Fundamental Neutron Physics: Nuclear and Particle Physics with Slow Neutrons

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Studies of neutron properties, its interactions with matter

Fundamental neutron physics

[Fr. *Physique Fondamental*, c. 1975, first used to describe a variety of interdisciplinary research activities carried out at the high flux reactor of the Institut Laue Langevin, Grenoble]

Particle Physics

- Short-ranged forces
- N-N scattering lengths in matter

Astrophysics/Cosmology

- Hadronic T-invariance
- EDM
- Beta decay
- Neutron cross-sections
- Beta decay
- Nucleon structure

Nuclear Physics

- Ann & anA in low A systems
- Scattering lengths in matter

*Includes BBN and nuclear astrophysics

**Mass & mag. Moment (& el. Scattering)
In particular, for

Neutron interferometry

Tests of Quantum Mechanics

Geometrical phases, coherence and quantum non-demolition measurements, EPR tests, Dynamical diffraction, etc…

New: gravitational spectroscopy with ultracold neutrons
Exciting Progress in the past year!

- Hadronic weak interactions and T non-invariance: D. Bowman’s talk this session!
- EDM: sensitivity for neutron EDM finally below $10^{-26}$ ecm for the PSI EDM experiment (…benchmark for more than 10 y)
This Talk:

Progress here too, with Connections to Some of the Really Big Questions in Particle Physics and Cosmology!

All of this research involves the use of “slow” neutrons…
“Slow” Neutrons: MeV to neV

Produced at neutron scattering facilities

Nuclear reactor

Need: cold and ultracold neutrons (UCN)

Fission neutron spectrum

$0.05 \text{ meV} < E_n < 1 \text{ meV}$

$E_n < 350 \text{ neV}$
U.S. Facilities

Exciting Developments in Past 6 Years!

Spallation Neutron Source Fundamental Neutron Physics Beamline (FNPB)

Experiments started in 2010!

UCN
Order of magnitude+ upgrade being commissioned now!

Cold Neutron Beams

Upgrade of factor of 20 complete this year!

Los Alamos Neutron Science Center (LANSCE) Area B Source

National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR)
Guiding Neutrons to Experiments

Neutrons transported many meters to experiment through guides – typically highly polished material with specific material coatings

Coherent interaction with many nuclear sites makes an effective potential barrier $U_{\text{eff}}$ similar to light scattering from transparent or metallic surfaces ($n$)

$E_n < U_{\text{eff}}$

Neutrons reflect at all angles
Can store in material bottles!

Neutrons reflect below critical angle $\theta_c$
Experiments (1): Neutron Beta Decay

Questions these measurements address:

Is there new physics above the LHC scale (charged Higgs particles)?

What is our most precise characterization of the SM for the charged weak current?

What are our most reliable, highest precision predictions for Big Bang Nucleosynthesis?
Neutron $\beta$-decay

**Straightforward semi-leptonic decay process**

"Switch off" the strong interaction:

$$d \text{ quark} \rightarrow u \text{ quark} + \text{electron} + \text{anti-neutrino}$$

(interaction mediated by $W^-$)

High precision measurements of beta decay establish the precision frontier for the Standard Model (SM) for the charged weak interactions and permit sensitive tests for Beyond SM (BSM) interactions.
Theory Developments

Motivation from models:
High mass scale physics connected to neutrino mass (seesaw models), and warm dark matter motivate possible contributions from L/R symmetric models and leptquarks at EW scale

Discovery of Higgs particle motivates contributions from a charged Higgs sector

Baryogensis, dark matter, etc… motivate supersymmetry at EW scale

Beta Decay is Sensitive to these models!

Recent Developments:
Model Independent (MI) analysis provides generic framework for comparing constraints from LHC measurements with beta decay

High precision lattice results for form factors in nucleon couplings constants now available!

CC interactions and BSM physics

V. Cirigliano, 2013

- In the SM, W exchange $\Rightarrow$ only V-A structure, universality relations
  Also need Lorentz symmetry of couplings to get helicity dep!
  **Only** $C_V$, $C_A$ in SM

At low energy
"contact interaction"
$G_F \sim g^2 V_{ij} / M_W^2 \sim 1 / v^2$

$\nu \sim 170$ GeV

**SM:** $\Delta_{e/\mu} = \Delta_{CKM} = 0$

Peculiar "V-A" pattern in spectra and decay correlations

Helicity (spin) structure of SM!

Lepton universality

$[G_F]_e / [G_F]_\mu = 1 + \Delta_{e/\mu}$

$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM}$

Cabibbo universality
CC interactions and BSM physics

- In the SM, W exchange $\Rightarrow$ only V-A structure, universality relations

At high energy, produce W’s

At low energy

\[ G_F \sim g^2 V_{ij}/M_w^2 \sim 1/v^2 \]

\[ I/\Lambda^2 \]

\[ C_X, C'_X, \text{ with } X \in \{V, A, S, T, P\} \text{ to L, R-handed } \nu \]

Model Independent (MI) analysis: treat all higher scale ints as “contact int”

- BSM: sensitive to tree-level and loop corrections from large class of models $\Rightarrow$ “broad band” probe of new physics
$V_{ud}$ and the Status of CKM Unitarity

$V_{ub}^2 \ll 1 \quad \rightarrow \quad V_{ud}^2 + V_{us}^2 = 1$?

$N_f = 2+1$: Fit to results for $|V_{td}|, |V_{td}|, |V_{td}|/|V_{td}|$

$f_+(0) = 0.9661(32), \quad f_K/f_\pi = 1.192(5)$

$V_{us} = 0.2248(7)$

$\chi^2/\text{ndf} = 1.16/1 \ (28.1\%)$

$\Delta_{\text{CKM}} = -0.0005(5)$

$-1.0\sigma$

$V_{ud} = 0.97416(21)$

$V_{us} = 0.2243(5)$

$\chi^2/\text{ndf} = 2.64/1 \ (10.4\%)$

$\Delta_{\text{CKM}} = -0.0007(5)$

$-1.5\sigma$

$N_f = 2+1+1$: Fit to results for $|V_{td}|, |V_{td}|, |V_{td}|/|V_{td}|$

$f_+(0) = 0.9704(32), \quad f_K/f_\pi = 1.1960(25)$

New lattice results

Things still pretty good!

(stay tuned)
Impact for (V,A): Unitarity

- Current status: $\Delta_{CKM} = (7 \pm 5) \times 10^{-4}$

  **MI analysis:** $\Lambda > 11 \text{ TeV}$ for contact interactions (coupling to electrons) with (V,A) symmetry

- Expected constraints from LHC roughly 7 TeV

  High precision measurements provide “post-LHC” sensitivity

  constrains universality of supersymmetric models
  2-3 TeV lower bound on generic $W^*$ from Kaluza-Klein theories


Note for (S,T) couplings – helicity changing couplings
  suppressed relative to helicity conserving (V,A) → **evade unitarity constraint**!
$V_{ud}$ and Superallowed Decays

Decay between $0^+$ isobaric analog states: only vector coupling contributes and Vector SM matrix elements ($C_V M_F$) known very precisely, so measurement of absolute decay rate provides the vector coupling

Inputs:

- Decay rates, Branching Ratios, Q Values
- $G_F$ from $\mu$ decay & Theoretical Corrections
- Q Values – trapping groups in US
  - LEBIT (NSCL), CPT (Argonne) and (Brodeur at ND)

Most precise value for $V_{ud}$:

$$V_{ud}^2 = \frac{G_v^2}{G_\mu^2} = 0.94907 \pm 0.00041$$

Test of CKM unitarity:

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99985 \pm 0.00055$$

Potential Issue: very precise nuclear structure calculations required!
\( V_{ud} = 0.97420 \pm 0.00021 \)

\[
V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99985 \pm 0.00055
\]

\( |V_{ud}|_{0+} = 0.97425(22), \quad |V_{ud}|_{n} = 0.97520(140), \quad |V_{ud}|_{m} = 0.97190(170) \)
Scalar and Tensor Couplings

- **Not expected** in SM
- Do appear in Fierz terms “b” (i.e. for neutron, assuming no right-handed neutrinos):

  \[ b \propto 2C_S C_V + 2C_T C_A = C_V^2 \left( 2\text{Re} \left( \frac{C_S}{C_V} \right) + 2\rho^2 \left( \frac{C_T}{C_A} \right) \right) \text{ with } \rho = \frac{C_A}{C_V} \]

  *Interference with SM amplitudes*

  \[ b \frac{m_e}{E_e} \approx \pm \frac{\gamma m_e}{E_e} \left[ \text{Re} \left( \frac{2C_S}{C_V} \right) + \rho^2 \text{Re} \left( \frac{2C_T}{C_V} \right) \right] \]

  *1/E dependence*

  Severijns, Beck and Naviliat-Cuncic, Rev. Mod. Phys. 78, 991 (2006)

- Appear in RATE and some CORRELATIONS sensitive to scalar and tensor couplings

  Due to interference w/SM amplitudes, Fierz effects much larger than other effects produced by (S,T) couplings!
Nucleon Charge

Rigorous lattice calc. (PNDME collab.)

\[ C_X = \varepsilon_X g_X \]

- Coupling constant
- Structure-dep form factor

Lattice spacing:
0.06 \lesssim a \lesssim 0.23 \text{ fm}

Pion mass:
135 \lesssim M_\pi \lesssim 320 \text{ MeV/c}^2

Lattice volume:
3.3 \lesssim M_\pi L \lesssim 5.5

\[ g_A = 1.195(33)(20) \]
\[ g_S = 0.97(12)(6) \]
\[ g_T = 0.987(51)(20). \]

\[ \delta g_A = 3.3\% \]

First values for \( g_s \),
\[ g_A - g_A(\text{exp}) = 2\sigma \]

MI Analysis: Comparison Between LHC and Beta Decay (Left-Handed $\nu'$s)

Precise form factors make a difference!

**CURRENT CONSTRAINTS**

Low-energy: $g_{S,T}$ from quark model

Low-energy: $g_{S,T}$ from lattice

LHC: $\sqrt{s} = 8$ TeV
$\lambda = 20$, fb$^{-1}$

**PROSPECTIVE CONSTRAINTS**

Low-energy: $g_{S,T}$ from quark model

Low-energy: $g_{S,T}$ from lattice

LHC: $\sqrt{s} = 14$ TeV
$\lambda = 10,300$, fb$^{-1}$

Beta decay can compete!

Low energy decays: limits from Fierz terms in neutron, $^6$He decay at 0.1% level and integral limits end-pt dependence of $0^+ \rightarrow 0^+$ decays

LHC limits from pp -> e$\nu$ + X+ MET

Note: better constraints from LHC for couplings to left-handed neutrinos…
Summary: neutron decay provides

- Stringent cross-check of the vector coupling from $0^+ \rightarrow 0^+$ decays without nuclear structure dependence

- BSM (S,T) limits at sensitivities above that for LHC

- The definitive value for the axial form factor of the nucleon, $g_A$

- Critical input (n lifetime) for BBN predictions of $^4\text{He}$ (dominant source of uncertainty) – ~1s level required for envisioned BBN needs

Challenge: field a diverse and sensitive enough set of experiments to provide a robust assessment of systematic uncertainties...

Tremendous surge of activity driven by new sources and current expctl status
Beta Decay Observables

Many accessible observables:
\[ \{ \vec{l}_i, \vec{l}_f, \vec{p}_p, E_p, \hat{\sigma}_e, \vec{p}_e, E_e \} \]

Do not observe final state spins or neutrino.

Decay rate
Energy spectrum: p, e
Directional distribution (angular correlations)

Use momentum consv:
\[ \vec{p}_{\nu e} = -\vec{p}_p - \vec{p}_e \]
Beta Decay Parameters


\[
\frac{d^5 W}{dE_e d\Omega_e d\Omega_{\nu_e}} = \frac{G_F^2 |V_{ud}|^2}{(2\pi)^5} p_e E_e (A_0 - E_e)^2 \xi \left( 1 + \frac{a_{\beta\nu}}{E_e E_{\nu_e}} \right) \frac{\vec{p}_e \cdot \vec{p}_{\nu_e}}{E_e E_{\nu_e}} + \frac{b}{E_e} \Gamma_m e + \ldots
\]

On-going or planned efforts to measure:

(1) Decay rates and \(\beta\)-spectra \((G_F V_{ud}, \xi, b)\)
(2) Unpolarized angular correlations \((a_{\beta\nu}, b)\)
(3) Polarized angular correlations \((A_\beta, B_\nu, b, b_\nu)\)
(4) New program to measure circular polarization asymmetry

Note: to specify both \(C_V\) and \(C_A\), 2 meas. needed
At least 10 US Laboratories involved, 34 US groups
Neutron Data Sets for $\tau$ and $A_\beta$

PDG $\tau$: 880.3(1.1) (unc x 1.9)
PDG $A_\beta$: -0.1184(10) (unc. x 2.4)
PDG $\lambda$: -1.2723(23) (unc. x 2.2)

Need O.M. improvement

$\rho_n = (\sqrt{3})\lambda$

Uncertainties expanded to account for scatter (systematic error)

Latest $A_\beta$ results in reasonable accord, not so for lifetime (blue = beam measurements, red = UCN storage)
### Ongoing and Planned Measurements with Neutrons

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Quantity</th>
<th>unc</th>
<th>Technique</th>
<th>Group</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCNA</td>
<td>$\bar{A}_\beta$</td>
<td>0.2%</td>
<td>UCN</td>
<td>LANSCE UCN source</td>
</tr>
<tr>
<td>PERKEO III</td>
<td>$\bar{A}_\beta$</td>
<td>0.19%</td>
<td>Cold neutron beam</td>
<td>ILL and MLZ (Munich)</td>
</tr>
<tr>
<td>PERC</td>
<td>$\bar{A}_\beta$</td>
<td>0.05%</td>
<td>Cold neutron beam</td>
<td>MOT</td>
</tr>
<tr>
<td>aCORN</td>
<td>$\bar{a}_{\beta\nu}$</td>
<td>~1%</td>
<td>Cold neutron beam</td>
<td>NIST</td>
</tr>
<tr>
<td>aSPECT</td>
<td>$\bar{a}_{\beta\nu}$</td>
<td>~1%</td>
<td>Cold neutron beam</td>
<td>ILL</td>
</tr>
<tr>
<td>Nab</td>
<td>$\bar{a}_{\beta\nu}$</td>
<td>0.1%</td>
<td>Cold neutron beam</td>
<td>SNS</td>
</tr>
<tr>
<td>BL2</td>
<td>$\tau$</td>
<td>1s</td>
<td>Cold neutron beam</td>
<td>NIST</td>
</tr>
<tr>
<td>BL3</td>
<td>$\tau$</td>
<td>&lt; 0.3s</td>
<td>Cold neutron beam</td>
<td>NIST</td>
</tr>
<tr>
<td>JPARC lifetime</td>
<td>$\tau$</td>
<td>1s</td>
<td>Cold neutron beam</td>
<td>J-PARC lifetime collab</td>
</tr>
<tr>
<td>Gravitrap</td>
<td>$\tau$</td>
<td>0.2 s</td>
<td>UCN storage in material bottle</td>
<td>ILL and PNPI</td>
</tr>
<tr>
<td>Ezhov</td>
<td>$\tau$</td>
<td>0.3 s</td>
<td>UCN storage in magnetic bottle</td>
<td>ILL</td>
</tr>
<tr>
<td>HOPE</td>
<td>$\tau$</td>
<td>0.5 s</td>
<td>UCN storage in magnetic bottle</td>
<td>ILL (new superthermal src)</td>
</tr>
<tr>
<td>PENEOPE</td>
<td>$\tau$</td>
<td>0.1 s</td>
<td>UCN storage in magnetic bottle</td>
<td></td>
</tr>
<tr>
<td>Mainz</td>
<td>$\tau$</td>
<td>0.2 s</td>
<td>UCN storage in magnetic bottle</td>
<td>Mainz TRIGA source</td>
</tr>
<tr>
<td>UCN$\tau$</td>
<td>$\tau$</td>
<td>Well below 1 s</td>
<td>UCN storage in magnetic bottle</td>
<td>LANSCE UCN source</td>
</tr>
<tr>
<td>Radiative $\tau$</td>
<td>$\tau+\gamma$</td>
<td>Br to ~1%</td>
<td>Cold neutron beam</td>
<td>NIST</td>
</tr>
</tbody>
</table>
Lifetime measurements

Cold neutron beams: $\tau = 888.0(2.0) \text{ s}$

Beam lifetimes: count decay protons in precisely characterized volume (ion Penning trap) with knowledge of absolute neutron density (count neutrons that “die”)

UCN storage experiments in material traps:
$$\tau = 879.6(6) \text{ s}$$

differs by 4σ!

Count neutrons which survive after well defined storage time (count survivors)

Actually measures loss rate from trap...

$$\frac{1}{\tau_{\text{mea}}} = \frac{1}{\tau_\beta} + \frac{1}{\tau_{ab}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{sf}} + \frac{1}{\tau_{\text{heat}}} + \frac{1}{\tau_{qb}} + \ldots$$
“Exotic” Tensor and Scalar Interactions

Create Fierz terms that influence all measured total decay rates and (and correlations since typically normalized to total rate)!

Tensor Coupling Constant Limits (no RH neutrinos)

Conclusions: (1) current limits consistent with $C_T = 0$ already near ultimate sensitivity of LHC (7 TeV scale)
(2) limits from neutron and Fermi’s comparable to all data
“Exotic” Tensor and Scalar Interactions

Use the beam lifetime in the constraint from neutrons and superallowed...

Conclusion: lifetime discrepancy matters!
Mount R&D campaign to develop improved approaches to beam and storage experiments with sub-1 s sensitivity!

CN beam BL2 and BL3 project will scale up the NIST lifetime experiment, based on the breakthrough calibration methods developed by Yue et al., Phys. Rev. Lett 111, 222501 (2013)

The UCNτ experiment at Los Alamos: magnetic storage to reduce corrections due to losses (one of several magnetic trap experiments currently underway…)
UCNτ at LANL

Magneto-gravitational trap: store UCN in a vessel lined with magnets, which provide a repulsive force to the low-field seeking spin-state – UCN don’t touch surfaces! Vertical trapping force provided by gravity!

Array of permanent magnets (PMs) \( \sim 1.35 \) T surface field

PMs in a given row share same \( \mathbf{M} \) alignment

Rows trace out the surface of a torus patch (circumferentially)

Energy scale:

at LANL, UCN \( E < \sim 180 \) neV

\( E_Z = mgh = 100 \) neV per m

\( E_B = \mu B = 60 \) neV per T

3410 PMs NdFeB

Downward \( (\hat{z}) \) confining force: \( F_z = -mg \)

Surface repulsive force: \( F_z = -\nabla \left( \mathbf{\mu} \cdot \mathbf{B} \right) \)
Improvements over material traps

- Eliminate losses due to absorption and upscattering on material surfaces
- Minimize corrections due to UCN with energies above the trapping potential by “cleaning” spectrum to remove these UCN:
  1. Asymmetric trap to ensure rapid exploration of phase space
  2. Active “dagger” detector inserted into trap (very rapid draining time)
  3. Positionable upscattering “cleaner” materials permanently fixed near top of trap

ArXiv:1610.04560 posted in October for preliminary results of 2015 run! X10 statistics still in analysis
UCN Detection

Wave Length shifting fibers capture light from ZnS read out by two PM tubes

Thresholds on PM tubes are set at ~.5 photoelectrons (pe).
20 ns wide signals are used as stops in a 800 ps list mode multichannel scalar. Coincidences and pe are formed in software.

<table>
<thead>
<tr>
<th>Material</th>
<th>V_{Fermi} (nV)</th>
<th>Absorption time (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10B</td>
<td>-3.7</td>
<td>8.4</td>
</tr>
<tr>
<td>Al</td>
<td>54.7</td>
<td>3.3×10^5</td>
</tr>
<tr>
<td>ZnS</td>
<td>75.7</td>
<td>1.1×10^5</td>
</tr>
<tr>
<td>Acrylic</td>
<td>27.6</td>
<td>2.4×10^5</td>
</tr>
<tr>
<td>Polyimide91.2</td>
<td>2.8×10^5</td>
<td></td>
</tr>
</tbody>
</table>
How measurement is made

Simplified Measurement:
- Load trap through bottom – close trap door when density near saturation
- Clean spectrum (use dagger and cleaners)
- Measure \( N(t_s) \) for short storage time
- Repeat for long storage time \( N(t_l) \)

\[
\tau = -\Delta t_S \ln \left( \frac{N_2}{N_1} \right)
\]
Results

Preliminary result submitted to Rev. Sci. Instrum:

\[ \tau = 878.8(2.6)_{stat}(0.6)_{sys} \ s \]

Full data set (x10 stats) and more detailed exploration of systematics still under analysis!

Deeper cleaning with dagger

Negligible counts leaking into highest region!
UCNτ: a measurement of the neutron lifetime using ultracold neutrons stored in an asymmetric magnetic trap

California Institute of Technology
K. P. Hickerson

DePauw University
A. Komives

Indiana University/CEEM
E. R. Adamek, N. B. Callahan, W. Fox, C.-Y. Liu (co-PI), F. Gonzalez, D. J. Salvat,
T. O’Connor, W. M. Snow, J. Vanderwerp

Joint Institute for Nuclear Research
E. I. Sharapov

Los Alamos National Laboratory
D. Barlow, S. M. Clayton (co-PI), S. Curry, M. A. Hoffbauer, T. M. Ito, M. Makela, J. Medina, D. J. Morley, C. L. Morris,
Z. Wang, T. L. Womack, H. Weaver

North Carolina State University

Oak Ridge National Laboratory
J. D. Bowman, L. J. Broussard, S. I. Penttilä

Tennessee Technological University

University of Kentucky
A. Sprow

Virginia Polytechnic Institute and State University
X. Ding, B. Vogelaar
Determining the Vector Coupling ($V_{ud}$)

For an independent cross-check of vector coupling need 2 measurements, one is lifetime, other is an angular correlation...

Example: the beta asymmetry

$$R = R_o (1 + \frac{v}{c} P \ A(E) \ \cos \theta)$$

$\beta$-asymmetry $= A(E)$ in angular distribution of $\beta$

$$A_{\beta}(0) = \frac{\rho^2 - 2 \rho \sqrt{J(J+1)}}{(1 + \rho^2)(J+1)}$$

Ignoring recoil order terms – just a function of $\lambda = \frac{C_A}{C_V} = \rho/\sqrt{3}$
Measurement Challenges

\[ \beta \text{ directional distribution: } 1 + P \frac{v}{c} A(E) \cos \theta \]  
(polarized neutrons)

Must determine:

- Beta rates
- Beta spectra
- \( \langle \cos \theta \rangle \)
- Polarization

Systematic effects:

- Backgrounds
- Calibration/Linearity
- Scattering (esp. backscattering)
- Absolute polarization required!

\[ A(E) \propto \frac{N_+ - N_-}{N_+ + N_-} \]  
(ratios of spin dependent rates are used to cancel efficiencies)
Neutron Asymmetry Measurements

Published...

PERKEO II (2013) \( \frac{d\lambda}{\lambda} = 0.11\% \)

Cold Neutron Beam (at ILL)
- Decay rate: \( \sim 375 \text{ s}^{-1} \)
- Polarization: 99.7(1)
- (Crossed SM polarizer, AFP flipper, 3He analyzer)
- Background Corr: 0.09(9)%
- Scattering Corr.: 0.08(8)%
- Mirror Effect: 0.6(2)%
- \( A_\beta = -0.11972(63,-55) \)

UCNA (2013) \( \frac{d\lambda}{\lambda} = 0.24\% \)

Ultracold Neutrons (at LANL)
- Decay rate: \( \sim 30 - 60 \text{ s}^{-1} \)
- Polarization: 99.33(56)
- (Magnetic retarding pot. Polarizer/analyzer, AFP flipper)
- Background Corr: 0.01(2)
- Scattering Corr.: 0.15(43)
- Energy Recon: 0.00(31)
- \( A_\beta = -0.11954(55)_{\text{stat}}(98)_{\text{sys}} \)
PERKEO III: Beta Asymmetry

Nearly published…

State of the art…

PERKEO III
Neutron decay in a pulsed cold neutron beam at ILL

Electron spectra

Experimental asymmetry

Result (value still blinded)

\[ \frac{\Delta A}{A} = 1.9 \cdot 10^{-3} \]
\[ \frac{\Delta \lambda}{\lambda} = 5 \cdot 10^{-4} \]

\[ d\lambda/\lambda \sim 0.05\% \]

Dissertation H. Mest, 2011
Dissertation H. Saul, 2016
Coming Soon...

**PERC at the MLZ**

Munich

1.5 T

6 T

L = 11.9m

Image: Babcock-Noell

Courtesy of B. Maerkisch

Magnet delivery, summer 2017

Goal: \( \frac{dA_\beta}{A_\beta} \sim 0.05\% \)

Requires \( dP/P \sim 0.01\% \)!

**Nab at the SNS**

Magnet delivery, summer 2017

Goal: \( \frac{da_\beta}{a_\beta} \sim 0.1\% \)

Sufficient for competitive CKM tests!
Radiative Decay...

Beautiful work is being done by the NIST group characterizing neutron radiative decay, with the goal of measuring the BR to a few percent soon.
Experiments (2):
A Search for Strongly Coupled Chameleon Fields
(a search for short-ranged interactions)

What is the dark energy?
Energy Density of the Universe: Present Inventory

- Dark Energy: 73%
- Dark Matter: 23%
- Atomic Matter: 4.6%
- Light: 0.005%
- Neutrinos: 0.0034%
History of the Universe: Today’s Party Line

From Type IA supernovas

\[
\frac{\dot{a}}{a} \text{ known, } \frac{\ddot{a}}{a} > 0 \quad \text{From Type IA supernovas}
\]
Expansion of the Universe in Einstein’s Equations

\[ R_{\mu\nu} - \frac{1}{2} Rg_{\mu\nu} = 8\pi G T_{\mu\nu} \]

“spacetime curvature”
=energy/momentum
(A. Einstein)

\[ ds^2 = -dt^2 + a^2(t) d\vec{r}^2 \]

“spherical cow”
spacetime metric

\[ \frac{\ddot{a}}{a} = -\frac{4\pi G}{3} (\rho + 3p) \]

Friedmann equations
for a flat universe

\[ \left( \frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3} \rho \]

To explain acceleration, Need \( \rho - 3p < 0 \! \)!
“negative pressure”

Unknown function \( a(t) \) is the scale factor for distances and times in the expanding universe
Possible Dark Energy candidates:

- **The vacuum energy**
  \[ w_q = p_q / \rho_q = \frac{-\Lambda / \kappa}{\Lambda / \kappa} = -1 \]

- **A Scalar field (quintescence)**
  \[ w_q = p_q / \rho_q = \frac{1}{2} \frac{\dot{Q}^2 - V(Q)}{\dot{Q}^2 + V(Q)} \]
  Potential which gives us the correct behavior (increasing acceleration as matter density drops):
  \[ \dot{Q}^2 \ll V(Q) \]
  \[ w_q \sim -1 \]
  Scalar field permeates space...

Potential which gives us the correct behavior (increasing acceleration as matter density drops):

\[ V_{eff} = \frac{\Lambda^{4+n}}{Q^n} + \frac{\beta \rho}{M_{Pl}} Q \]

Where \( \Lambda = 2.4 \text{ meV} \) for dark energy and interactions with matter suppress interaction \((\beta \text{ and } n \text{ constrained by expt}) \).
Chameleon Fields: Awaiting Surprises for Tests of Gravity in Space

Justin Khoury and Amanda Weltman
ISCAP, Columbia University, New York, New York 10027, USA
(Received 10 September 2003; published 22 October 2004)

We present a novel scenario where a scalar field acquires a mass which depends on the local matter density: the field is massive on Earth, where the density is high, but is essentially free in the solar system, where the density is low. All existing tests of gravity are satisfied. We predict that near-future satellite experiments could measure an effective Newton’s constant in space different from that on Earth, as well as violations of the equivalence principle stronger than currently allowed by laboratory experiments.
What is a neutron interferometer?

1) Coherently split by diffraction
2) Recombined: also by diffraction!
3) Coherent superposition
4) Neutron detected: absorbs in 3He nucleus, charged nuclei ionize gas, gives voltage pulse in detector

Another way: magnetic field gradient acting on the neutron magnetic moment. Done at CEEM! (see R. Pynn’s group)
Neutron Optics and Interferometry Facility (NIOF) at NIST

Isolated 40,000 Kg room is supported by six airsprings
Active Vibration Control eliminates vibrations less than 10Hz
Temperature Controlled to +/- 5 mK

NIOFα is Here

Interferometer
Chameleons Search using Neutron interferometry

Idea of experiment:

Vary gas pressure to make chameleon field appear and disappear. A few mbar of helium is enough to kill the field.

Look for phase shift on the neutron

\[ \delta \phi = \frac{m}{k \hbar^2} \int_{-R}^{R} \beta \frac{m}{M_{Pl}} \varphi(x) \, dx \]
Our Experimental Data from NIST

No evidence for dark energy!
Constraints in Chameleon-Matter coupling/
Ratra-Peebles index space

All of this data has appeared just in the last 6 months.

Experiments are ongoing.

Lower bound $\beta > 50$ at $n=1$ from inverse square law tests of Gravity.

We can kill this theory.

Lemmel et al, PLB 743, 310 (2015)

Searching for Dark Energy using Neutron Interferometry

K. Li, W. M. Snow, CEEM, Indiana University
M. Arif, M. G. Huber, NIST Center for Neutron Research
D. G. Cory, D. Pushin, Institute for Quantum Computing, University of Waterloo
R. Haun, C. B. Shahi, Tulane University
B. Heacock, V. Skavysh, A. R. Young, North Carolina State University
J. Nsofini, P. Saggu, D. Sarenac, University of Waterloo

(thanks for slides to Mike Snow, Ke Li, Guillame Pignol, Mike Turner, …)
Experiments (3): Neutron-Antineutron Oscillations

Tied to many questions...
Central Questions for the Standard Model

Origin of neutrino mass

The cosmological baryon asymmetry

Pattern of charges and masses for the SM Fermions

Sources of Baryon Number Violation

All potentially connected by physics at or above EW scale

Observable N-N oscillations in a next generation experiment!

For example…
Gaps in the Standard Model

• Many cosmological issues
  – Dark matter and dark energy
  – Not enough CP violation in the quark sector for baryogenesis
  – Baryon number violation required for the baryon asym but where does it come from?

• Present in the SM through B-L (sphalerons)
  → Baryogenesis through leptogenesis and B-L?

Also find B violation in GUTs
$\Delta B=1$: proton decay $\rightarrow \Lambda > 10^{13}$ TeV
strong exptl limits…

$\Delta B=2$: not constrained by p decay
(wide range of scales for new physics…)
produces oscillations!
• Potential V (if different for n vs $\bar{n}$)
  - Nuclear potential $\sim 100$ MeV
  - $\mu_{n}.B_{\text{Earth}} \sim 10^{-18}$ MeV
  - Current limit: $\alpha < \sim 10^{-29}$ MeV (same order as nEDM)

• Strongly suppressed unless quasi-free condition holds ($Vt/\hbar \ll 1$)
  - Free neutron experiment requires substantial cancellation of Earth magnetic field, then:
  - For free neutron experiment, magnetic field can be used to check result if signal is seen
    • A few operators identified that allow oscillation with B, but not present in usual BSM physics

\[
P_{n \rightarrow \bar{n}}(t) = \frac{\alpha^2}{\alpha^2 + V^2} \cdot \sin^2 \left( \frac{\sqrt{\alpha^2 + V^2}}{\hbar} \cdot t \right)
\]

\[
P_{n \rightarrow \bar{n}} = \left( \frac{\alpha}{\hbar} \times t \right)^2 = \left( \frac{t}{\tau_{n\bar{n}}} \right)^2
\]

FOM: $Nt^2$

arXiv:1504.01176
Current Limits

- \( Nt^2 = 1.5 \times 10^9 \text{s}, \ P < 1.6 \times 10^{-18} \) (run lasted \(~1\text{ year}\)) and \( \tau > 0.86 \times 10^8 \text{s} \)
  - Many subtle optimizations to minimize losses and backgrounds
  - Experiment was background-free

- Bound neutron limits \(~3\times\) better
  - But model-dependent, and now limited by atmospheric \( \nu \) background

New physics could be enhanced or suppressed for bound neutrons.

\[ \tau_{\text{bound}} = R \times \tau_{\text{free}}^2 \]

\[ R_{\text{Ox}} = 5 \times 10^{22} \text{ s}^{-1} \]

Recent S-K (2011) limit based on 24 candidates and 24.1 bkgr. from atm. $\nu$.

Free Neutron vs Bound Neutrons
NNbar Search Sensitivity Comparison

LBNE 35 kt, 10 years, if zero atm. $\nu$ background (R&D issue).

Factor of 1,000 sensitivity increase.

Post-Sphaleron Baryogenesis
Babu et al.

Future Hyper-K

New nuclear theory and uncertainty
Friedman and Gal, 2008

Goal of new n-nbar search with free neutrons

Free neutron search limit (ILL - 1994)

Goal of new n-nbar search with free neutrons

New physics could be enhanced or suppressed for bound neutrons.
Next Generation Free Neutron Experiment

• Increase number of neutrons
  – Flux
    • Moderator brightness and area
  – Angular acceptance
  – Longer run

• Increase time-of-flight
  – Colder neutrons
  – Longer beamline

• Keep (or even increase) detection efficiency (~50%), keep background at ~0
  – Exploit current, established hardware and software technologies

• Better $B_{\text{Earth}}$ suppression
  – Improved passive (+ active?) shield
Next Generation Free Neutron Experiment

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European Spallation Source
Large beam port still in baseline! (details under discussion)

2.0 GeV superconducting linac, 14 Hz, 5 MW
ESS Timeline

• 2014: ESS construction start
• 2019-2022: Initial phase: commissioning, intensity ramp, experiments by friendly users
  – Experiment construction begins (first source recycle?)
• 2023-2025: Initial user program operations: reliable operations with public users; establish basis for future cost sharing
  – Experiment construction completion, commissioning, physics start
• 2026+: routine operations, completion of final public instruments
  – Physics run
Next Generation Free Neutron Experiment

• Increase number of neutrons
  – Flux
    • Moderator brightness and area
  – Angular acceptance
  – Longer run
• Increase time-of-flight
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• Keep (or even increase) detection efficiency (~50%), keep background at ~0
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• Better $B_{\text{Earth}}$ suppression
  – Improved passive (+ active) shield
Conceptual Design

- High-m super-mirror
- Residual B field < 5 nT
- Good vacuum < $10^{-5}$ Pa


MC optimization of parameters ongoing!
Supermirror Reflector

- Crucial in acceptance gain
  - 2D, so acceptance scales quadratically
  - Modern multi-layer supermirrors have good reflectivity at increasingly large momentum transfers

Ni reflectivity → 0 defines m=1

Active R&D at Nagoya University, with devices used at JPARC
~ 2 GeV annihilation energy released primarily as pions (avg no = 5)
Early Simulations: Detector

Identify Target

Improvements over ILL

~90% (x1.8)

X3 red. in timing window (50 ns)

Lots of possibilities for detector development!
Potential Gains wrt ILL

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Brightness</td>
<td></td>
<td>≥ 1</td>
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<tr>
<td>Moderator Area</td>
<td>Needs large aperture</td>
<td>2</td>
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<tr>
<td>Angular Acceptance</td>
<td>2D, so quadratic sensitivity</td>
<td>40</td>
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<tr>
<td>Length</td>
<td>Scale with $t^2$, so $L^2$</td>
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<tr>
<td>Run Time</td>
<td>ILL run was 1 year</td>
<td>3</td>
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<tr>
<td>Total</td>
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<td>≥ 1000</td>
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$x\ 1000$ in probability, reach $\tau \sim 2-3 \times 10^9$ s
Early Simulations: Sensitivity

- Neutron spectrum files from ESS
- 50% detection efficiency (as for ILL)
Collaboration

• Collaboration growing
• ESS very supportive
  • Agreed to target area modifications needed
• Revisiting sensitivity studies now that ESS has frozen moderator configuration
• Regular collaboration meetings

Expression of Interest for
A New Search for Neutron-Anti-Neutron Oscillations at ESS

<table>
<thead>
<tr>
<th>Name</th>
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<tr>
<td>ESS coordinator</td>
<td>Camille Thacrine</td>
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Neutron-antineutron oscillations: Theoretical status and experimental prospects

Conclusions

• Fundamental neutron science provides a window onto a broad range of important physics questions, often providing the strongest constraints and the highest discovery potential among many competing methods

• Vigorous experimental activity in neutron beta-decay is likely to provide us with a deep “look” for new physics, complimentary to the work at LHC

• There is an expanding community of physicists pursuing short range force searches, with neutron physics making a significant contribution

• NNbar with free neutrons can provide unique access to the question of baryon-number violation, setting limits likely to hold for years to come
Neutron Lifetime & $^4\text{He}$ abundance ($Y_p$)

- L. Salvati et al. JCAP 1603 (2016) no.03, 055; arXiv:1507.07243
BBN: $\tau_n$ and $Y_p$ (primordial $^4$He abundance)

R. H. Cyburt, B.D. Fields, K.A. Olive, T-H Y
arXiv:1505.01076
U.S. Facilities

**Spallation Neutron Source** Fundamental Neutron Physics Beamline (FNPB)

~1MW, 1 GeV p- beam
Hg spallation target
H₂O premoderator
20K H₂ moderator

**UCN**

**Cold Neutron Beams**

National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR)

20 MW reactor, D₂O thermal pre-moderator, 20K H₂ moderator

Los Alamos Neutron Science Center (LANSCE) Area B Source

10kW, 800 MeV p- beam
W spallation target
Poly premoderator
30K poly moderator
5K SD₂ converter