Nuclear/Particle/Astrophysics with Slow Neutrons

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1. Neutron technology and slow neutrons
2. Neutron lifetime
3. NN weak interaction: parity violation
4. Search for neutron electric dipole moment: time reversal violation
5. Neutron gravitational bound states and search for extra dimensions


Thanks for slides to: Geoff Greene, Chen-Yu Liu, Jen-chieh Peng, Philip Harris, Hartmut Abele, Hiro Shimizu, T. Soldner,…
Nuclear/Particle/Astrophysics with Slow Neutrons...

is “Nuclear” physics, but with an “isotope of nothing”

is Particle Physics: but at an energy of $10^{-20}$ TeV, using a low energy decelerator

employs a particle which, according to Big Bang Cosmology, is lucky to be alive

relies on experimental techniques and ideas from nuclear, particle, atomic, and condensed matter physics

is pursued at facilities built mainly for chemistry, materials science, and biology
Neutron Properties

Electric charge: $q_n = 0$, electrically neutral \([q_n < 10^{-21} \text{e}]\)

Size: $r_n \sim 10^{-5} \text{Angstrom} = 1 \text{ Fermi} \ [\text{area} \sim 10^{-25} \text{ cm}^2 = 0.1 \text{ “barn”}]$

Internal Structure: quarks \([\text{ddu}, m_d \sim m_u \sim \text{few MeV}]\) + gluons

Spin: $s_n = 1/2$ [Fermi statistics]

Magnetic Dipole Moment: $\mu_n/\mu_p = -0.68497935(17)$

Electric Dipole Moment: zero \([d_n < 3 \times 10^{-26} \text{ e-cm}]\)

Mass: $m_n = 939.56536(8) \text{ MeV} \ [m_n > m_p + m_e, \text{ neutrons can decay}]$

Lifetime: $\tau_n = 885.7 +/- 0.8 \text{ seconds}$
Why is it such hard work to get slow neutrons?

Neutrons are bound in nuclei, need several MeV for liberation. We want $E \sim kT \sim 25$ meV (room temperature) or less.

How to slow down a heavy neutral particle with $M_n = M_p$? Lots of collisions…

$$[1/2]^N = (1 \text{ MeV})/(25 \text{ meV})$$

for N collisions.

Neutrons are unstable when free->they can’t be accumulated easily.
The ILL reactor

Cold Source
Inside the ILL Reactor
The Spallation Neutron Source

- $1.4B--1\text{GeV}$ protons at $2\text{MW}$, started in 2007.
- Short ($\sim1\ \text{usec}$) pulse—mainly for high TOF resolution
“Slow” Neutrons: MeV to neV

Nuclear reactor/Spallation source

Neutron Moderator (LH2, LD2)

Fission neutron spectrum

Nuclear reactor/Spallation source

Neutron Moderator (LH2, LD2)

Fission neutron spectrum

Nuclear reactor/Spallation source

Neutron Moderator (LH2, LD2)
Neutron Energy, Momentum, and Wavelength

Maxwell-Boltzmann: $\Phi_{th}(E) = \left[\frac{\Phi_0}{T^{3/2}}\right] E \exp \left(-\frac{E}{kT}\right)$

<table>
<thead>
<tr>
<th>Moderator Temperature (K)</th>
<th>Most Probable Energy (meV)</th>
<th>Wavelength (Angstroms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>315</td>
<td>30</td>
<td>1.6</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>6.4</td>
</tr>
</tbody>
</table>

Energy:
$$E = \frac{1}{2}mv^2 = \frac{\hbar^2}{2m}k^2 = \hbar\omega$$

Momentum:
$$\mathbf{mv} = \mathbf{p} = \hbar\mathbf{k} = \hbar\frac{2\pi}{\lambda}$$
for a “thermal” neutron \((E_K=\frac{mv^2}{2}=\frac{3}{2} k_B T, T=300K \rightarrow E_K=25 \text{ meV})\)
the de Broglie wavelength of the neutron is \(\lambda \approx 2 \text{ Angstroms}\)

Thermal neutrons have the right energies and momenta to match excitation (phonons, spin waves, molecular rotations…) and static structures (crystals, molecular shapes,…) in condensed media
Many Condensed Matter Phenomena lie within the Ranges of Length & Time Seen by Neutron Scattering
Potential step -> neutron index of refraction

with

\[ n = \sqrt{1 - \frac{V_0}{E_n}} \]

Neutron kinetic energy

If \( a > 0 \), total external reflection

\[ n_{\text{out}} = 1 \]

\[ n_{\text{in}} = \sqrt{1 - \frac{V_0}{E}} \]

All forces contribute to the neutron optical potential:

\[ <V_{\text{strong}}>=2\pi \hbar^2 \rho_{bs}/m, \sim+/− 100 \text{ neV} \]

\[ <V_{\text{mag}}>=\mu B, \sim+/− 60 \text{ neV/Tesla} \]

\[ <V_{\text{grav}}>=mgz\sim 100 \text{ neV/m} \]

\[ <V_{\text{weak}}>=[2\pi \hbar^2 \rho_{bw}/m]s \cdot k/|k|\sim 10^{-7}<V_{\text{strong}}> \]
Neutron optical guides at ILL/Grenoble (top view)
Cold Neutron Guide Hall at NIST
What methods are used to polarize neutrons?

B gradients (Stern-Gerlach, sextupole magnets) electromagnetical

\[ F = (\mu \cdot \nabla)B \]

Reflection from magnetic mirror: electromagnetic+ strong

\[ f = a(\text{strong}) \pm a(\text{EM}) \]

with \( |a(\text{strong})| = |a(\text{EM})| \)

\[ \Rightarrow f^+ = 2a, f^- = 0 \]

Transmission through polarized nuclei: strong

\[ \sigma_+ \neq \sigma_- \Rightarrow T_+ \neq T_- \]

Spin Filter: \[ T_\pm = \exp[-\rho \sigma_\pm L] \]
Ultra-Cold Neutrons (UCN) (Fermi/Zeldovich)

- What are UCN?
  - Very slow neutrons
    \((v < 8 \text{ m/s}, \lambda > 500 \text{ Å, } E < V_{\text{optical}})\)
    that cannot penetrate into certain materials

Neutrons can be trapped in material bottles or by magnetic fields
The weak interaction: just like EM, but not really:

one EM photon  3 “weak photons” \([W^+, W^-, Z^0]\), can change quark type

\[V(r) = \frac{e^2}{r}, \quad m_\gamma = 0\]

‘\(V'(r) \approx [\frac{e^2}{r}] \exp(-Mr), \quad M_{Z,W} \approx 80-90 \text{ GeV}\)'

“Empty” space (vacuum) is a weak interaction superconductor

\(|B|\)

penetration depth

\(r\)

vacuum

superconductor

weak field

\(1/ M_{Z,W}\)

our “vacuum”
The weak interaction violates mirror symmetry and changes quark type.

\[ \text{weak interaction} = [\text{CKM}]^* \]

Quark mass eigenstates

Matrix must be unitary

Only the weak interaction breaks mirror symmetry: not understood

Discovered by C.S. Wu

\[ V_{ud} \text{ in } n \text{ decay} \]

\[ r \rightarrow -r \text{ in mirror, but } s \rightarrow +s \]
Neutron $\beta$-decay

Input for theory of Big Bang element creation

Clean extraction of fundamental parameters of the electroweak theory.
Neutron Lifetime Effect on Primordial 4He Abundance in Universe

Influence of $\tau$: Shift $\tau$ by $9\sigma$ (1%)

$\tau = 885.7(8)\text{s} \Rightarrow Y_p = 0.2479(6)$

$\tau = 878.5(8)\text{s} \Rightarrow Y_p = 0.2463(6)$

Astrophysical observations: large systematic uncertainties,

$Y_p = 0.238(2)(5)$, $Y_p = 0.232 \ldots 0.258, \ldots$
Neutron Lifetime Measurement with a Proton Trap and Flux Monitor (Dewey et al)

\[ \frac{dN(t)}{dt} = -\frac{N(t)}{\tau} \]
measure decay rate and total # of neutrons in a known beam volume

Protons from neutron decay trapped in a Penning trap and counted

Neutron # in trap inferred from flux monitor
In-Beam Lifetime Apparatus @ NIST
Neutron Lifetime Using UCN Bottle

Measure storage time, vary S/V

Lifetime extrapolated to S/V->0 limit
“History” of Neutron Lifetime Measurements

World average [PDG]

Neutron lifetime (s)

Year


Last (single) measurement
N-N Weak Interaction: Size and Mechanism

NN repulsive core $\rightarrow$ 1 fm range for NN strong force

$|N\rangle = |qq\rangle + |qqqq\rangle + \cdots$ = valence + sea quarks + gluons + ...

NN strong force at low energy mediated by mesons $|m\rangle = |q\bar{q}\rangle + |q\bar{q}q\bar{q}\rangle + \cdots$

QCD possesses only vector quark-gluon couplings $\rightarrow$ conserves parity

Both W and Z exchange possess much smaller range [$\sim1/100$ fm]

Relative strength of weak / strong amplitudes: $\left(\frac{e^2}{m_W^2}\right)/\left(\frac{g^2}{m_\pi^2}\right) \approx 10^{-6}$

NN weak amplitudes first-order sensitive to $qq$ correlations

Weak interaction violates parity. Use parity violation to isolate the weak contribution to the NN interaction.
PV Gamma Asymmetry in Polarized Neutron Capture

- Asymmetry $A_\gamma$ of gamma angular distribution upon polarized neutron capture due to weak NN interaction [from $s_n \cdot p_\gamma$]
- Goal: $1 \times 10^{-8}$ at SNS/7000 MW-hours
- Asymmetry depends mainly on the weak pion coupling $f_\pi$ for n-p
- PV gamma asymmetry in $n+D \rightarrow 3H+\gamma$ also possible (SNS letter of intent)
\[
\frac{d\omega}{d\Omega} = \frac{1}{4\pi} (1 + A_{\gamma} \cos(\Theta_{\sigma_n \cdot k_n}))
\]
Parity Violating Asymmetry in n+p->D+gamma at LANSCE

\[ A_\gamma = (X.X \pm 2.1) \times 10^{-7} \]
Another Parity-Violating Observable: Neutron Spin Rotation

\[ |\uparrow\rangle_i = \frac{1}{\sqrt{2}} (|+\rangle + |\rangle - \rangle) \]

- Analogous to optical rotation in an “handed” medium.
- Transversely-polarized neutrons corkscrew due to the NN weak interaction
- **PV Spin Angle** is independent of incident neutron energy in cold neutron regime,

In combination with n-p experiment, determine weak interactions between nucleons and use it to calculate parity violation in atoms

\[ f(0) = f_{PC} + f_{PV} (\bar{\sigma} \cdot \bar{k}) \]

Refractive index dependent on neutron helicity

\[ \frac{1}{\sqrt{2}} \left( e^{-i(\phi_P + \phi_{PV})} |z\rangle + e^{i(\phi_P - \phi_{PV})} |-z\rangle \right) \]

\[ \phi_{PV} = \phi_+ - \phi_- = 2\phi_{PV} = 4\pi l \rho f_{PV} \]
Cross section of Spin Rotation Apparatus

- Radiation Shielding
- Magnetic Shielding
- Cryostat
- Feedthroughs
- Motion-Control Manifold

Polarizer → INPUT GUIDE TUBE → INPUT COIL → VAC-CAN & TARGET → OUTPUT COIL → OUTPUT GUIDE TUBE → Analyzer → DETECTOR → BEAM DUMP
Liquid Helium Motion Control System

Nonmagnetic cryostat: target feedthroughs and liquid motion control system
Distribution of Raw Asymmetries

Data under analysis

Result consistent with zero at 1E-6 rad/m level

Future experiments in H, D, and 4He possible

Pi-coil On:

\[ y_0 = 0.18838 \pm 0.106 \]
\[ A = 520.31 \pm 1.65 \]
\[ x_0 = xxx \pm 1.99e07 \]
\[ width = 0.00010919 \pm 2.31e-07 \]
Where’s the antimatter in the universe?

In the lab we make equal amounts of matter and antimatter. So why is the universe lopsided? Is it just an accident?

"Search for antihelium in cosmic rays"

Cohen, De Rujula, Glashow;
astro-ph/9707087
Matter/Antimatter Asymmetry in the Universe in Big Bang, starting from zero

Sakharov Criteria to generate matter/antimatter asymmetry from the laws of physics

- Baryon Number Violation (not yet seen)
- C and CP Violation (seen but too small by $\sim 10^{10}$)
- Departure from Thermal Equilibrium (no problem?)

A.D. Sakharov, JETP Lett. 5, 24-27, 1967

Relevant neutron experimental efforts

- Neutron-antineutron oscillations ($\bar{B}$)
- Electric Dipole Moment searches ($\mathcal{J}=\mathcal{CP}$)

Relevant neutron experimental efforts
Neutron Electric Dipole Moment

\[ \vec{d}_n = \int \vec{x} \rho(x) d^3x = d_n \hat{s} \]

Non-zero \( d_n \) violates both P and T

Under a parity operation: \[ \hat{s} \rightarrow \hat{s}, \quad \vec{E} \rightarrow -\vec{E} \]

\[ \vec{d}_n \cdot \vec{E} \rightarrow -\vec{d}_n \cdot \vec{E} \]

Under a time-reversal operation: \[ \hat{s} \rightarrow -\hat{s}, \quad \vec{E} \rightarrow \vec{E} \]

\[ \vec{d}_n \cdot \vec{E} \rightarrow -\vec{d}_n \cdot \vec{E} \]
EDM limits: the first 50 years

Reality check

If neutron were the size of the Earth...

... current EDM limit on neutron would correspond to charge separation of

\[ \delta x \approx 10 \mu \]
EDM Measurement Principle

\[ <S_z> = \pm \hbar/2 \]

\[ <S_z> = -\hbar/2 \]

\[ \nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = -4 E \frac{d}{\hbar} \]

assuming \( B \) unchanged when \( E \) is reversed.

Present EDM limit corresponds to energy difference of \( 1E-22 \) eV!
nEDM apparatus at ILL using UCN

- Use $^{199}$Hg co-magnetometer to sample the variation of B-field in the UCN storage cell
- Limited by low UCN flux of $\sim$ 5 UCN/cm$^3$
- Figure-of-merit $\sim E(NT)^{1/2}$
UCN production in liquid helium

- 1.03 meV (11 K) neutrons downscatter by emission of phonon in liquid helium at 0.5 K
- Upscattering suppressed: Boltzmann factor $e^{-E/kT}$ is small if $T<<11$ K
nEDM experiment at SNS, ~2014

**GOAL**: \( \sim 1 \times 10^{-28} \text{ e-cm} \)

**Figure–of-merit**: \( E(NT)^{1/2} \)

**New approach aims at**: 
- \( N \rightarrow 100 N \)  
- \( T \rightarrow 5 T \)  
- \( E \rightarrow 5 E \)
Classical/QM Bouncing Neutrons

**Classical View**
- Neutron absorber
- Neutron mirror
- Classical neutron trajectories
- Width $h$ is varied

**Quantum View**
- Neutron absorber
- Neutron mirror
- Initial neutron state: plane wave
- Bound neutron states: Airy functions
- Width $h$ is varied

[Diagram of bouncing neutrons showing classical and quantum views with relevant labels and trajectories.]
Neutron Probability Distributions Above the Mirror

The diagram illustrates the behavior of neutrons in the region above a reflecting mirror. The $z$ axis represents the vertical direction, with horizontal lines indicating distances of 10, 20, and 30 micrometers. The function $\psi_n^2(z)$ indicates the probability density of neutron distribution at various $n$ values, with $n=1, 2, 3, 4, \ldots$ etc. The graph shows how the neutron probability density varies with distance from the mirror, reflecting the interference pattern typical of wave phenomena.
General scheme of the experiment (flow-through integral mode)

\[ V_{\text{horizont}} \approx 4-15 \, \text{m/s} \quad V_{\text{vertic}} \approx 2 \, \text{cm/s} \quad \Delta E \approx \frac{\dot{n}}{\Delta \tau} \]

**Figure 2** Layout of the experiment. The limitation of the vertical velocity component depends on the relative position of the absorber and mirror. To limit the horizontal velocity component we use an additional entry collimator. The relative height and size of the entry collimator can be adjusted.

Selection of vertical and horizontal velocity components
Experimental Apparatus

1. Neutron guide
2. Anti-vibration table
3. Polished granite stone
4. Piezo translators
5. Vacuum chamber
6. Mirrors and absorber
7. Detector
8. Anti-magnetic shielding
9. Input collimator
10. Neutron shutter
11. Inclinometers
the Experiment
Observation/Comparison to Theory

Dash: Classical Expectation

Solid: Quantum expectation for gravitational bound neutrons:
WKB I
\[ \chi^2_{\text{red}} = 1.7 \ (35 \text{ DOF}) \]

Dot: Quantum expectation for gravitational bound neutrons:
WKB II
\[ \chi^2_{\text{red}} = 1.9 \ (35 \text{ DOF}) \]
Maybe gravity is so weak because some of its flux flows into extra “compact” dimensions of size $\lambda$.

If so, $V$ is not $1/r$ if $r \sim \lambda$. 
Limits for alpha and lambda

\[ V(r) = G \frac{m_1 \cdot m_2}{r} \left(1 + \alpha \cdot e^{-r/\lambda}\right) \]
Potential Applications in fundamental physics

- Search for extra fundamental forces at short distances of 1 nm - 10 μm
- Verification of electrical neutrality of neutrons

\[ E_i - E_j = \hbar \cdot w_{ij} \]

\[ \nu_{21} \approx 260 \text{Hz} \]

\[ \delta E_{\text{min}} \approx 10^{-18} \text{eV} \]

\[ \frac{\delta E_{\text{min}}}{E_2 - E_1} \approx 10^{-6} \]

Perturbation frequency, Hz

V.V. Nesvizhevsky
Nuclear/Particle/Astrophysics with Slow Neutrons

Uses techniques and concepts from atomic physics, condensed matter physics, low temperature physics, optics.

Neutron physics measurements test fundamental laws of weak interaction and can be used to search for new phenomena.

New facilities are on the way (NIST, SNS, JSNS, UCN facilities).

Neutron EDM Experiment with Ultra Cold Neutrons

Most Recent ILL Measurement

- Use $^{199}$Hg co-magnetometer to sample the variation of B-field in the UCN storage cell
- Limited by low UCN flux of $\sim 5$ UCN/cm$^3$
- Figure–of-merit $\sim E(NT)^{1/2}$

A new approach aims at $N \rightarrow 100$ N, $T \rightarrow 5$ T, $E \rightarrow 5$ E
P, CP, T, and CPT

- Parity violation (1956)
  - only in weak interaction

- CP violation (1964)
  - parametrised but not understood
  - only seen so far in $K^0$ & $B^0$ systems
  - Doesn’t seem to be responsible for baryon asymmetry of universe

- T violation (1999)
  - CPT is good symmetry: $T \leftrightarrow CP$
Big Bang Nucleosynthesis (BBN)

\[ n + e^+ \leftrightarrow p + \bar{\nu}_e \]
\[ n + \nu_e \leftrightarrow p + e^- \]

\[ \tau \Rightarrow \text{reaction rate} \]
\[ \frac{N_n}{N_p} = \exp\left( -\frac{\Delta m c^2}{kT} \right) \]

Freeze-out if Hubble expansion rate greater than reaction rate \( \tau \Rightarrow T_f \)
\[ \frac{N_n}{N_p} \approx \frac{1}{6} \]

\[ n \rightarrow p + e^- + \bar{\nu}_e \]

\[ \tau \Rightarrow \text{decay rate} \]
d destroyed by \( \gamma \)
\[ (kT < 2.2 \text{MeV}, \text{but } N_\gamma / N_B \approx 10^9) \]
\[ \frac{N_n}{N_p} \approx \frac{1}{7} \]

\[ ^4\text{He formation} \]
\[ n + p \rightarrow D + \gamma \]
\[ D + p \rightarrow ^3\text{He} \]
\[ ^3\text{He} + n \rightarrow ^4\text{He} \]

\[ M_{\text{He}} \approx \frac{4 N_n}{M_{\text{tot}} N_p + N_n} \]

All rates depend on baryon density \( N_B / N_\gamma = \eta_1 \cdot 10^{10} \)
$V_{ud}$ from neutron $\beta$ decay needs the neutron lifetime

![Graph showing neutron lifetime and related calculations](image-url)
Classical Theory of Weak Decay

Standard Model for neutron decay:

\[ H = \frac{G_F}{\sqrt{2}} V_{ud} \bar{p} \left\{ \gamma_\mu \left( 1 + \lambda \gamma_5 \right) + \frac{\mu_p - \mu_n}{2m_p} \sigma_{\mu\nu} q^\nu \right\} n \bar{e} \gamma^\mu \left( 1 - \gamma_5 \right) \nu_e \]

\[ \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = U_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \]

\[ U_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \]

Unitarity of CKM matrix

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta \]

Expression for neutron lifetime in Standard Model

\[ \tau^{-1} = V_{ud}^2 G_F^2 \left( 1 + 3 \lambda^2 \right) \frac{f_R m_e^5 c^4}{2\pi^3 \hbar^7} \]