Physics with Cold Neutrons

- Hadronic Parity Violation
- CP/T Violation
- Beta Decay
- $n-\bar{n}$ Oscillations
- Neutron Interferometry
- Quantum Information
- Few-body Interactions
- Gravity

J. Nico, NIST Physics Laboratory Workshop on Fundamental Symmetries and Neutrinos
Chicago, August 10, 2012
Cold Neutrons for Nuclear Physics

Neutron as a probe

- Hadronic parity violation - QCD
- Few-body nuclear physics
- Cross sections
- Scattering lengths
- Neutron charge radius

Neutron itself

- Neutron lifetime
- Angular correlations ($a$, $A$, $b$, $B$, $D$, ...)
- $n$--$\bar{n}$ oscillations
U.S. Cold Neutron Facilities

**NIST:** Center for Neutron Research
- NG-6 (and NG-C) high-flux beams and neutron interferometry facility
- Beam time advised by BTAC

**ORNL:** Spallation Neutron Source (SNS)
- FNPB pulsed high-flux cold beam
- Beam time advised by PRAC

**LANL:** LANSCE
- FP-12 pulsed cold beam

*Operating costs of these facilities are not borne by DOE or NSF Nuclear Physics*
Recent Accomplishments

Hadronic Parity Violation:
➢ Limit on parity-violating gamma ray asymmetry  - PRC (2011)
➢ Limit on parity-violating neutron spin rotation  - PRC (2012)

Beta Decay:
➢ Limit on T-violation in neutron beta decay (emiT)  - PRL (2011)

Interferometry:
➢ Precision measurement of n-3He incoherent scattering length  - PRL (2009)
➢ Decoherence-free neutron interferometry  - PRL (2011)
Major scientific priorities:

I. The search for a neutron electric dipole moment with the nEDM experiment.

II. Continuation of the UCNA experiment to obtain improved precision on $\lambda$, the ratio of the weak axial-vector to vector coupling constants of the neutron.

III. Completion of the NPDGamma experiment to obtain a precision measurement of the weak isovector nucleon-nucleon-pion coupling constant.

IV. Investment in the Nab apparatus with the main goal to determine $\lambda$ to unprecedented precision, using a complementary observable to that of UCNA.

V. Continuation of the NIST experiment to perform the most precise cold beam-based measurement of the neutron lifetime.
The weak interaction among quarks is a fundamental part of the Standard Model, but the hadronic weak interaction between nucleons remains one of the most poorly-understood areas.

If the quarks are close, the weak interaction can produce non-negligible, parity-violating observables. Use hadronic parity violation as a probe of QCD in low energy, non-perturbative regime.

For light quarks and low-Z nuclei, nucleon-nucleon interactions are one of the (calculable) places to study the hadronic weak interaction. Much theoretical work being done with EFT and lattice QCD.

Currently there are about 10 precise experiments (pp scattering, F-18, p- asymmetries, Cs anapole moment) for 4 couplings.
Hadronic Weak Interaction Models

1. **DDH model** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 7 weak meson coupling constants

   \[ f_\pi, h_\rho^0, h_\rho^1, h_\rho^{1'}, h_\rho^2, h_\rho^0, h_\omega^1 \]

   \[ f_\pi \approx 4.5 \times 10^{-7} \]

   \[ A_\gamma \approx -0.11 f_\pi^1 \]

   • Observables can be written as their combinations

   \[ A = a_\pi^1 f_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1 \]

2. **Lattice QCD**

   – J. Wasem, PRC C85 (2012)

   \[ f_\pi = 1.099 \pm 0.505 \pm 0.058 \pm 0.064 \times 10^{-7} \] (\( m_\pi \approx 589 \text{MeV} \))

3. **Effective Field Theory** (hybrid and pure)

   – model-independent

   • NN potentials are expressed in terms of 12 parameters, whose linear combinations give us 5 low energy coupling constants

   • connect to 5 parity-odd S-P NN amplitudes

   \[ A_\gamma^{np} \approx -0.27 \tilde{C}_6 - 0.09 m_N \rho_t \]

**courtesy G. Greene**
The NPDGamma experiment at the SNS

\[ \frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi} \left( 1 + (A_\gamma \cos \theta) \right) \]

\( A_\gamma \) – directional asymmetry in the gammas emitted from cold neutron capture on protons

courtesy G. Greene
The NPDGamma collaboration

P. Alonzi\textsuperscript{3}, R. Alracon\textsuperscript{1}, S. Balascuta\textsuperscript{1}, L. Barron-Palos\textsuperscript{2}, S. Baeßler\textsuperscript{3}, A. Barzilov\textsuperscript{25}, J.D. Bowman\textsuperscript{4}, J.R. Calarco\textsuperscript{9}, R.D. Carlini\textsuperscript{5}, W.C. Chen\textsuperscript{6}, T.E. Chupp\textsuperscript{7}, C. Crawford\textsuperscript{8}, M. Dabaghyan\textsuperscript{9}, A. Danagoulian\textsuperscript{10}, M. Dawkins\textsuperscript{11}, N. Fomin\textsuperscript{10}, S.J. Freedman\textsuperscript{13}, T.R. Gentile\textsuperscript{6}, M.T. Gericke\textsuperscript{14}, R.C. Gillis\textsuperscript{11}, K. Grammer\textsuperscript{12}, G.L. Greene\textsuperscript{4,12}, F. W. Hersman\textsuperscript{9}, T. Ino\textsuperscript{15}, G.L. Jones\textsuperscript{16}, S. Kucuk\textsuperscript{12}, B. Lauss\textsuperscript{17}, W. Lee\textsuperscript{18}, M. Leuschner\textsuperscript{11}, W. Losowski\textsuperscript{11}, E. Martin\textsuperscript{8}, R. Mahurin\textsuperscript{14}, M. McCrea\textsuperscript{14}, Y. Masuda\textsuperscript{15}, J. Mel\textsuperscript{11}, G.S. Mitchell\textsuperscript{19}, S. Muto\textsuperscript{15}, M. Musgrave\textsuperscript{12}, H. Nann\textsuperscript{11}, I. Novikov\textsuperscript{25}, S. Page\textsuperscript{14}, D. Počančić\textsuperscript{3}, S.I. Penttilä\textsuperscript{4}, D. Ramsay\textsuperscript{14,20}, A. Salas Bacci\textsuperscript{10}, S. Santra\textsuperscript{21}, P.-N. Seo\textsuperscript{3}, E. Sharapov\textsuperscript{23}, M. Sharma\textsuperscript{7}, T. Smith\textsuperscript{24}, W.M. Snow\textsuperscript{11}, W.S. Wilburn\textsuperscript{10}, V. Yuan\textsuperscript{10}

\textsuperscript{1}Arizona State University
\textsuperscript{2}Universidad Nacional Autonoma de Mexico
\textsuperscript{3}University of Virginia
\textsuperscript{4}Oak Ridge National Laboratory
\textsuperscript{5}Thomas Jefferson National Laboratory
\textsuperscript{6}National Institute of Standards and Technology
\textsuperscript{7}University of Michigan, Ann Arbor
\textsuperscript{8}University of Kentucky
\textsuperscript{9}University of New Hampshire
\textsuperscript{10}Los Alamos National Laboratory
\textsuperscript{11}Indiana University
\textsuperscript{12}University of Tennessee
\textsuperscript{13}University of California at Berkeley
\textsuperscript{14}University of Manitoba, Canada
\textsuperscript{15}High Energy Accelerator Research Organization (KEK), Japan
\textsuperscript{16}Hamilton College
\textsuperscript{17}Paul Scherrer Institute, Switzerland
\textsuperscript{18}Spallation Neutron Source
\textsuperscript{19}University of California at Davis
\textsuperscript{20}TRIUMF, Canada
\textsuperscript{21}Bhabha Atomic Research Center, India
\textsuperscript{22}Duke University
\textsuperscript{23}Joint Institute of Nuclear Research, Dubna, Russia
\textsuperscript{24}University of Dayton
\textsuperscript{25}Western Kentucky University

This work is supported by
DOE and NSF (USA)
NSERC (CANADA)
CONACYT (MEXICO)
BARC (INDIA)
Neutron Spin Rotation (NSR) in LHe

- It's a very small angle measurement $O(10^{-7})$ rad.
  \[
  \frac{d\phi_{PNC}}{dz} = (0.1 \pm 1.5) \times 10^{-6} \text{ rad/m} \quad \text{Dmitriev et al 1983}
  \]

- Target is placed between a crossed (supermirror) polarizer-analyzer pair (analyzing power $PA$).

- Output field is rotated every second, and neutrons are counted in a $^3\text{He}$ ion chamber.

\[
\sin \phi = \frac{1}{PA} \frac{N_+ - N_-}{N_+ + N_-}
\]

Two critical issues:

- Beam fluctuations exist at $O(1\%)$.

- Difficult to shield below 100 $\mu$G. Rotation angle from this field is about 3 orders of magnetic greater than $\phi_{PNC}$.
Apparatus acquired data on NG-6 January through May 2008.

Result was published in 2011 and is statistics limited.

\[
\frac{d\phi_{PNC}}{dz} = [+1.7 \pm 9.1 (stat) \pm 1.4 (sys)] \times 10^{-7} \text{ rad/m}
\]

Collaboration: Indiana, NIST, Gettysburg, George Washington, Washington, N. Carolina Central, JINR- Dubna, and Al-Farabi Kazakh National
Toward an improved NSR measurement

Statistical Improvement

Expect x40 more polarized neutron flux through apparatus from
1) NIST NCNR expansion and NG-C
2) Increasing apparatus acceptance

1) Reduce heat load
2) Reduce fill/drain times

NSR Status

- Redesign in progress: cryogenics, ion chamber, and magnetics.
- Purchase of large area supermirror polarizer and analyzer pair and guides is in progress
- Mounting of new experiment on NG-C in approximately 2 years.

Goal: \[
\frac{d\phi_{PNC}}{dz} \leq 2 \times 10^{-7} \text{ rad/m}
\]
Physics from Neutron Decay

- Solar physics: \( p + p \rightarrow ^2H + e^+ + \nu_e \)

- Big Bang Nucleosynthesis and light element abundance.

- Test of CKM unitarity; determination of \( V_{ud} \).

- Over-constrained measurements give model-independent SM checks.

- Look for scalar, tensor forces, non-SM physics.

- Measurement of radiative corrections.

- New source of time-reversal \((CP)\) violation?
Neutron Decay

\[ dW \propto (g_V^2 + 3g_A^2)F(E_e)[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b \frac{m}{E_e} + \sigma_n \cdot \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right)] \]

**Electron-antineutrino correlation**

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

**Spin-electron asymmetry**

\[ A = -2 \frac{|\lambda|^2 + |\lambda|\cos\phi}{1 + 3|\lambda|^2} = (-0.1176 \pm 0.0011) \]

**Spin-antineutrino asymmetry**

\[ B = 2 \frac{|\lambda|^2 - |\lambda|\cos\phi}{1 + 3|\lambda|^2} = (0.9807 \pm 0.0030) \]

**Lifetime**

\[ \tau = \frac{1}{K/\ln 2} \frac{g_V^2}{(1 + \Delta_V)(g_V^2 + 3g_A^2)} = (880.1 \pm 1.1) \text{s} \]

**Coupling ratio**

\[ \lambda = \frac{|g_A|}{|g_V|} e^{i\phi} = (-1.2701 \pm 0.0025) \]


Jackson, Treiman, Wyld, Nucl. Phys. 4, 206 (1957)
Caveats:
- PDG scaling factors for both $A$ and lifetime.
- PDG 2012 only. Does not include final UCNA or PERKEO results.
A Novel Method to Measure $a$
(Yerozolimsky and Mostovoy, 1996)
aCORN

We separate groups I and II by the beta energy and time-of-flight between beta and proton detection.

\[ a(E_\beta) = \frac{1}{v_\beta} K(E_\beta) \left( \frac{N_I - N_{II}}{N_I + N_{II}} \right) \]

Our goal is a 0.5% measurement (10x improvement)

courtesy F. Wietfeldt
Currently online on NG-6.

Acquiring data until early 2013 until statistics limited at about 2%.

Move to NG-C in 2013; acquire precision data for $5 \times 10^{-3}$ measurement of $a$.

Collaboration: Tulane, Indiana, Hamilton, NIST, DePauw, Harvard, and Sussex
Nab Experiment

- Measure the electron-neutrino parameter $a$ in neutron decay with accuracy of $\frac{\Delta a}{a} \approx 10^{-3}$ or $\sim 50\times$ better than:
  - $-0.1054 \pm 0.0055$ Byrne et al '02
  - Current results: $-0.1017 \pm 0.0051$ Stratowa et al '78
  - $-0.091 \pm 0.039$ Grigorev et al '68

- Measure the Fierz interference term $b$ in neutron decay with accuracy of $\Delta b \approx 3 \times 10^{-3}$

  Current results: none (not yet measured in n decay)

- Nab will be followed by the abBA/PANDA polarized program to measure $A$, electron, and $B/C$, neutrino/proton, asymmetries with $\sim 10^{-3}$ relative precision, an independent measurement of $\lambda$.  

courtesy D. Počanić
Nab principles of measurement

- Collect and detect both electron and proton from neutron beta decay.
- Measure $E_e$ and $TOF_p$ and reconstruct decay kinematics.
- Segmented Si det's:


Nab experiment at FnPb/SNS

courtesy D. Počanić
Nab at the SNS

Nab apparatus in FnPB

Apparatus extends:
- \( \sim 6 \text{ m above beam height} \),
- \( \sim 1.5 \text{ m below beam height} \).

Fully funded (NSF-MRI, plus DOE constr. + operating funds);
Spectrometer design currently being finalized;
Experiment projected to be ready for beam sometime in 2015.

courtesy D. Počanić
Status of the Neutron Lifetime - 2012

PDG 2012 Evaluation
- Cold neutron beam
- UCN confinement

Neutron Lifetime (s)

Publication Year


875 880 885 890 895 900
2003 Measurement in Cold Beam

\[ \tau = \frac{\dot{N}_{\alpha+t}}{\bar{N}_p} \left( \frac{\varepsilon_p}{\varepsilon_o v_o} \right) (nl + L_{end}) \]

Requires absolute knowledge of neutron and proton counting. Fit for lifetime and end effects.
New Beam Lifetime Status

- 2003 result was limited by neutron counting systematics; statistics were at the 1 s level.
- Alpha-Gamma neutron calibration technique demonstrated at better than $10^{-3}$ level.
- New effort in progress; goal to mount the experiment at NIST within 1 to 2 years (NIST, Tulane, Tennessee/ORNL, and IRMM).
- J-PARC effort with a beam via $^3$He(n,p)$^3$H and TPC.
Lifetime via Magnetic Trapping

Magnetic Trapping of Neutrons
- Neutrons lose energy in liquid helium
- Electrons from decay excite helium
- De-excited helium gives off photons
- Light is detected by outside PMTs

Status
- 2004-10 construction of new apparatus.
- 2011 six month data run. Data analysis nearing completion.
- He-3 purity runs at ANL completed.
- Any future runs pending result of this analysis.

Collaboration: NIST, N. Carolina State, Maryland, and Illinois
emiT: T-Violation Search in Neutron Decay

- Completed emiT II analysis in 2011 yielding best limit on $D$ in nuclear beta decay.
- NG-C beam line could provide a factor of 10 increase in neutron flux and approach final state effects with an upgraded emiT apparatus.
- No definite plan at this time.

Radiative Neutron Decay

Status:

- Second run completed on NG-6. Analysis to extract branching ratio and energy spectrum at 1% level in progress.

- Examining possibility of extracting Fierz term $b$.

- Physics beyond 1% level:
  - Non-leading order: proton bremsstrahlung, recoil terms, vertex contribution.

  - Polarization

  - New classes of angular correlations with photon, e.g. $A(J_n \cdot k)$, $D[J_n \cdot (k \times p_{\nu})]$.

- No new efforts planned within 5-year time frame.
Radiative $\beta$-decay admits a T-odd correlation in momenta alone, $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$. Under CPT this probes new spin-independent sources of CP violation.

**How can a $\vec{p}_\gamma \cdot (\vec{p}_e \times \vec{p}_\nu)$ correlation emerge at low energy?**

Enter Harvey, Hill, and Hill (2007, 2008): Gauging the axial anomaly of QCD under $SU(2)_L \times U(1)_Y$ gives rise to interactions containing $\varepsilon^{\mu \nu \rho \sigma}$ at low energy.

**This means the weak vector current can mediate parity violation on its own.**

Such terms appear at N²LO in the chiral effective theory gauged under $SU(2)_L \times U(1)_Y$ [Hill (2010)]

The decay correlation probes the Im part of the interference with the leading vector amplitude. An experiment could set limits on the imaginary part of the low-energy constant.

Such would give a window on new CP phases arising from hidden fermionic matter. Existing constraints are poor.
Neutron Interferometry

A 40,000 kg room (supported by airsprings) provides a stable experimental environment.

- Interferometer Contrast ~ 90%
- Acceptable wavelengths: 0.2 to 0.47 nm
- Extremely Low Backgrounds: < 0.1 /s
- Highly efficient detectors
- Actively controlled
- Phase stability 0.25 deg/day
- Position Stability (actively controlled):
  - better than 0.1 micron
  - better than 0.1 μrad
- Temperature controlled to +/-5 mK
Precision Phase Shift Measurement

\[ \Delta \chi = N b \lambda \frac{D}{\cos \theta} \]

Example:
- Aluminum sample, \( \lambda = 2.70 \text{ Å} \), <111> reflection
- \( D = 100 \mu\text{m} \rightarrow \Delta \chi = 2\pi \)
Interferometry Program

- Few-body neutron scattering length measurements. Motivated to provide input for few body theory in both quantum MC and EFT methods.
  - n-H
  - n-D
  - n-\(^{3}\)He (unpolarized)
  - n-\(^{3}\)He (polarized)
  - n-\(^{4}\)He
  - n-T
  - n-Xe (done)

- Search for “long-range” nuclear forces using ultracold neutrons and noble gases, specifically Ar and Ne (A. Serebrov).

- Neutron mean square charge radius.

- Collaborators: Tulane, NIST, UNC-Wilmington, Waterloo, and Indiana
International Context

Cold Neutron Facilities:

- Institut Laue-Langevin (France)
  - aSPECT
  - PERKEO III

- FRM-II (Germany)
  - PERC

- J-PARC (Japan)
  - Beam lifetime in He-3.
In the next 5 years...

SNS - FNPB
- NPDGamma - in progress
- n- $^3$He
- Nab
- nEDM

NIST - NG-6/C
- aCORN - in progress
- Neutron spin rotation
- Neutron lifetime

NIST - Interferometer
- Few-body systems ($^4$He, T, Xe)
- Neutron charge radius
- Long-range forces (Ar, Ne)

- Precision measurements in neutron physics still play an important role in searching for new physics and provide complementary information to HEP as well as important questions in QCD.

- New high-flux facilities coming online worldwide for fundamental neutron physics: PSI, FRM-II, SNS, LANL, JSNS, NIST, TRIUMF, ESS...

- Theoretical work and new ideas are critical for progress.

- Experiments supported by DOE, NSF, DoC, and internationally by NSERC (Canada), CONACYT (Mexico), and BARC (India).

- Facility and operations costs borne by other sources and agencies.

S. Baessler - U. Virginia
S. Gardner - U. Kentucky
G. Greene - U. Tennessee/ORNL
M. Huber - NIST
D. Počanić - U. Virginia
M. Snow - Indiana U.
F. Wietfeldt - Tulane U.
S. Wilburn - LANL

Thanks for information and images: