaskawa (CKM) Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

UCN Trapping and Lifetime



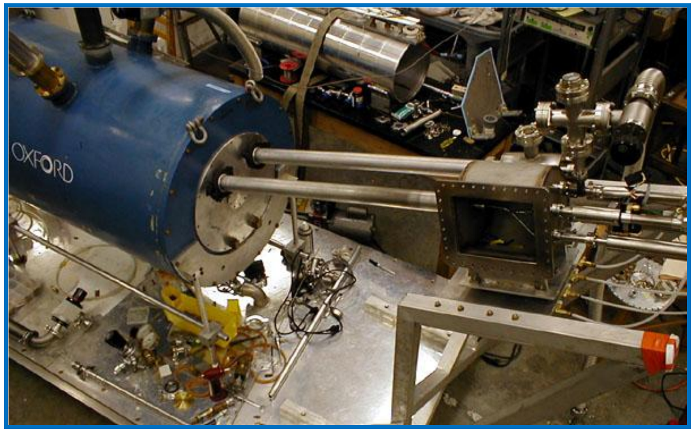


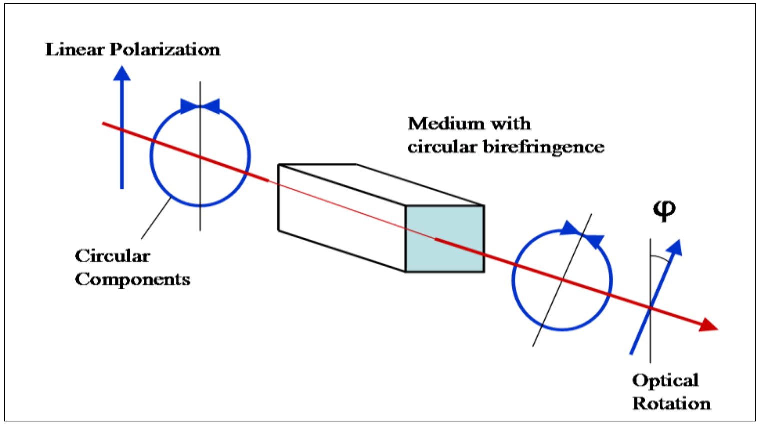


- Confine UCN with a magnetic trap to eliminate wall losses.
- Produce UCN using the superthermal process in superfluid helium to increase the UCN density.
- Ramp Magnet Field to remove above threshold neutrons
- Detect neutron decay from helium scintillation light, giving continuous monitoring of decays.

UCN Lifetime apparatus

Parity-violating spin-rotation of polarized neutrons





- When linearly polarized light passes through a "handed" medium, such as sucrose, the axis of polarization transversely rotates due to the interaction with the handed molecule. Analogous to optical rotation, a polarized neutron experiences a transverse rotation of it spin vector about its momentum vector due to the interaction with target nuclei via the weak force, which violates parity.

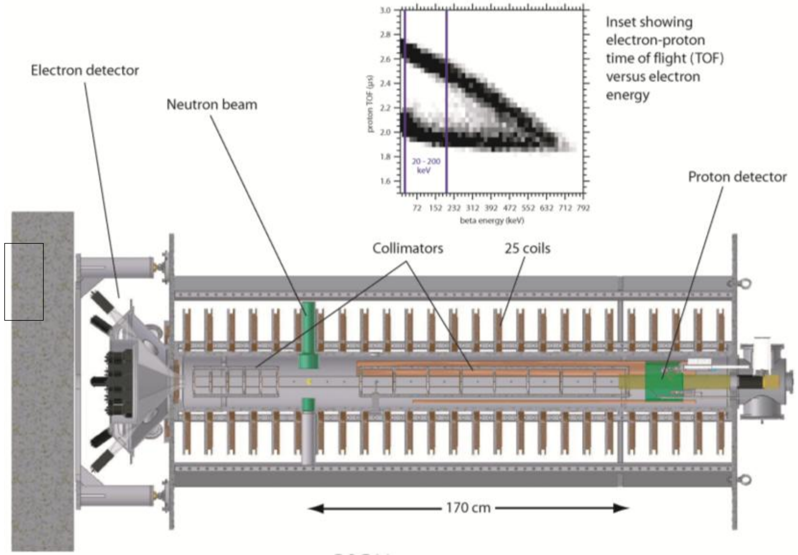
$$f(0) = f_{PC} + f_{PV}\left(\vec{\sigma}\cdot\vec{k}\right)$$

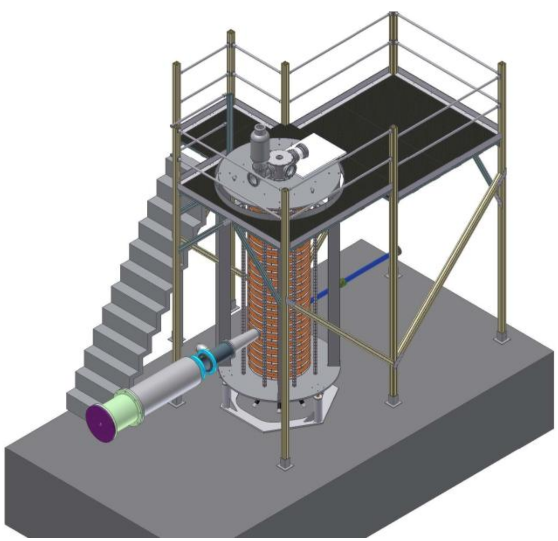
The PV rotation of the angle of transverse spin is the accumulated difference: $\varphi_{PV} = \phi_{+} - \phi_{-} = 2\varphi_{PV} = 4\pi l\rho f_{PV}$

Goal: $\varphi_{PV}\left(\vec{n},{}^{4}\mathrm{He}\right) \approx 3\times 10^{-7}\,\mathrm{rad/m}$

- A measurement of the PV neutron spin-rotation in helium would provide information about the relative strengths of the nucleon-meson weak couplings.
- A measurement of PV neutron spin-rotation will allow the first comparison between isospin mirror systems in nucleon-nucleon weak interaction.

e - $\overline{\nu}_e$ Correlation (aCORN) in Neutron β Decay



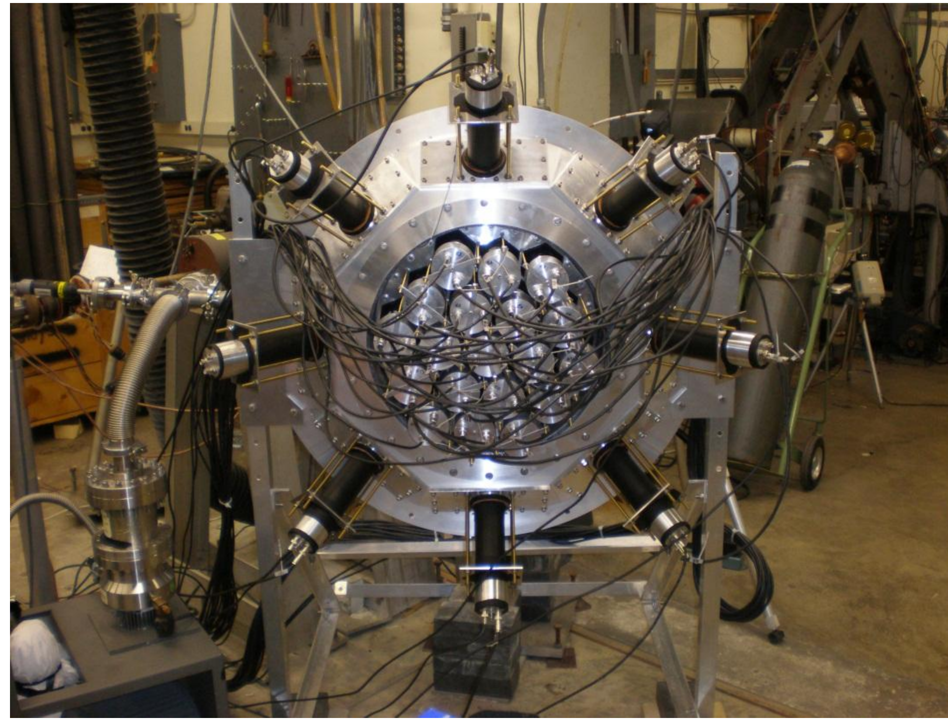


- This correlation is the least accurately known of the major correlations. Unlike most of the others, it can be measured using unpolarized neutrons.

- In combination with the other correlation coefficients and the neutron lifetime, a precise value for it tests the validity of the Standard Model of Electroweak Interactions.

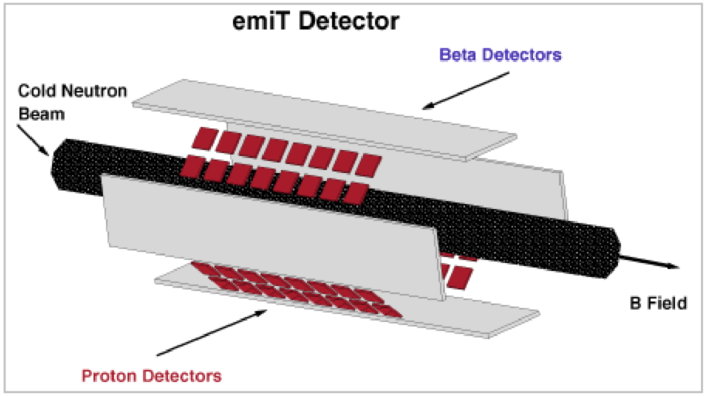
- The experiment measures the correlation between the outgoing elector and anti neutrino directions in unpolarized neutron beta decay. Conservation of momentum implies that there will be a fast group of protons (antineutrino traveling with the electron) and a slow group (antineutrino traveling with the proton). The correlation is the asymmetry between the number of events in each group (see inset showing the "wishbone" pattern of arrival time difference versus electron energy).

aCORN Setup at being assembled at Indiana University

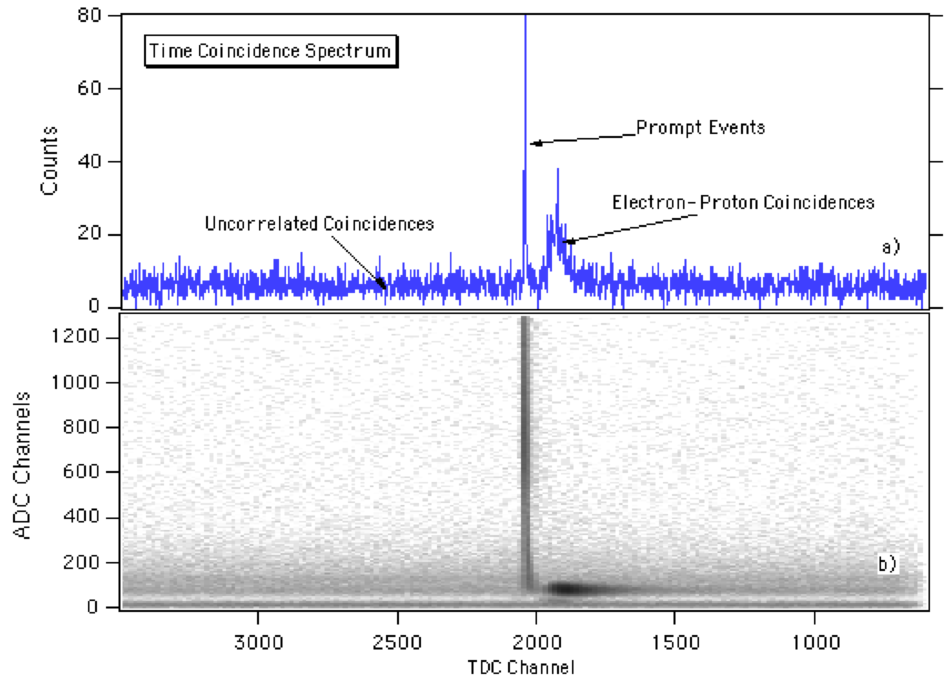


Electron Detector

Search for Time Reversal Violation in Polarized Neutron Decay (emiT II)



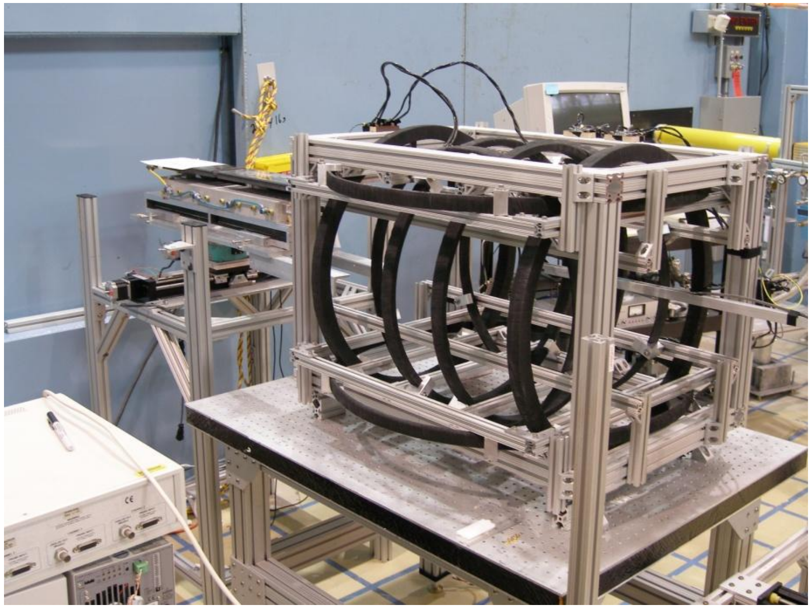
(Top) Schematic of the emiT apparatus. The beta detectors are plastic scintillator, the proton detectors consist of arrays of surface barrier diode detectors. (Right) Histogram of coincidence events. The peak is due to neutron decay.

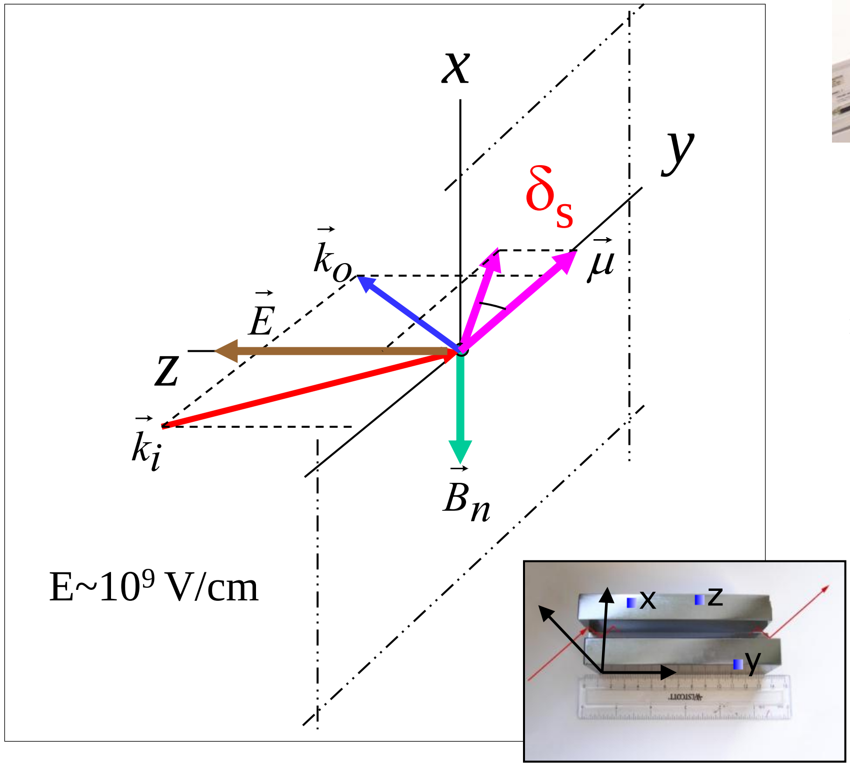


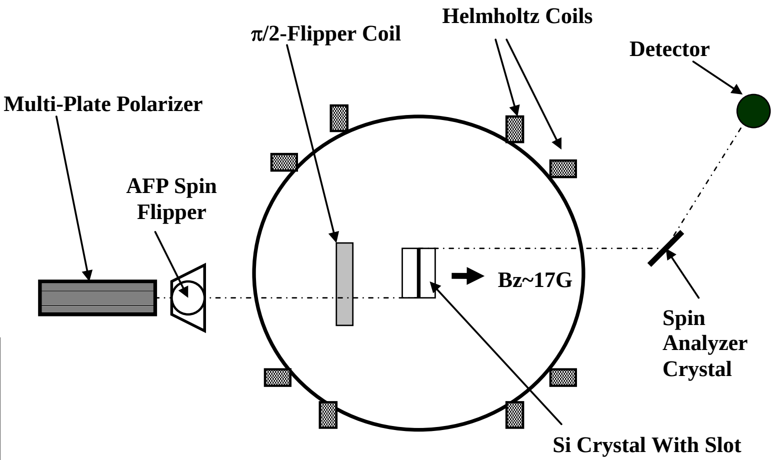
This term is a triple correlation involving the neutron spin and the momenta of the electron and neutrino decay products. The “emiT” experiment searches for ‘D’ or will set an improved upper bound on the ‘D coefficient’ the time-reversal asymmetry term in neutron beta decay. It does so by measuring electron-proton coincidence events from the decay of polarized neutrons. An asymmetry in coincidence pairs is formed as a function of the direction of the neutron spin. A measurement of a nonzero asymmetry would be an unambiguous indication of time-reversal violation

Neutron Magnetic Dipole Moment (MDM)

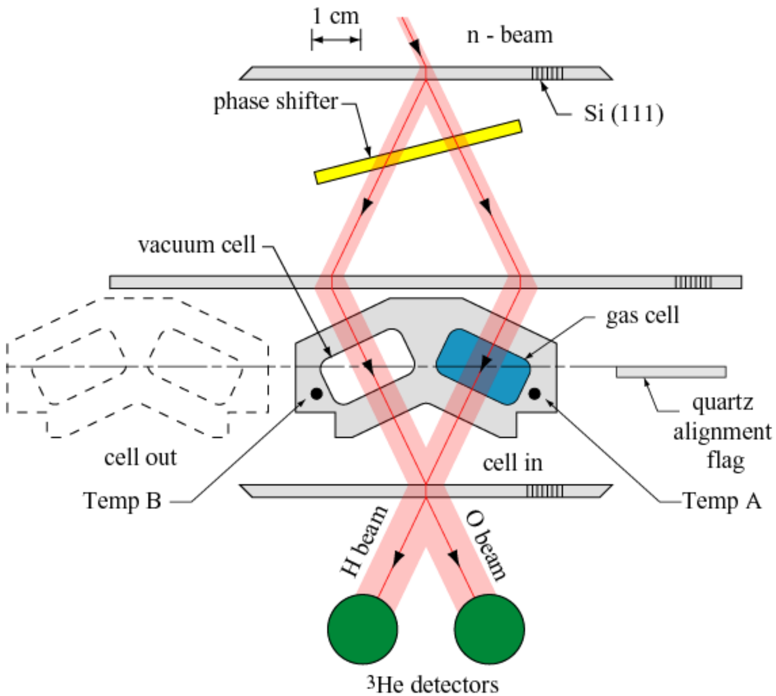
In the MDM experiment, called *"Schwinger scattering"*, the neutron MDM moving through the atomic electric fields in single crystal sees a magnetic field in its rest frame, *producing a rotation.* We can use the *Neutron Magnetic Dipole moment* (MDM ~ 10^5 x EDM) measurement to test our concepts for a possible EDM measurement.



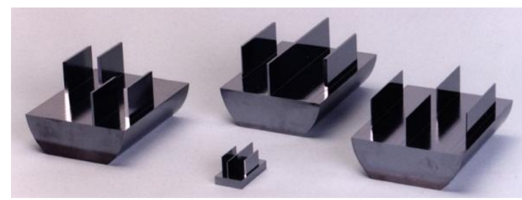




n-Few body scattering lengths



- The bound coherent scattering length is unambiguously related to the free nuclear elastic coherent scattering lengths in the two S-wave spin channels.
- Precisely measured scattering lengths are becoming benchmarks for using few body systems as the building blocks for modern many body nuclear potentials, neutron cross-section standard and are also used in materials science research.



$$b_{np} = A_{np}\left[\tfrac{1}{4}\,{}^{0}a_{np} + \tfrac{3}{4}\,{}^{3}a_{np}\right]$$

b_{np} = (-3.7384 ± 0.0020) fm - Two Body System

$$b_{nd} = A_{nd}\left[\tfrac{1}{3}\,{}^{2}a_{nd} + \tfrac{2}{3}\,{}^{4}a_{nd}\right]$$

b_{nd} = (6.6649 ± 0.0040) fm - Three Body System

$$b_{n^3He} = A_{n^3He}\left[\tfrac{1}{4}\,{}^{0}a_{n^3He} + \tfrac{3}{4}\,{}^{3}a_{n^3He}\right]$$

b_{n^3He} = (5.8572 ± 0.0072) fm - Four Body System

These are the most precisely measured values in the world today

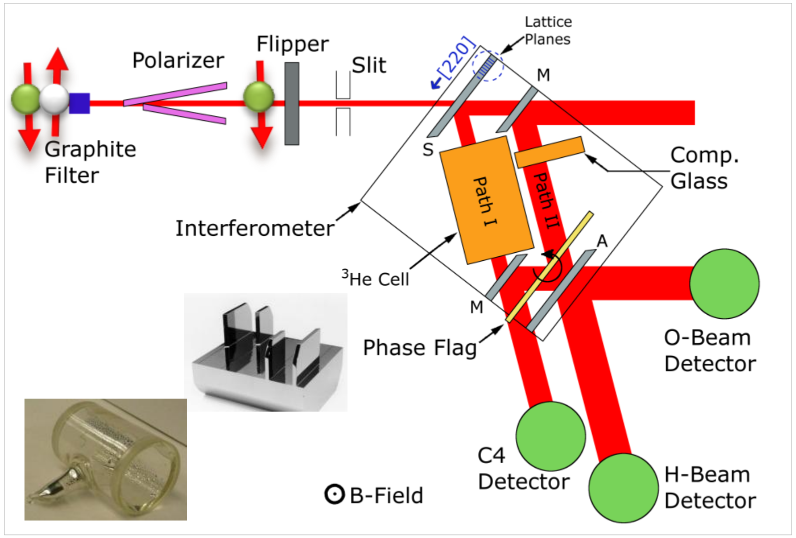
Precision Measurement of the Incoherent n-^{3}He Scattering Length

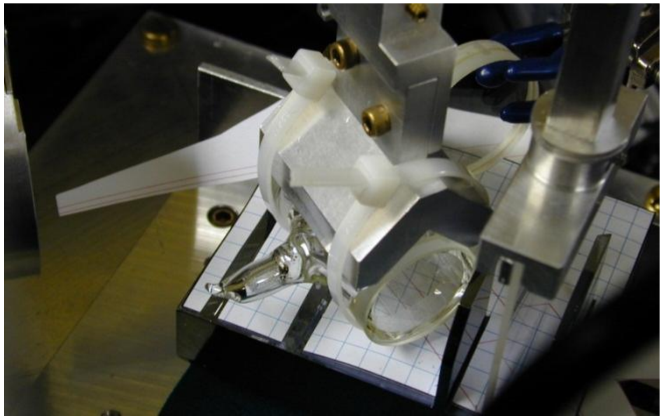
We measure the spin-incoherent (spin-dependent) scattering length using polarized ^{3}He gas trapped in a glass cell.

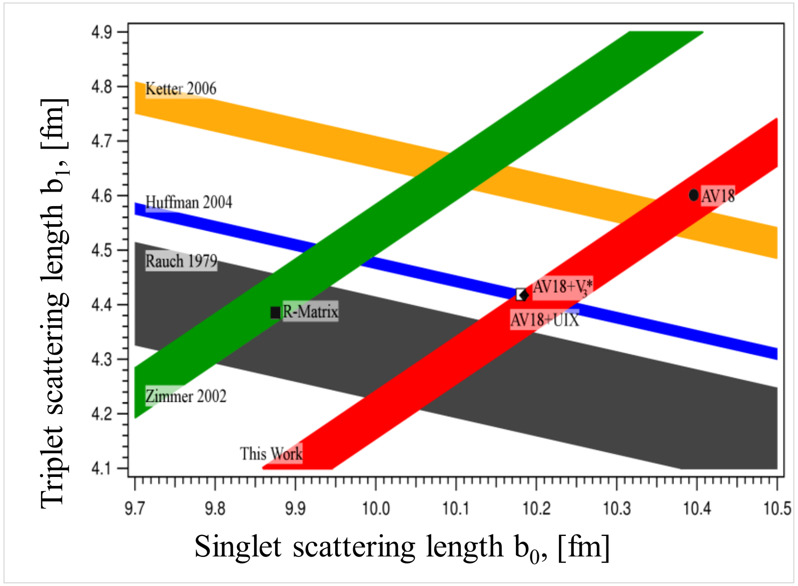
$$b_i = \frac{\sqrt{3}}{4} b_1 - b_0$$

Our Result:

b_i= -(2.512 +/- 0.018) fm



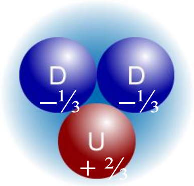


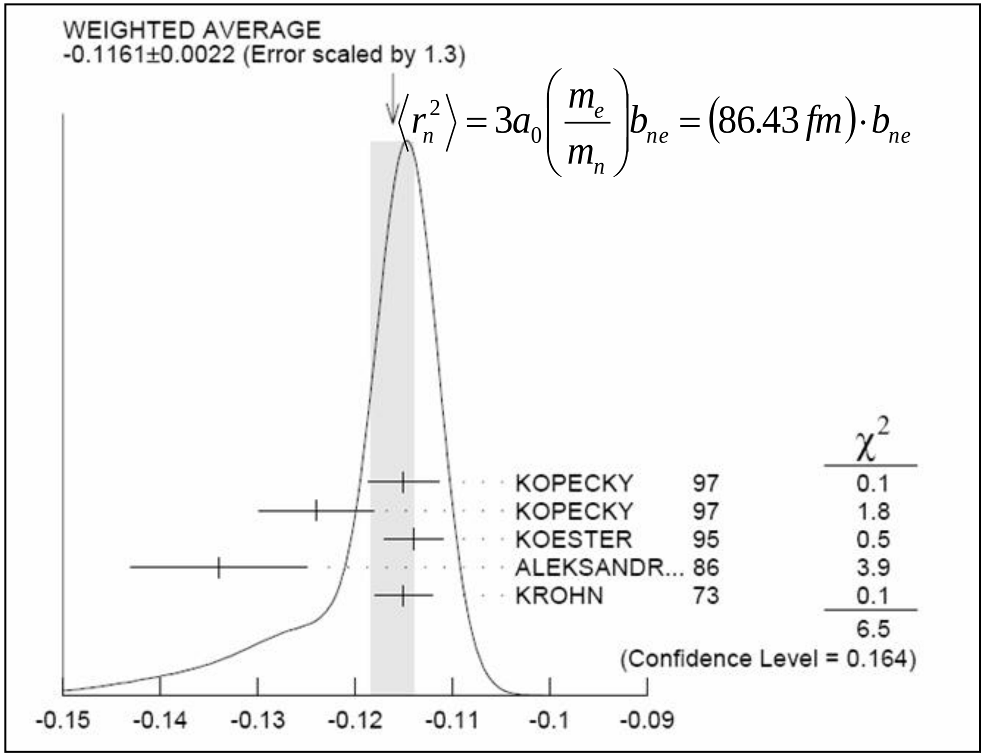


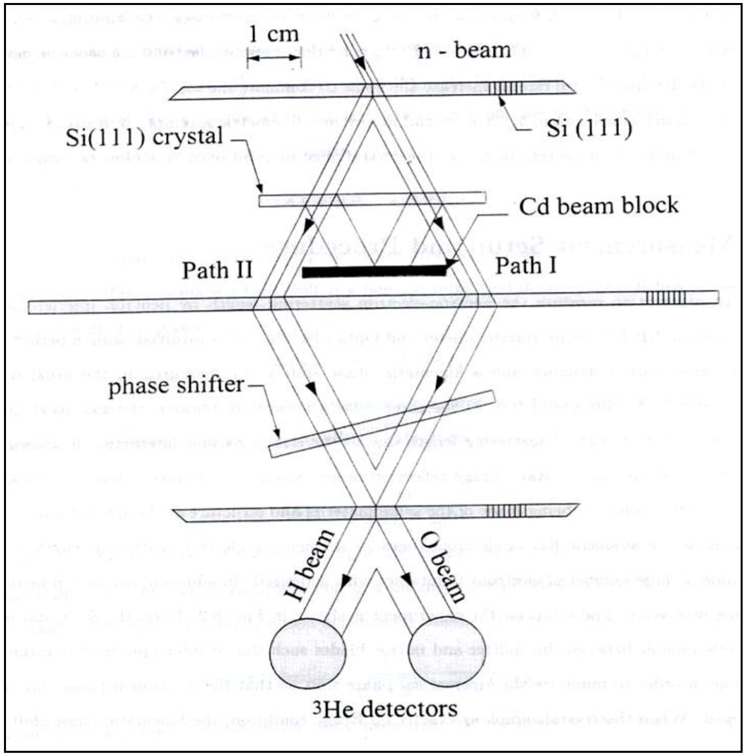
DH5, October 15

Charge Structure of a Neutron

Test of quantum chromodynamics







The charge radius of the neutron is an important quantity for understanding quark structure inside a nucleon. Previous experiments to determine b_{ne} used energy dependent total transmission cross-sections of neutrons on targets such as Lead and Bismuth.

b_{ne} can be found by measuring the dynamical phase shift caused by a silicon crystal placed within the beams paths of the interferometer, and rotated through its Bragg condition at very small angles.

Neutron Interferometeric Study QIP

$|\psi\rangle = a_y|yes\rangle + a_n|no\rangle$

Will you marry me?

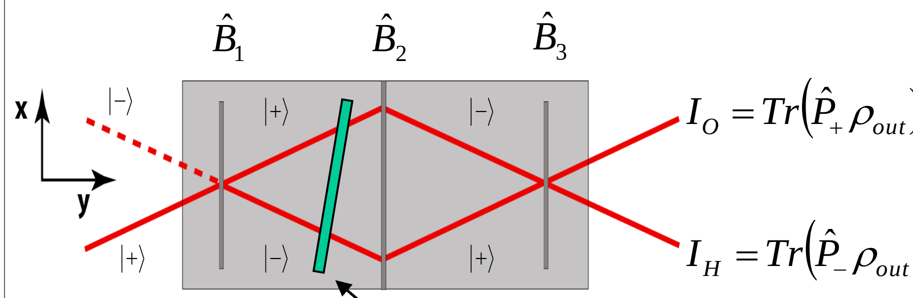
Bit or Qbit?

Classical Information

$$\begin{pmatrix} P_y & 0 \\ 0 & P_n \end{pmatrix} \qquad yes = 1 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \qquad no = 0 = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

Quantum information

$$\begin{pmatrix} |a_y|^2 & a_n a_y{}^* \\ a_y a_n{}^* & |a_n|^2 \end{pmatrix} = \begin{pmatrix} P_y & C^* \\ C & P_n \end{pmatrix}$$



$$|\Psi_{in}\rangle = 1\cdot|+\rangle + 0\cdot|-\rangle \qquad \hat{\Phi} = \begin{pmatrix} e^{i\phi} & 0 \\ 0 & 1 \end{pmatrix}$$

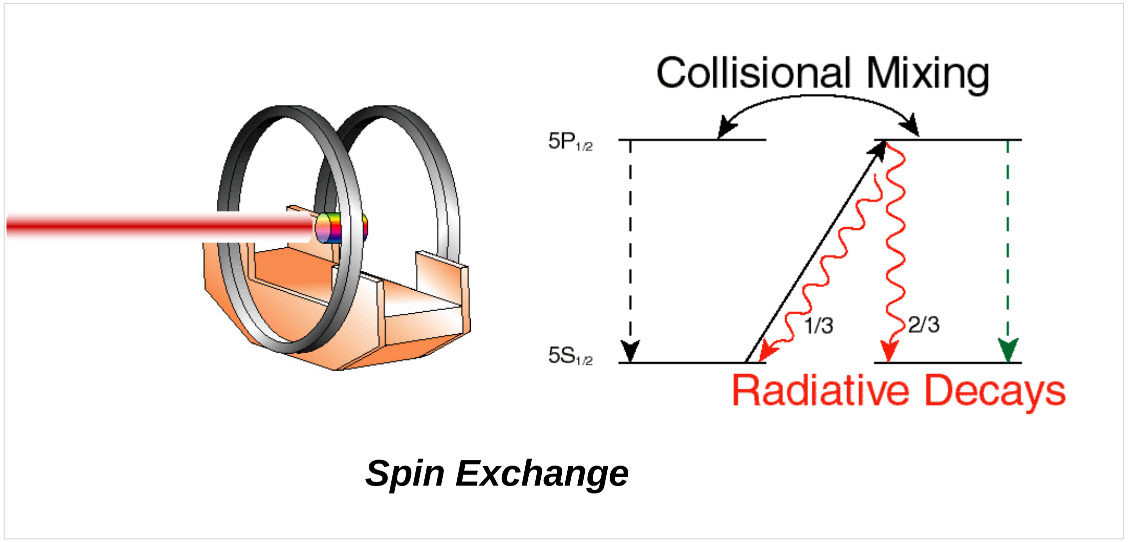
$$\rho_{in} = |+\rangle\langle+|$$

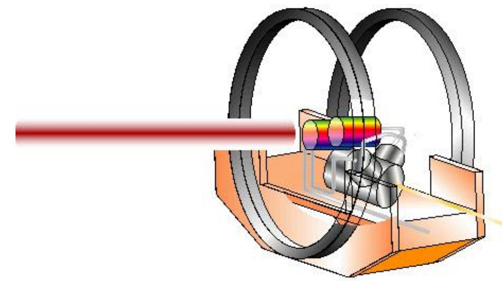
$$\rho_{out} = \hat{B}_3\hat{B}_2\hat{\Phi}\hat{B}_1\rho_{in}\hat{B}_1{}^+\hat{\Phi}^+\hat{B}_2{}^+\hat{B}_3{}^+$$

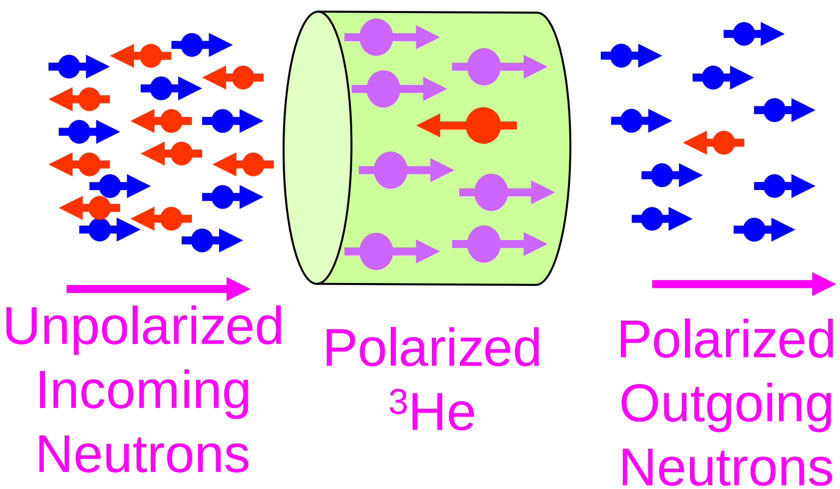
'2 qbit' quantum computer'

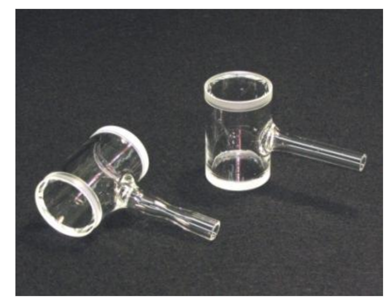
- Adding spin to Neutron Interferometer makes it operate like a 2 qbit Quantum Information Processor and may allow study of the all important quantum decoherence phenomena in QIP.
- In neutron interferometry we can detect individual events and the time scale of the evolution is such that we can modify the experiment between counts. This is different from other method such as NMR where it possible to influence a classical ensemble only.

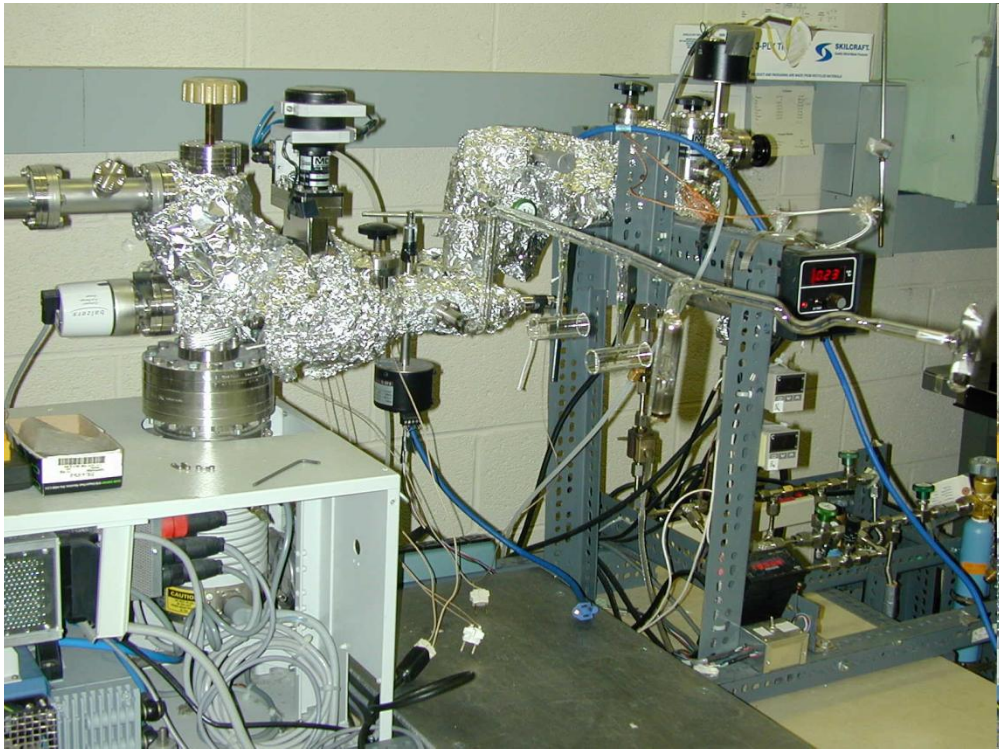
^{3}He Spin Filters

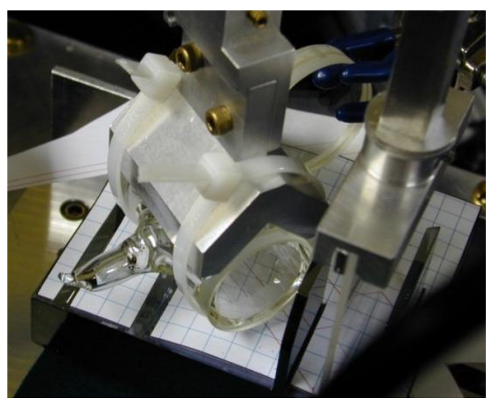






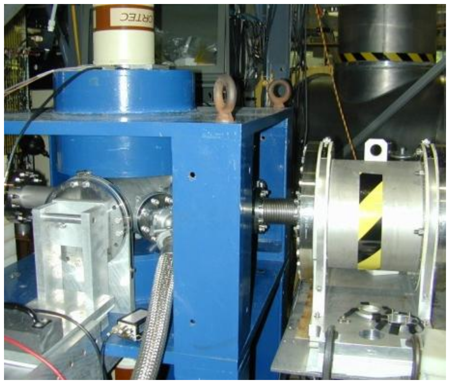






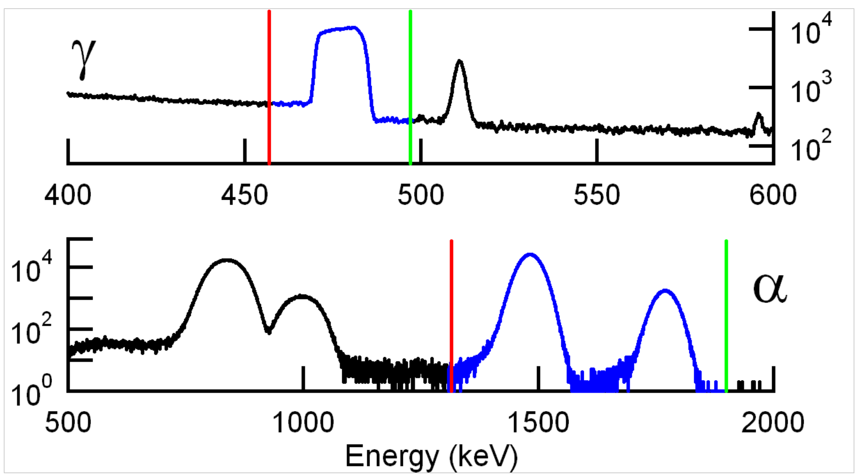
- BT-7: Polarized thermal TAS; BT-7 optimized simultaneously both in unpolarized and polarized modes.
- SANS: full PA; Visualization of 3D magnetization.
- Reflectometry: much more efficient collection of polarized off-sepcular data.
- Ongoing development of wide-angle PA entirely by ^{3}He spin filters -> most compact polarized neutron instrumentation.
- Ongoing development of *in-situ* SEOP on the beam line.
- Collaboration with SNS and other institutions

Absolute Neutron Counting



Alpha-gamma counting for High Accuracy Fluence Measurement

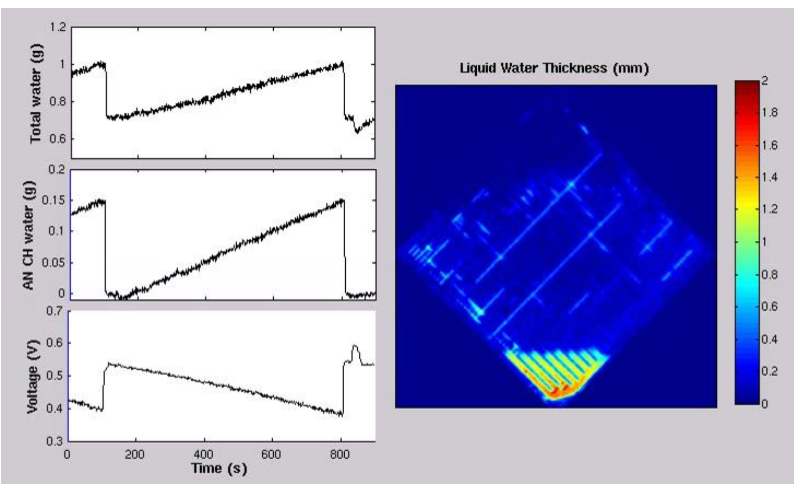
Neutron fluence is measured by counting gamma-rays from the reaction $n + {}^{10}B \rightarrow {}^{4}He + {}^{7}Li + \gamma$(478KeV) with a calibrated gamma detector.

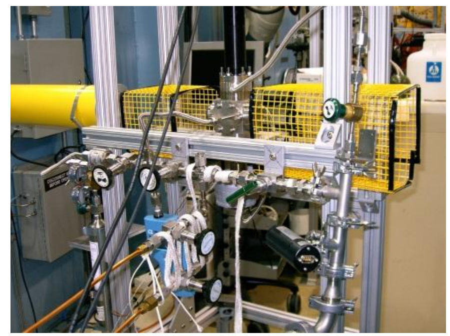


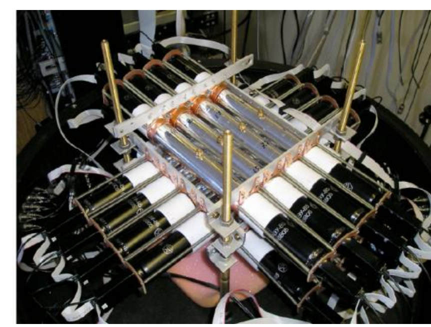
Alaph-Gamma detector with the 1/v detector to the right (L). Inside of the chamber showing the alpha detector and the target (R). Typical alpha and gamma spectrum are shown at the bottom.

The Other Half

- Neutron Imaging
- Neutron Instrument Calibrations
- Neutron Source Calibrations
- Detector Developments
- Neutron Standards Development
- Homeland Security Related Research
- Neutron Cross-sections Standards

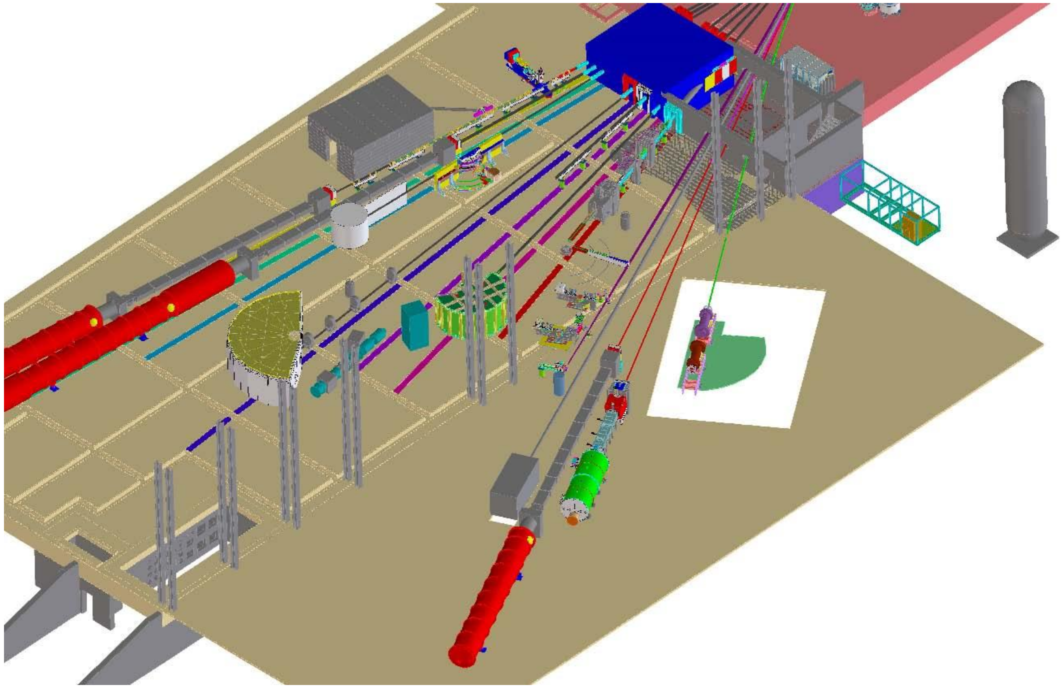


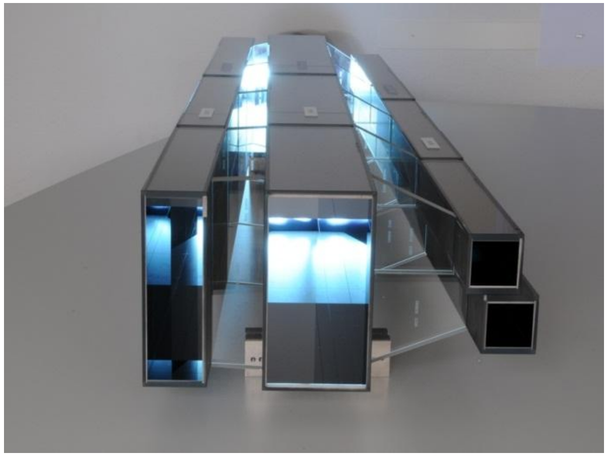




NCNR EXPANSION

Up to 3 additional monochromatic beam lines and an end position





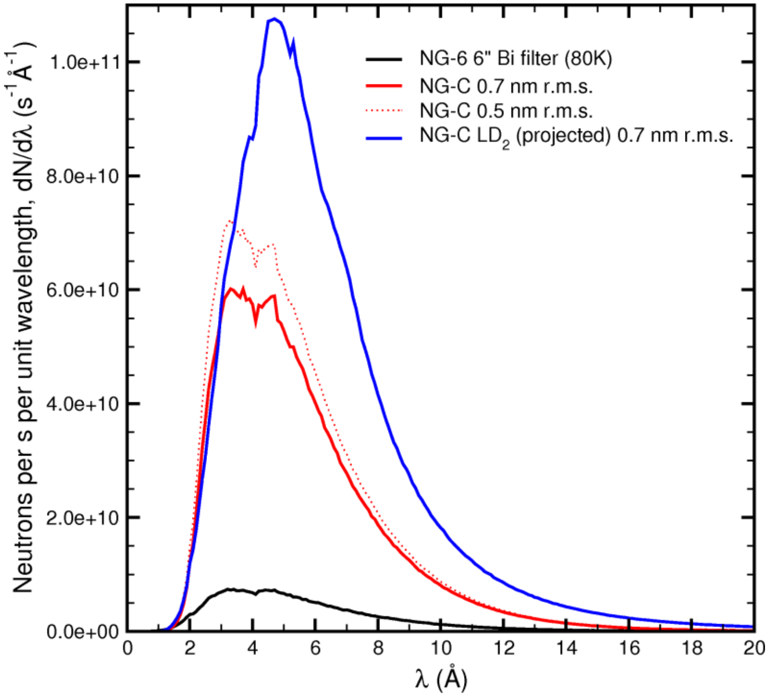
Planned Experiments

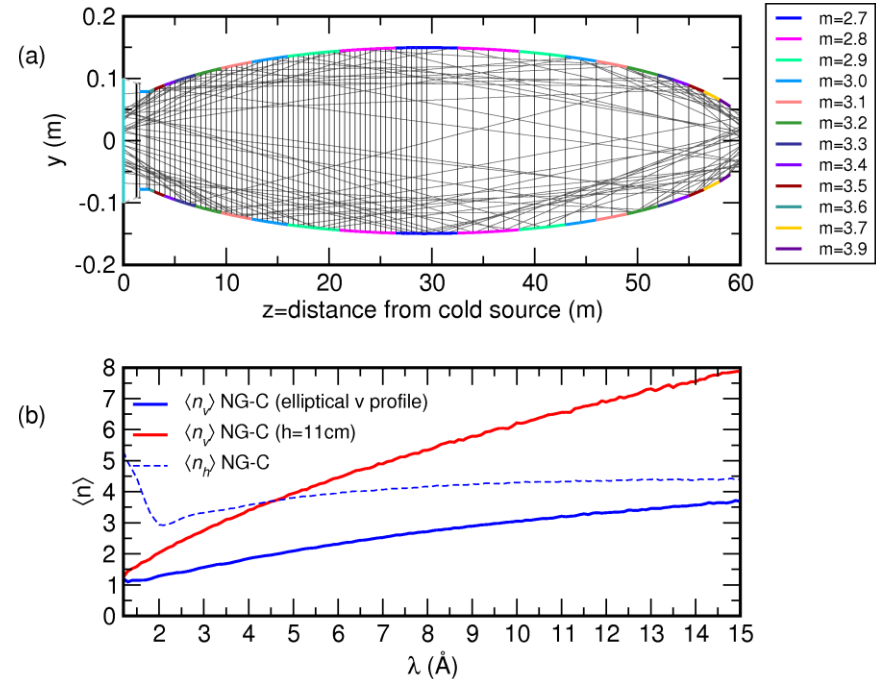
(2009) Precision radiative decay
(2010) Magnetic dipole moment (=> EDM?)
(2009) aCORN ("little a" correlation expt)
(2010) Decoherence in quantum computation
(2012) Improved neutron lifetime using a proton trap
(2013) Proton asymmetry (correlation expt)

Potential New Experiments

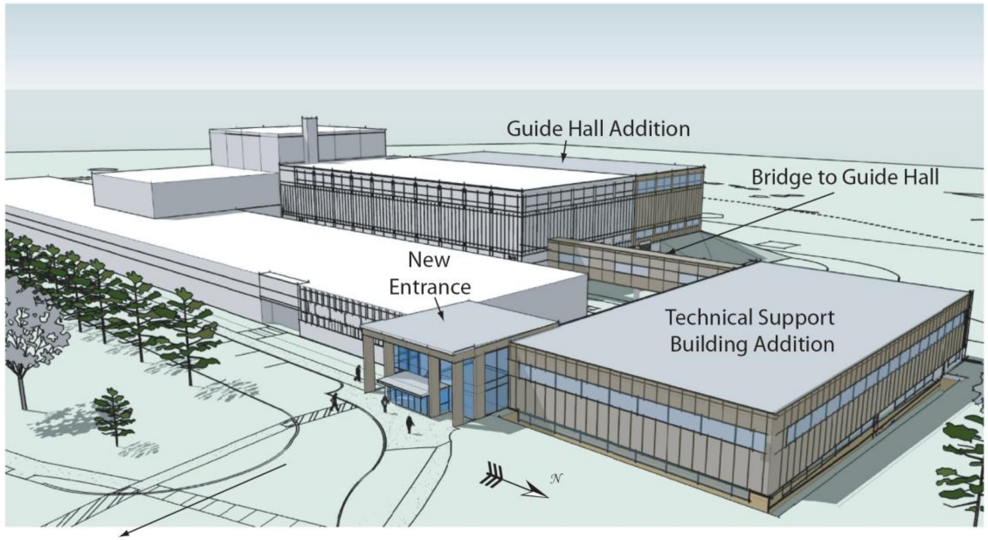
emiT III (time-reversal expt)
Neutron spin rotation in liquid hydrogen
Neutron decay into hydrogen
Correlation type expts
QIP with neutron Interferometry

NG-C Characteristics





Guide/position CTW (LH_2 cold source) CTW (projected LD_2 cold source) Existing NCNR guide reference	Phase space tailoring?	Capture flux, φ_c (cm^{-2}s^{-1})	Integral flux, φ_{int} (cm^{-2}s^{-1})	Neutrons/s	Mean wavelength (Å) $\langle\lambda\rangle$˜ $1.8\varphi_c/\varphi_{int}$
NG-C 11cm×11cm guide exit	Yes, but with under-illumination	7.64×10^9 1.57×10^{10}	2.49×10^9 4.47×10^9	3.01×10^{11} 5.41×10^{11}	5.51 6.29
NG-6 guide exit at fundamental physics station (6" Bi filter)	No	1.39×10^9	4.48×10^8	4.03×10^{10}	5.56


Guide Hall Addition
Bridge to Guide Hall
New Entrance
Technical Support Building Addition
To parking lot
Existing
Expansion

Conclusions

- There has been a strong, scientifically diverse cost-effective program in place at the NCNR for more than two decades. NIST has been a premier facility in fundamental physics research in the USA during this period.
- With the expansion, NCNR can become competitive for the best facility and experiments in neutron physics in the world.
- We are interested in attracting collaborators with new ideas.
- The experiments are generally very challenging, technologically uncharted and often long. However, the underlying science is exquisite and always offers the promise of ground breaking new physics.
- But there is also a un-flattering side……..

Thank You