Muon Decay Distributions

\[ \mu \rightarrow e \nu_{\mu} \nu_{e} \]

- Energy dependence
- Angular dependence
- Called Michel parameters

\[
\frac{dN_e}{d\Omega_e dE_e} \propto x^2 \left[ 3 - 3x + \frac{2}{3} \rho (4x - 3) + 3\eta x_o \left( \frac{1-x}{x} \right) + P_\mu \xi \cos \theta_e \left( 1 - x + \frac{2}{3} \delta(4x - 3) \right) \right]
\]

*Spectral shape* in \( x, \cos\theta_e \) is characterized in terms of four parameters \( \rho, \eta, \xi, \delta \)

\( P_\mu \) is the muon polarization

D. Koetke (TWIST)
Useful References

• http://www.krl.caltech.edu/ucn/

• "Fundamental neutron physics",

• "Low energy tests of the weak interaction",

• "Demonstration of a solid deuterium source of ultracold neutrons",

• "Measurement of electron backscattering in the energy range of neutron beta decay",

• "Measurements of ultracold neutron lifetimes in solid deuterium",
Ultra-Cold Neutrons: UCN

- Previous record density at Institut Laue-Langevin (ILL) reactor in Grenoble

\[ \approx 40 \text{ UCN/cm}^3 \text{ stored in bottle (1971)} \]

Can we make more UCN?
Higher Density UCN Sources

• Use non-equilibrium system (aka Superthermal)
  - Superfluid $^4$He ($T<1\text{K}$)

11K ($9\text{Å}$) incident n produces phonon & becomes UCN

Very few 11K phonons if $T<1\text{K}$
∴ minimal upscattering
- **Solid deuterium** \( \text{(SD}_2 \text{)} \) \cite{gollub:83}
  - Small absorption probability
  - Faster UCN production
  - Small upscattering if \( T < 6 \text{K} \)
New UCN Sources

• Superthermal $^4$He
  - Neutron lifetime experiment at National Institute of Standards and Technology (NIST) Research reactor
  - Under development for neutron electric dipole moment experiment at Spallation Neutron Source (SNS) and ILL

• Superthermal SD$_2$
  - Neutron EDM at Paul Scherrer Institute
  - Neutron decay correlation at LANSCE
LANSCe
(Los Alamos Neutron Science CEnter)

Proton Linac (½ mile long) 1 mA of 0.8 GeV protons

UCN Source
Thanks Google Maps
High Intensity Pulsed Neutrons

• Proton-induced spallation

~ 20 n's/incident proton
Schematic of prototype SD$_2$ source

(LANL/Caltech/ILL/Kyoto/Princeton/VaTech/NCState collaboration)
First UCN detection

Total flight path $\sim$ 2 m

\[
2 \text{ m} \left( \frac{1}{6 \text{ m/s}} \right) = 0.33 \text{ sec}
\]

Proton pulse at $t = 0$

50 ml SD$_2$

0 ml SD$_2$
Bottled UCN

Bottle

UCN valves

UCN Detector

counts/08 sec

Time (sec)
New World Record UCN Density

Measurements of Ultra Cold Neutron Lifetimes in Solid Deuterium
[PRL 89, 272501 (2002)]

Demonstration of a Solid Deuterium Source of Ultra-Cold Neutrons

Previous record for bottled UCN = 41 UCN/cm³ (at ILL)
The Caltech UCN group

Nick Hutzler
Gary Cheng
Jenny Hsiao
Riccardo Schmid
Kevin Hickerson
Junhua Yuan
Brad Plaster
Bob Carr
Jianglai Liu
Michael Woods
BF
Physics with higher density
UCN Sources

• Macroscopic Quantum States

• Neutron decay (lifetime & correlations)
  - Solid Deuterium Source

• Neutron Electric Dipole Moment (EDM)
  - Superfluid He Source
Macroscopic Quantum States in a Gravity Field

1-d Schrödinger potential problem

$V \neq mgz$

neutron in ground state “bounces” $\sim 15 \mu m$ high
Schroedinger Equation Solutions

\[-\hbar^2 \frac{\partial^2 \Psi}{2m_I \partial z^2} + m_G g z \Psi = E \Psi\]

• \(m_I\) is inertial, \(m_G\) is gravitational mass

• Eigenstates are Airy functions:
  \[\psi(z) = A \phi(z-\delta)\]

• Eigenenergies are
  \[E_n = \left(\frac{\hbar^2 m_G^2 g^2}{2m_I}\right)^{-1/3}\alpha_n = \left(0.60 \cdot 10^{-12} \text{ eV}\right)\alpha_n\]
  - Where \(\alpha_n\) are the zeros of the Airy function
    \(-\alpha_1 = 2.34, \alpha_2 = 4.09, \alpha_3 = 5.52\)

For Neutrons
Neutron Energy Levels in Gravity

UCN @ ILL

Height Selection

$E_n, n=1, E_1=1.4\text{peV}$

$E_n, n=2, E_2=2.5\text{peV}$

$E_n, n=3, E_3=3.3\text{peV}$

$E_n, n=4, E_4=4.1\text{peV}$
Classical expectation


May allow improved tests of Gravity at short distances (need more UCN!)
Physics with quantum neutron states

• May allow a test of the weak equivalence principle

\[ E_n = \left( \frac{m_G}{m_l} \right)^{2/3} \left( \frac{\hbar^2 m_l g^2}{2} \right)^{1/3} \alpha_n \]

• May improve tests of the behavior of gravity at short distances
  - Small (but finite) extra dimensions may cause gravity to be much stronger at short distance
Behavior of gravity at short distance

Constraints on non-Newtonian gravity from the experiment on neutron quantum states in the earth’s gravitational field

V V Nesvizhevsky¹ and K V Protasov²

\[ V_{\text{eff}}(r) = G \frac{m_1 m_2}{r} (1 + \alpha_G e^{-r/\lambda}). \]
Neutron Decay Correlation with UCN

**UCNA** – 1\textsuperscript{st} correlation exp with UCN

\[ N_+ \]
\[ N_- \]

\[ N_e = N_0 (1 + A\beta \cos \theta) \]

\[ A_{\text{exp}} = \frac{N_+ - N_-}{N_+ + N_-} \]

\[ V_{ud} = f(A, \tau_n, RC) \]

\( RC = \) Electroweak Radiative Corrections
Reduced Background with pulsed Source of UCN

Best previous A-correlation experiment (at Reactor)

Proposed A-correlation experiment (pulsed source)
UCN Polarization via high B-field

Can produce polarized neutrons with $\bar{P}_n \geq 99.9\%$

\[ V = -\vec{\mu} \cdot \vec{B} > E_{UCN} \text{ if } B \geq 6 \text{ T} \]

Note: $\bar{\sigma}_n$ anti-parallel to $\vec{\mu}_n$
Experiment Design

[Diagram of experiment design with labels such as "To UCN Flux and/or Polarization Monitor", "6Li-doped Epoxy", "Decay Volume Solenoid Magnet (1.0 T)", "Diamond Film", "Polarizer Solenoid (7 T)", "MWPC", "Light Guides (to PMTs)", "Plastic Scintillator", "AFP", "To UCN Source", and "Emitted Betas Spiral Along Magnetic Field Lines"]]
UCNA experiment

Experiment commissioning underway
Initial goal is 0.2% measurement of A-correlation
(present measurement ~ 1%)

UCNA
Most Recent Collaborator
CKM Summary: New $V_{us}$

New $\tau_n$!!
Neutron Electric Dipole Moment (EDM)

- Why Look for EDMs?
  - Existence of EDM implies violation of Time Reversal Invariance

Cartoon

- Time Reversal Violation seen in $\bar{K}^0-K^0$ system
- May also be seen in early Universe
  - Matter-Antimatter asymmetry but the Standard Model effect is too small!
Quantum Picture – Discrete Symmetries

Charge Conjugation: \( \hat{C} \cdot \psi_n \Rightarrow \psi_{\bar{n}} \)

Parity: \( \hat{P} \cdot \psi(x, y, z) \Rightarrow \psi(-x, -y, -z) \)

Time Reversal: \( \hat{T} \cdot \psi(t) \Rightarrow \psi(-t) \)

Assume \( \bar{\mu} = \mu \frac{\vec{J}}{J} \) and \( \vec{d} = d \frac{\vec{J}}{J} \)

Non-Relativistic Hamiltonian

\[
H = \bar{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}
\]

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Non-zero \( d \) violates T and CP
But some molecules have EDMs!

\[ \text{NH}_3: \quad d = 0.3 \times 10^{-8} \text{ e-cm} \]
\[ \text{H}_2\text{O}: \quad d = 0.4 \times 10^{-8} \text{ e-cm} \]
\[ \text{NaCl}: \quad d = 1.8 \times 10^{-8} \text{ e-cm} \]

Note: n-EDM < 3 \times 10^{-26} \text{ e-cm}

\text{NH}_3 \text{ EDM is not T-odd or CP-odd}

since \[ \tilde{d} \neq d \frac{\vec{J}}{J} \]

If Neutron had degenerate state

it would not violate T or CP
CP Violation and the Matter/Antimatter Asymmetry in the Universe

• **Sakharov Criteria**
  - Baryon Number Violation
  - Departure from Thermal Equilibrium
  - CP & C violation

• **Standard Model CP violation is insufficient**
  - Must search for new sources of CP
    • B-factories, Neutrinos, EDMs
Electroweak Baryogenesis

Possible source of Matter-Antimatter Asymmetry

Before Electroweak Phase Transition

After EW Phase Transition

Today

$A_{BB} = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \approx 0$

$A_{BB} \approx 10^{-10}$

$A_{BB} \approx 1$

$N$
Status of Electroweak Baryogenesis

• Appeared to be “ruled out” several years ago
  – First order phase transition doesn’t work for Standard Model with $M_{\text{Higgs}} > 120 \text{ GeV}$

• Recent work has revived EW baryogenesis
  – Minimal Supersymmetric Standard Model (MSSM) parameters ineffective ($\phi_{\text{CP}} << 1$)
  – First order phase transition still viable (with new gauge degrees of freedom)

  – Resonance in MSSM during phase transition

$\rightarrow$ Note: Leptogenesis is also possible
How to measure an EDM?

Recall magnetic moment in B field:

\[ \hat{H} = \vec{\mu} \cdot \vec{B}; \quad \vec{\mu} = 2 \left( \frac{\mu_N}{\hbar} \right) \vec{S} \]

\[ \vec{\tau} = \frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} \Rightarrow 2 \left( \frac{\mu_N}{\hbar} \right) |\vec{S}| |\vec{B}|; \quad \text{if } \vec{S} \perp \vec{B} \]

Classical Picture:

• If the spin is not aligned with B there will be a precession due to the torque
• Precession frequency \( \omega \) given by

\[ \omega = \frac{d\varphi}{dt} = \frac{1}{S} \frac{dS}{dt} \]

\[ = \frac{2\mu_N B}{\hbar} \Rightarrow \frac{2d_N E}{\hbar} \quad \text{for } \vec{d}_N \quad \text{in } \vec{E} \]
Simplified Measurement of EDM

1. Inject polarized particle
2. Rotate spin by $\pi/2$
3. Flip E-field direction
4. Measure frequency shift

$$\nu = \frac{2\vec{\mu} \cdot \vec{B} \pm 2\vec{d} \cdot \vec{E}}{h}$$

Must know B very well
What systems work well?

• **Charged particle is difficult**
  - Electric field accelerates
  - May work for storage ring

• **Neutral particle is easier**
  - Atoms (for electron EDM)
    • Also can work for quark EDM
  - Free Neutrons (for quark EDM)
Atomic EDMs

• Schiff Theorem
  - Neutral atomic system of point particles in Electric field readjusts itself to give zero E field at all charges
But ...

- Magnetic effects and finite size of nucleus can break the symmetry (relativistic effects can also enhance)
  - Enhancement for $d_e$ in paramagnetic atoms (magnetic effect with mixing of opposite parity atomic states)
  - Suppression for hadronic EDMs in diamagnetic atoms (e.g., Hg) - but Schiff Moment survives (due to finite size of nucleus and nuclear force)

Thus $d_{\text{Tl}} \sim -585 \, d_e$ & $|d_e| < 1.6 \times 10^{-27}$ e-cm

- Suppression for hadronic EDMs in diamagnetic atoms (e.g., Hg) - but Schiff Moment survives (due to finite size of nucleus and nuclear force)

Naively expect $d_A \sim \left( \frac{R_{\text{Nucleus}}}{r_{\text{Atom}}} \right)^2 \, d_{n,p} \sim \left( \frac{A^{1/3} R_0}{a / Z} \right)^2 \, d_{n,p} \sim 10^{-4} \, d_{n,p}$

for $^{199}\text{Hg}$
Experimental EDMs

• Present best limits come from atomic systems and the free neutron
  - Paramagnetic atoms (e.g. $^{205}$Tl) are primarily sensitive to $d_e$
  - Diamagnetic atoms (e.g. $^{199}$Hg) and the free neutron are primarily sensitive to $\theta_{QCD}, d_q, \tilde{d}_q$

• Future best limits may come from
  - Molecules (PbO, YbF)
  - Liquids ($^{129}$Xe)
  - Solid State systems (Gadolinium-Gallium-Garnet=GGG)
  - Storage Rings (Muons, Deuteron)
  - Radioactive Atoms ($^{225}$Ra, $^{223}$Rn)
  - New Technology for Free Neutrons (PSI, ILL, SNS)
$e^- \text{ EDM from } ^{205}\text{TI}$
$^{199}$Hg EDM

$^{199}$Hg EDM Experimental Setup

- Picoamp Leakage Monitor
- Si Photodiodes
- BBO Lin. Pol.
- Hg cells
- Hg laser
- Magnetic Shields
- Ultra-low noise current source
- Relayless Reversible 10kV Supply
- Analog Divider
- Opto-isolator
- EDM Computer
- HV Computer

Graphs:
- Rotation vs. Time (sec)
- Rotation vs. Time (sec) for a different dataset
Trapped Ultra-Cold Neutrons (UCN) with $N_{UCN} = 0.5$ UCN/cc

$|E| = 5 - 10$ kV/cm

100 sec storage time

$\sigma_d = 3 \times 10^{-26} \text{ e cm}$
n-EDM vs Time (Moore's Law)