How to turn things into Gold?

\[ ^{197}\text{Au}_{79} : 79 \text{ protons; 118 neutrons} \]

From Chris Wrede’s lectures yesterday

1. Add neutrons
2. Beta-decay
Topics I will cover:

**Lecture 1: beta-decay**
- A brief history of the electroweak theory---the precursor to the Standard Model.
- Neutron decay to test the V-A theory & beyond the SM interactions
- Current status with neutron experiments on gA & lifetime
- Physics is Symmetries

**Lecture 2: EDM**
- CP violation
- Electric Dipole Moments: Highly sensitive low-energy probes of new Physics
- muon- g-2

**Lecture 3: other symmetry violation measurements/tests**
- Baryogenesis & symmetry violations
- Nnbar oscillation: B violation
- Hadronic weak interactions: P violation
- NOPTREX: T violation
- Neutron interferometry: Lorentz symmetry violation
Chen-Yu Liu

Larry Langer
(1914--2000)
IU: 1938-1979
Department chair: ‘65-’73

Emil Konopinski
(1911 - 1990)
IU: 1938-1990
Continuous* Beta spectrum

*Crisis in the 1930s: Energy in beta-decays is not conserved! Pauli proposed the (non-detectable) neutrino, which carries away the missing energy.

J. Townsend, et al., PRB 79, 99 (1948)

Pauli showed 5 possible forms of Lorentz-invariant couplings:

\[(\bar{\phi}_p \hat{O}_i \phi_n)(\bar{\phi}_e \hat{O}_i \phi_\nu)\]

<table>
<thead>
<tr>
<th>(\hat{O}_i)</th>
<th>Transformation property of (\bar{\Psi} \hat{O}_i \Psi)</th>
<th>Number of matrices</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (\gamma^\mu)</td>
<td>Scalar ((S)) Vector ((V))</td>
<td>1</td>
</tr>
<tr>
<td>(\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]) (\gamma^\mu \gamma^5)</td>
<td>Tensor ((T)) Axial vector ((A))</td>
<td>6</td>
</tr>
<tr>
<td>(\gamma^5 = -i\gamma_0 \gamma_1 \gamma_2 \gamma_3)</td>
<td>Pseudoscalar ((P))</td>
<td>1</td>
</tr>
</tbody>
</table>

For non-relativistic fermions in nuclear beta decay:

- Fermi (spin-preserving) \(\phi_p^\dagger \phi_n\)
- Gamow-Teller (spin-changing, \(\Delta I = \pm 1,0\)) \(\phi_p^\dagger \sigma \phi_n\)
- 0

\(n \rightarrow p^+ + e^- + \bar{\nu}_e + 782\) keV
Spectral measurements (pre-1950)

\[ H_{\text{int}} = (\bar{\psi} \gamma_\mu \psi_n) (C \bar{\psi} \gamma_\mu \psi_v + C' \bar{\psi} \gamma_\mu \gamma_5 \psi_v) \]
\[ + (\bar{\psi} \gamma_\rho \gamma_\mu \psi_n) (C V \bar{\psi} \gamma_\rho \gamma_\mu \psi_v + C' V \bar{\psi} \gamma_\rho \gamma_\mu \gamma_5 \psi_v) \]
\[ + \frac{1}{2} (\bar{\psi} \gamma_\rho \gamma_\mu \gamma_5 \psi_n) (C T \bar{\psi} \gamma_\rho \gamma_\mu \gamma_5 \psi_v + C' T \bar{\psi} \gamma_\rho \gamma_\mu \gamma_5 \gamma_5 \psi_v) \]
\[ - (\bar{\psi} \gamma_\rho \gamma_\mu \gamma_5 \psi_n) (C A \bar{\psi} \gamma_\rho \gamma_\mu \gamma_5 \psi_v + C' A \bar{\psi} \gamma_\rho \gamma_\mu \gamma_5 \psi_v) \]
\[ + (\bar{\psi} \gamma_\rho \gamma_5 \psi_n) (C P \bar{\psi} \gamma_\rho \gamma_5 \psi_v + C' P \bar{\psi} \gamma_\rho \gamma_5 \psi_v) \]

+ Hermitian conjugate,

\[ 5 \times 2 \times 2 = 20 \text{ coupling constants} \]

Figure 2.4. “Influence of form of coupling on shape of spectrum for fixed values of the mass of the \( \mu \)-and \( \mu_\alpha \)-meson. Contrast this result with the case of ordinary beta-decay, where the atomic nucleus has negligible velocity and the decay curves have the same shape in all five cases” (Tiomno and Wheeler 1949a, p. 148).
"Their 1953 Annual Review article on what was then known about beta decay was a world standard."

--- Andrew Bacher, Robert Bent, Timothy Londergan, and Dan Miller (memorial resolution to the Bloomington Faculty Council)
Questions of Parity Conservation* in Weak Interactions
(T.D. Lee & C.N. Yang 1956)

* Crisis in the 1950s: Parity is not conserved (the $\theta-\tau$ puzzle)!

Proposed to measure P-violating observables, such as

$\sigma \cdot p$

$p_1 \cdot (p_2 \times p_3)$, or

Energy and angle distribution of the electron in an allowed transition:

$$N(W,\theta)dW \sin\theta d\theta = \frac{\xi}{4\pi^3} F(Z,W) p W (W_0 - W)^2$$

$$\times \left( 1 + \frac{a_\xi}{W} \cos\theta + \frac{b_\xi}{W} \right) dW \sin\theta d\theta,$$  (A.2)

where

$$\xi_S = (|C_S|^2 + |C_V|^2 + |C_S'|^2 + |C_V'|^2) |M_F|^2$$

$$+ (|C_T|^2 + |C_A|^2 + |C_{T'}|^2 + |C_{A'}|^2) |M_{G.T.}|^2,$$  (A.3)

$$a_\xi = \frac{1}{3} (|C_T|^2 - |C_A|^2 + |C_{T'}|^2 - |C_{A'}|^2) |M_{G.T.}|^2$$

$$- (|C_S|^2 - |C_V|^2 + |C_S'|^2 - |C_V'|^2) |M_F|^2,$$  (A.4)

$$b_\xi = \gamma [(C_S C_V + C_S' C_{V'}) + (C_S C_{V'} + C_S' C_{V'})] |M_F|^2$$

$$+ \gamma [(C_T C_A + C_{T'} C_{A'}) + (C_{T'} C_A + C_T C_{A'})]$$

$$\times |M_{G.T.}|^2.$$  (A.5)

(1) Beta asymmetry in oriented nucleus (Wu 1957)
(2) Circular polarization of gamma (Goldhaber 1958)
(3) Hyperon decays to form $p_1 \cdot (p_2 \times p_3)$

Total decay rate

Electron-neutrino correlation

Fierz interference

Lee, Yang, Phys. Rev. 104, 254 (1956)
Parity is violated in $^{60}\text{Co}$ decay! (1957)

Chien-Shiung Wu (1912-1997)
**Helicity of Neutrinos**

*How to measure the helicity state of neutrinos, while they cannot be detected?*

Helicity of Neutrinos*

*How to measure the helicity state of neutrinos, while they cannot be detected?

Positive helicity ($\sigma \cdot p$)

Left circularly polarized

Finally, it emerges the V—A theory!

The helicity projection operator $P_\pm$ selects the LH particle

$$P'_\pm = \frac{1}{2} (1 \pm \gamma_5)$$

$$(\bar{\phi}_p \hat{O}_i \phi_n)(\bar{\phi}_e \hat{O}_i \phi_\nu)$$

$$(\bar{\phi}_e^{RH}) \hat{O}_i (\phi_\nu^{LH}) = (\hat{P}'_+ \phi_e) \hat{O}_i (\hat{P}'_- \phi_\nu) = (\bar{\phi}_e) \hat{O}'_i (\phi_\nu)$$

$$\hat{O}'_i = \hat{P}'_+ \hat{O}'_i \hat{P}'_-$$

Table 1.3. Properties of helicity projected fermion transition operators

<table>
<thead>
<tr>
<th></th>
<th>$\hat{O}_i$</th>
<th>$\hat{O}'_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S$</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$V$</td>
<td>$\gamma^\mu$</td>
<td>$\gamma^\mu \hat{P}'_- = \frac{1}{2} \gamma^\mu (1 - \gamma_5)$</td>
</tr>
<tr>
<td>$T$</td>
<td>$\sigma^{\mu \nu}$</td>
<td>0</td>
</tr>
<tr>
<td>$A$</td>
<td>$\gamma^\mu \gamma_5$</td>
<td>$-\gamma^\mu \hat{P}'_- = -\frac{1}{2} \gamma^\mu (1 - \gamma_5)$</td>
</tr>
<tr>
<td>$P$</td>
<td>$\gamma_5$</td>
<td>0</td>
</tr>
</tbody>
</table>

R. P. Feynman and M. Gell-Mann, Phys. Rev. 109, 193 (1958);
Measurements of Asymmetries in the Decay of Polarized Neutrons*

M. T. Burg, V. E. Krohn, T. B. Novey, and G. R. Ringo,
Argonne National Laboratory, Lemont, Illinois

AND

V. L. Telegdi, University of Chicago, Chicago, Illinois
(Received April 17, 1958)

Fig. 1. Vertical cross section (normal to the neutron beam) through the detector system of the experiment measuring the correlation of the neutrino momentum and the neutron spin.

Table II. Predicted values for $\mathcal{G}$ and $\mathcal{B}$.

<table>
<thead>
<tr>
<th></th>
<th>$S+T^a$</th>
<th>$S-T$</th>
<th>$V+A$</th>
<th>$V-A^a$</th>
<th>Exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{G}$</td>
<td>$\bar{\nu}_L^b$</td>
<td>$\bar{\nu}_R$</td>
<td>$\bar{\nu}_L$</td>
<td>$\bar{\nu}_R$</td>
<td>$\bar{\nu}_L$</td>
</tr>
<tr>
<td>$\mathcal{B}$</td>
<td>$-1$</td>
<td>$+1$</td>
<td>$-0.07^c$</td>
<td>$0.07$</td>
<td>$+1$</td>
</tr>
</tbody>
</table>

* The relative signs in this row are those of the couplings present; i.e., $V-A$ means $G_d/C_V = -1.14$.

$^b$ $\bar{\nu}_L^{(R)}$ means left (right) handed antineutrino; i.e., $\bar{\nu}_L^{(R)}$ corresponds to $G_d/C_V = -1 (+1)$.

$^c$ The uncertainty of $\pm 0.05$ in $x$ introduces an uncertainty of $\pm 0.02$ in this number, 0.07, wherever it appears.
Experimental supports for V—A (nuclear data)

beta-neutrino correlation, a

\[^6\text{He}, ^8\text{Li}, ...\]

Superallowed \(0^+ \rightarrow 0^+\)

\(^{10}\text{C}, ^{14}\text{O}, \text{etc.}\)

\[
\chi = \frac{g_A M_{GT}}{g_V M_F}
\]

Neutron, Mirror Nuclei:

\(^{37}\text{K}, ^{19}\text{Ne}, ^{21}\text{Na}, ^{35}\text{Ar}\)
The Spatial Inversion Symmetry (or Parity) is Broken!

Gamow-Teller transition

RH antiparticle

LH particle

Mirror image

Chen-Yu Liu
Girl before a mirror, Pablo Picasso (1932)
Neutron beta-decay (minimal V—A)

\[ H_\beta = H_{V,A} \]

\[ = \frac{G_F V_{ud}}{\sqrt{2}} \phi_e \gamma_5 (1 - \gamma^5) \phi_\nu \phi_p (g_V + g_A \gamma^5) \gamma^\nu \phi_n \]

\[ = 1 \text{ (CVC)} \]

\[ g_V (\bar{p} \gamma_\mu n) = \langle p | \bar{u} \gamma_\mu d | n \rangle \]

\[ g_A (\bar{p} \gamma_\mu \gamma_5 n) = \langle p | \bar{u} \gamma_\mu \gamma_5 d | n \rangle \]


Neutron beta-decay

Fermi-Decay:
\[ g_V = G_F \cdot V_{ud} \]

\[ \frac{1}{\sqrt{2}} \left\{ \begin{array}{c} e^- \gamma^- \bar{v}_e^- e^- \bar{v}_e^- \end{array} \right\} \]
\[ S = 0, m_S = 0 \]

Gamow-Teller-Decay:
\[ g_A = G_F \cdot V_{ud} \lambda \]

\[ \frac{1}{\sqrt{2}} \left\{ \begin{array}{c} e^- \gamma^- \bar{v}_e^- + e^- \gamma^- \bar{v}_e^- \end{array} \right\} \]
\[ S = 1, m_S = 0 \]

\[ S = 1, m_S = 1 \]

Two unknown parameters, \( g_A \) and \( g_V \), need to be determined in 2 experiments

1. Neutron-Lifetime:
\[ \tau_n^{-1} \propto \left( g_V^2 + 3 g_A^2 \right) \]
\[ \tau_n \approx 885 \text{ s} \]
Neutron beta-decay & angular correlations

Fermi-Decay:
\[ g_V = g_F V_{ud} \]

Gamow-Teller-Decay:
\[ g_A = g_F V_{ud} \lambda \]

Beta asymmetry | Neutrino asymmetry | Beta-neutrino correlation
--- | --- | ---
\( A = 0 \) | \( B = 0 \) | \( a = 1 \)
\( A = 0 \) | \( B = 0 \) | \( a = 1 \)
\( A = -1 \) | \( B = 1 \) | \( a = -1 \)

\[ A = -2 \frac{\lambda^2 + \lambda}{1 + 3\lambda^2} \approx -0.1 \]
\[ a = \frac{1 - \lambda^2}{1 + 3\lambda^2} \approx -0.1 \]

Two unknown parameters, \( g_A \) and \( g_V \), need to be determined in 2 experiments

1. Neutron-Lifetime:
\[ \tau_n^{-1} \propto \left( g_V^2 + 3g_A^2 \right) \]
\[ \tau_n \approx 885 \text{ s} \]

\[ B = 2 \frac{\lambda^2 - \lambda}{1 + 3\lambda^2} \approx 0.98 \]
\[ \lambda = \frac{g_A}{g_V} \]
More angular correlations

Oriented nucleus:
\[
\omega(\langle J \rangle | E_e, \Omega_e, \Omega_v) dE_e d\Omega_e d\Omega_v
\]
\[
= \frac{1}{(2\pi)^5} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e d\Omega_v \xi \left\{ 1 + \frac{d}{E_e E_v} + \frac{b^m}{E_e} \right\}
\]
\[
+ c \left[ \frac{1}{3} \frac{p_e \cdot p_v}{E_e E_v} \right] J (J + 1) (3\langle J \cdot j \rangle^2) \left[ \frac{J (2J - 1)}{E_e + m} \right] \]
\[
+ \frac{\langle J \rangle}{J} \left[ \frac{A}{E_e} + \frac{B}{E_v} + \frac{D}{E_e E_v} + \frac{C}{E_e} \right] \text{.} \quad (2)
\]

Electron polarization in non-oriented nucleus:
\[
\omega(\sigma | E_e, \Omega_e, \Omega_v) dE_e d\Omega_e d\Omega_v
\]
\[
= \frac{1}{(2\pi)^5} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e d\Omega_v
\]
\[
\times \frac{1}{2} \xi \left\{ 1 + a \frac{p_e \cdot p_v}{E_e E_v} + b \frac{m}{E_e} \right\} + \sigma \cdot \left[ \frac{G}{E_e} + \frac{H}{E_v} \right]
\]
\[
+ K \frac{p_e}{E_e + m} \left( \frac{p_e \cdot p_v}{E_e E_v} \right) + L \frac{p_e \times p_v}{E_e E_v} \right\}\}
\]

In oriented nucleus:
\[
\omega(\langle J \rangle, \sigma | E_e, \Omega_e) dE_e d\Omega_e
\]
\[
= \frac{1}{(2\pi)^4} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e
\]
\[
\times \xi \left\{ 1 + b \frac{m}{E_e} + \left( \frac{\langle J \rangle}{J} + \frac{G \sigma}{J} \right) \cdot \frac{p_e}{E_e} + \sigma \cdot \left[ \frac{N}{J} \right]
\]
\[
+ Q \frac{p_e}{E_e + m} \left( \frac{\langle J \rangle}{J} \cdot \frac{p_e}{E_e} \right) + R \frac{\langle J \rangle \times p_e}{E_e} \right\}\}
\]

Chen-Yu Liu
Measurement of the Transverse Polarization of Electrons Emitted in Free-Neutron Decay

Spin-electron polarization asymmetry

\[ N = -0.218 \text{Re}(S) + 0.335 \text{Re}(T) - \frac{m}{E} A, \]

Spin-electron polarization-beta momentum (triple) corr.

\[ R = -0.218 \text{Im}(S) + 0.335 \text{Im}(T) - \frac{m}{137p} A, \]

\[ N = 0.056 \pm 0.011 \pm 0.005, \]

\[ R = 0.008 \pm 0.015 \pm 0.005. \]

FIG. 1. Schematic top view of the experimental setup. A sample projection of an electron V-track event is indicated.
Beta decays and new physics models

- Model → set overall size and pattern of effective couplings
- Beta decays can play very useful diagnosing role
- Qualitative picture:

<table>
<thead>
<tr>
<th></th>
<th>$\varepsilon_L$</th>
<th>$\varepsilon_R$</th>
<th>$\varepsilon_P$</th>
<th>$\varepsilon_S$</th>
<th>$\varepsilon_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRSM</td>
<td>$\times$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\times$</td>
</tr>
<tr>
<td>LQ</td>
<td>$\checkmark$</td>
<td>$\times$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>2HDM</td>
<td>$\times$</td>
<td>$\times$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
</tr>
<tr>
<td>MSSM</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
</tbody>
</table>

Can be made quantitative

YOUR FAVORITE MODEL

"\ldots"

\ldots"
Scalar and Tensor Couplings – beyond the Standard Model

\[ H_S = \frac{G_F V_{ud}}{\sqrt{2}} \varepsilon_S \left[ (\bar{e}(1 + \gamma_5)\nu) g_S^S (pn) \right] + \text{h.c.} \]

\[ H_T = \frac{G_F V_{ud}}{\sqrt{2}} 4 \varepsilon_T \left[ (\bar{e} \sigma_{\lambda\mu} (1 + \gamma_5)\nu) g_T^T (p \sigma_{\lambda\mu} n) \right] + \text{h.c.} \]

\[ \varepsilon_{S,T} \sim \left( \frac{\nu}{\Lambda_{S,T}} \right)^2 \sim 10^{-3} \]

\[ \nu = (2\sqrt{2}G_F)^{-1/2} \approx 174 \, \text{GeV} \]

\[ g_{S,u,d} = 0.97(12)(6) \]
\[ g_{T,u,d} = 0.987(51)(20) \]

PNDME: PRD 94, 054508 (2016)
PRD 92, 094511 (2015)

T. Bhattacharya et al., PRD 85, 054512 (2012)
Scalar and Tensor Couplings – beyond the Standard Model

Fierz interference

Scalar Currents: $b_F$

$f \propto 1 + \left(b_F \gamma, m_\gamma / E_e\right) \quad \gamma = \sqrt{1 - \alpha^2 Z^2}$

$C_S / C_V = -b_F / 2 = 0.0014(13)$

LHC: $pp \rightarrow e\nu + X$

$\varepsilon_S$: $0^+ \rightarrow 0^+$ Fierz $b_F$

$\varepsilon_T$: $\pi \rightarrow e \nu \gamma$

$\Lambda_S > 7 \text{ TeV}$

$\Lambda_T > 13 \text{ TeV}$

Future $\varepsilon_S$, $\varepsilon_T$: Neutron $b$, $b_\nu$

Future $\varepsilon_T$: $^6\text{He} b$

**CKM unitarity test**

<table>
<thead>
<tr>
<th>$V_{ud}$</th>
<th>$0^+ \to 0^+$</th>
<th>$n \to p e^-$</th>
<th>$\pi \to \mu \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>($\pi^+ \to \pi^0$ eV)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$V_{us}$</th>
<th>$K \to \pi \nu$</th>
<th>$\Lambda \to p e^-, \ldots$</th>
<th>$K \to \mu \nu$</th>
</tr>
</thead>
</table>

| $V$ | $V,A$ | $A$ |

- Currently, the most precise input comes from pure $V$ or $A$ channels
  
  - $V$: nuclear decays and semi-leptonic $K$ decays (need $f_+(0)$)
  - $A$: leptonic decays $\to V_{us}/V_{ud}$ (need $f_K/f_{TT}$)

---

*Hardy-Towner* 1411.5987

*FLAVIANET report* 1005.2323

*Lattice QCD input from* FLAG 1607.00299

*Chen-Yu Liu*
CKM unitarity test

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM}(\epsilon) \]

- Hardy-Towner 1411.5987
- FLAVIANET report 1005.2323
- Lattice QCD input from FLAG 1607.00299

- \( V_{us} \) from \( K \to \mu\nu \) (\( p_i \to \mu\nu \))
  \( \Delta_{CKM} = -(4 \pm 5) \times 10^{-4} \) 0.9\( \sigma \)
- \( V_{us} \) from \( K \to \pi\nu \nu \)
  \( \Delta_{CKM} = -(12 \pm 6) \times 10^{-4} \) 2.1\( \sigma \)

Worth a closer look: at the level of the best LEP EW precision tests

Slide: V. Cirigliano
**V_{ud} from Superallowed 0^+ \rightarrow 0^+ Decays**

\[
\mathcal{F}t \equiv ft(1 + \delta_R')(1 + \delta_{NS} - \delta_C) = \frac{K}{2G^2_V (1 + \Delta^V_R)}
\]

- $\sim 1.5\%$
- $0.5\% - 1.2\%$
- $2.361(38)\%$

\[
G_V = G_F \cdot V_{ud}
\]

---

J.C. Hardy and I.S. Towner, PRC 91, 025501 (2015)
$V_{ud}$ from neutron decays


\[ 1/\tau_n = f G_F^2 |V_{ud}|^2 m_e^5 (1+3g_A^2)(1+RC)/2\pi^3 \]

From $\mu$-decay: 0.6 ppm (MuLan 2011)

\[ |V_{ud}|^2 = \frac{4908.7 \pm 1.9s}{\tau_n (g_V + 3g_A^2)} \]

To math the theoretical uncertainty: $4 \times 10^{-4}$, it requires experimental uncertainties of: $\Delta A/A = 4\Delta \lambda/\lambda < 2 \times 10^{-3}$ and $\Delta \tau/\tau = 4 \times 10^{-4}$. 

f: Phase space factor=1.6886
(Fermi function, nuclear mass, size, recoil)
$V_{ud}$ from neutron decays

$g_V \equiv G_F V_{ud} f(0)$

Nuclear $O^+ \rightarrow O^+$ Decays, CKM Unitarity

Neutron Decay Correlations

$g_A / g_V$

How thick are the bands and do they overlap?

$n$ Lifetime

$g_A^2 + 3g_V^2$
The confusing situation of $g_A$, $g_V$ & $V_{ud}$

$$\tau_n = \frac{4908.7 \pm 1.9s}{|V_{ud}|^2 (g_V + 3g_A^2)}$$
Ultracold Neutrons (UCN)

Kinetic Energy

~350 neV
~50 μeV
~25 meV
~500 keV

ultracold
very cold
cold
epithermal
fast

UCN storage

Downscatter
cold moderation

superthermal production:
UCN can be accumulated to a density higher than the Boltzmann factor, $e^{-\Delta E/kT}$

R. Golub and J.M. Pendlebury, PLA 53, 133 (1975)
C.L. Morris et al., PRL 89, 272501 (2002)
F. Atchinson et al., PRL 95, 182502 (2005)
C.M. Lavelle et al., PRC 82, 015502 (2010)
Different ways to manipulate UCN

- Nuclear force (max: 350neV)
- Gravitational force (100neV/m)
- Magnetic force (60neV/T)
UCN improve data quality

Low background
Long storage time

Store for 1.5 hour

J. Liu et al. (UCNA Collaboration)
Phys. Rev. Lett. 105, 181803
However, the values of the Beta asymmetry and Neutron lifetime are changing...

\[ \frac{\sqrt{\chi^2}}{\nu} = 2.4 \]

\(~0.1\% \text{ Result for } A_0 \text{ would remove older results from } \chi^2\)

Beam and UCN measurements disagree by 10 s!
The History of Neutron Lifetime Measurement

1st UCN bottle lifetime experiment

Experiments

PDG average
$g_A$ From Lattice QCD

C.C. Chang et al., arXiv:1710.06523

1.33% Result for $g_A$!

Cirigliano, Gardner, Holstein,
Prog. Part. Nucl. Phys. 71, 93 (2013):

Experiments: $\left(1-2\varepsilon_R\right)g_A / g_V$  \quad \longleftrightarrow \quad Lattice: $g_A$
Big-Bang Nucleosynthesis: a sensitive probe to early universe (1000 s after the BB)

The ingredients: protons & neutrons
Big Bang nucleosynthesis

1 μs
Thermal equilibrium
(T > 1 MeV)

\[ \frac{n}{p} \propto e^{-Q/T} \]

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

\[ n + \nu_e \leftrightarrow p + e^- \]

1 s
After freezeout
n/p decreases due to neutron decay

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

100s
Nucleosynthesis (T~0.1 MeV)
Light elements are formed

\[ p + n \rightarrow d + \gamma \]

\[ d + d \rightarrow ^4\text{He} + \gamma \]

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

*Slide courtesy of H. P. Mumm*
Big Bang Nucleosynthesis (BBN): Neutron lifetime & the primordial $^4$He abundance ($Y_p$)

\[ Y_p \sim \frac{2e^{-t_d/\tau_n}}{1 + e^{\Delta m/kT_f}} \]

Sensitive to $\tau_n$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{bbn_plot.png}
\caption{BBN with $\tau_n = 880$ s}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{astrophysical_observations.png}
\caption{CMB Astrophysical Observations}
\end{figure}

References:
- L. Salvati et al. JCAP 1603 (2016) no.03, 055
Two ways to measure the neutron lifetime $\tau_n$

$$\tau_n = -\frac{\bar{N}_n}{\dot{N}_n}$$

**Cold Neutron Beam**

$n^+{^6}\text{Li} \rightarrow \alpha + t$

**Ultracold Neutron (UCN) Bottle**

Fill → Store → Count

$\tau_n = -\frac{(t_2 - t_1)}{\ln\left(\frac{N_2}{N_1}\right)}$
Halbach Array Completion: Dec 2012

An *in-situ* UCN (dagger) detector

Z. Wang et al., NIMA 798, 30 (2015).
C. Morris et al., RSI 88, 053508 (2017)
Multi-step UCN detection \(\rightarrow\) control over-threshold UCN

Uncleaned Correction

- Subtract From Total Population
- Count Total Uncleaned UCN

Fraction of Total Counts [\% s]

Time into Counting [s]
Lifetime measurements better than $10^{-3}$ are challenging

- In UCNtau, we store $N_1=25,000$ neutrons, and count $N_2=6000$ neutrons after storing them for $t_2-t_1=1000$ s.
  100 neutrons unaccounted for (due to upscatter, spin flip, or heating) will decrease the measured neutron lifetime by 10 s.

$$\frac{1}{\tau_{mea}} = \frac{1}{\tau_B} + \frac{1}{\tau_{ab}} + \frac{1}{\tau_{up}} + \frac{1}{\tau_{sf}} + \frac{1}{\tau_{heat}} + \frac{1}{\tau_{qb}} + \ldots$$

To reach 1 s, we can miss no more than 10 neutrons (per run).
To reach 0.1 s, no more than 1 neutron.

- In the beam experiment, underestimating the proton efficiency (storage, transport, detection) by 1 % will increase the measured neutron lifetime by 8 s.
Are neutrons disappearing at a rate faster than the rate of beta-decay?

*Crisis in 2000: mass density is dominated by unidentified dark matter & dark energy

Mirror matters

Does the difference in two methods of neutron lifetime measurement show a signal of neutron to mirror state transformation? 

or DM* scattering

JPARC TPC experiment (preliminary)

Serebrov’s large Gravitrap experiment (manuscript in preparation)

UCNtau experiment (submitted to Science)
Summary on neutron beta-decay experiments

- **SM tests:**
  - A single parameter yields $\lambda = \frac{g_A}{g_V}$, multiple angular correlations yield $V_{ud}$ (and S, T couplings)
  - New measurements on both $A$ and $\tau_n$ have been shifting values.
  - CKM unitarity: Do neutrons and super-allowed beta decays agree?

- **Searches for BSM new physics**
  - right-handed currents (250 GeV limit from n decay)
  - Scalar and tensor couplings from $B$ and $b$

- **Neutron lifetime discrepancy**
  - Neutron decays (bottle experiments) *faster* than the rate of beta-decay (beam experiments)

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Physics is Symmetries

Energy

- Newton’s Laws
- E. & M., Atoms, Molecules,....
- Cosmology, Astrophysics,....
- Newtonian Gravity

Standard Model

General Relativity

- Quantum Mechanics
- Lorentz Symmetry
- Curved Spacetime

Theory of Everything

String theory, quantum gravity, non-commutative geometry,....

Slide courtesy: Matt Mewes
Question: Why Lorentz Violation?

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Quantum Mechanics

Parity

CP

Lorentz Symmetry

CPT

Curved Spacetime

Theory of Everything

& Discrete Symmetries
Question: Why Lorentz Violation?

& Discrete Symmetries

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Lorentz Symmetry

CPT

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L-R Symmetric; CP Symmetric

Theory of Everything
Symmetry is broken (at low T), after phase transition(s).
Spontaneous Symmetry Breaking

The simplest interacting QFT involves a Lorentz scalar field:

\[
\mathcal{L} = \frac{1}{2} (\partial_\mu \phi)(\partial_\nu \phi) - \frac{1}{2} m^2 \phi^2 - \frac{1}{4!} \lambda \phi^4
\]

The (L-R) symmetry is respected in the Lagrangian, but the (L-R) symmetry is broken in the particular solution.

Chen-Yu Liu
Answer: Symmetry violations (at low E-scales) are evidence, pointing to new physics that unifies all forces at high E-scales.
Question: Why Lorentz Violation?

& Discrete Symmetries

Energy

Newton's Laws
E. & M., Atoms, Molecules, ...
Cosmology, Astrophysics, ...
Newtonian Gravity

Standard Model

Quantum Mechanics

PV
CPV

L-R Symmetric; CP symmetric

Baryon #
Lepton #

Lorentz Symmetry

CPT

Curved Spacetime

Answer: Symmetry violations (at low E-scales) are evidences, pointing to new physics that unifies all forces at high E-scales.
Questions?