WEAK INTERACTION STUDIES WITH $^6$HE

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The Weak Interaction for “point-like particle” decays

\[ H = 2C_V \overline{\Psi}_f V^\mu \Psi_i^L - e^L \gamma_\mu \nu_e^L + \overline{\Psi}_f A^\mu \Psi_i^L - 2C_A \overline{e}^L \gamma_\mu \gamma_5 \nu_e^L \]

Ignore propagator \((q^2 \ll M_W^2)\)

The Weak Interaction for nucleons

\[ H = \begin{cases} \overline{\Psi}_f V^\mu \Psi_i^L - 2C_V \overline{e}^L \gamma_\mu \nu_e^L + \\ \overline{\Psi}_f A^\mu \Psi_i^L - 2C_A \overline{e}^L \gamma_\mu \gamma_5 \nu_e^L \end{cases} \]

\[ \overline{\Psi}_f V^\mu \Psi_i^L = \overline{\Psi}_f \left( f_V \gamma_\mu + f_{WM} \sigma_{\mu\nu} q^\nu \right) \Psi_i^L \]

\[ \begin{array}{ll} \text{‘Vector’} & \text{Conserved current} \\ \text{‘Axial V’} & \text{Not conserved} \end{array} \]
The Weak Interaction for "point-like particle" decays

\[ H = 2C_V \bar{\Psi}_f^L \gamma^\mu \Psi_i^L + \bar{e}^L \gamma_\mu \nu_e^L \]

The Weak Interaction for nucleons

\[ H = \begin{cases} 
\bar{\Psi}_f V^\mu \Psi_i^L & 2C_V \bar{e}^L \gamma_\mu \nu_e^L \\
\bar{\Psi}_f A^\mu \Psi_i^L & 2C_A \bar{e}^L \gamma_\mu \gamma_5 \nu_e^L 
\end{cases} \]

Weak Magnetism

\[
\bar{\Psi}_f V^\mu \Psi_i = \bar{\Psi}_f \left( f_V \gamma_\mu + f_{WM} \sigma_{\mu\nu} q^\nu \right) \Psi_i \\
\bar{\Psi}_f A^\mu \Psi_i = \bar{\Psi}_f \left( f_A \gamma_\mu \gamma_5 + f_T \sigma_{\mu\nu} \gamma_5 q^\nu \right) \Psi_i
\]

Pseudo-Induced Tensor

(fashionable in 70's, not now!)

\[ \text{'Vector'} \quad \text{Conserved current} \]

\[ \text{'Axial V'} \quad \text{Not conserved} \]
The Weak Interaction in nuclear “allowed” decays

\[ H = \overline{\Psi}_f \gamma^\mu \Psi_i \quad 2C_V \overline{e}^L \gamma_\mu \nu_e^L + \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_i \quad 2C_A \overline{e}^L \gamma_\mu \gamma_5 \nu_e^L \]

`Vector’

`Axial Vector’

Nucleons move slowly

\[ V_\mu \equiv \phi_f (\gamma_\mu I^\pm) \phi_i = \]

\[ \phi_f (1, \frac{\vec{V}}{c}) I^\pm \phi_i \approx \phi_f (1, 0) I^\pm \phi_i \]

Simplest operator!

\[ \langle \phi_f (\gamma_\mu) \phi_i \rangle \approx \int d^3 x \, \phi_f^* I^\pm \phi_i \]

\[ \Delta \vec{J}^\pi = \vec{0}^+ \quad \text{“Fermi”} \]

\[ \langle \phi_f (\gamma_\mu \gamma_5) \phi_i \rangle \approx \int d^3 x \, \phi_f^* \vec{\sigma} I^\pm \phi_i \]

\[ \Delta J^\pi = 1^+ \quad \text{“Gamow-Teller”} \]

\[ A_\mu \equiv \phi_f (\gamma_\mu \gamma_5 I^\pm) \phi_i = \]

\[ \phi_f (\frac{\vec{V}}{c}, \vec{\sigma}, \vec{\sigma}) I^\pm \phi_i \approx \phi_f (0, \vec{\sigma}) I^\pm \phi_i \]

More complicated.
Searches for Scalar and Tensor currents.

Are weak decays carried only by W’s?

Or is there something new?

Lepto-Quark

\[ H = \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_i \quad 2C_A \bar{e}^L \gamma_\mu \gamma_5 \nu_e^L + \]
\[ \bar{\Psi}_f \gamma^\mu \gamma^\nu \gamma \Psi_i \left[ (C_T - C'_T) \bar{e}^L \gamma_\mu \gamma_\nu \nu_e^R + (C_T + C'_T) \bar{e}^R \gamma_\mu \gamma_\nu \nu_e^L \right] \]

Decay rate:

\[ dw = dw_0 \left[ 1 + a \frac{p_e \cdot p_\nu}{E_e E_\nu} + b \frac{\Gamma m_e}{E_e} \right] \]

\[ b \approx \frac{\text{Re} [2C_A (C_T + C'_T)]}{2 |C_A|^2 + |C_T|^2 + |C'_T|^2} \]

\[ a \approx -\frac{1}{3} \frac{2 |C_A|^2 - |C_T|^2 + |C'_T|^2}{2 |C_A|^2 + |C_T|^2 + |C'_T|^2} \]
Precision beta decay versus “LHC”:
Can “precision” compete with “energy”? Yes.

From Bhattacharya et al.

\[
\begin{align*}
\varepsilon_s &= \frac{C_S + C'_S}{2 g_s} \\
\varepsilon_T &= \frac{C_T + C'_T}{8 g_T}
\end{align*}
\]

\[g_s = 0.8(4)\quad g_T = 1.05(35)\]
Ultimate accuracy:
Need to calculate “forbidden” components

\[ C_V \int \vec{\alpha} \times \vec{r} \rightarrow \frac{f_V}{M} \left[ \int \vec{\sigma} + \int \vec{r} \times \vec{p} \right] - 2 f_{WM} \int \vec{\sigma} \right] \]
\[ C_A i \int \gamma_5 \vec{r} \rightarrow g_A i \int \tau^+ \vec{\sigma} \times \vec{r} \right] \}

... and radiative corrections.

Under control for neutron decay.
Ultimate accuracy:
Need to calculate “forbidden” components
\[
C_V \int \vec{\alpha} \times \vec{r} \rightarrow \frac{f_V}{M} \left[ \int \vec{\sigma} + \int \vec{r} \times \vec{p} \right] - 2 f_{WM} \int \vec{\sigma}
\]
\[
C_A i \int \gamma_5 \vec{r} \rightarrow g_A i \int \tau^+ \vec{\sigma} \times \vec{r}
\]

… and radiative corrections.

Under control for neutron decay.

However, experiments with neutrons are difficult.
6He:
“forbidden” components

\[ C_v \int \vec{a} \times \vec{r} \rightarrow \frac{f_v}{M} \left[ \int \tau^+ \vec{\sigma} + \int \tau^+ \vec{r} \times \vec{p} \right] - 2f_{WM} \int \tau^+ \vec{\sigma} \right] \]
\[ C_A i \int \gamma_5 \vec{r} \rightarrow g_A i \int \tau^+ \vec{\sigma} \times \vec{l} \]

Small and under control for 6He decay.

... and radiative corrections.

Can nuclear theorists save us?

ANL group: Talk this afternoon at CENPA
6He: “forbidden” components

\[
C_V \int \widetilde{\alpha} \times \vec{r} \rightarrow \frac{f_V}{M} \left[ \int \tau^+ \sigma \widetilde{\sigma} + \int \tau^+ \vec{r} \times \vec{p} \right] - 2f_{WM} \int \tau^+ \widetilde{\sigma} \right] 
\]

\[
C_A i \int \gamma_5 \vec{r} \rightarrow g_A i \int \tau^+ \sigma \vec{v} \times \vec{l} 
\]

Small and under control for 6He decay.

… and radiative corrections.

Can nuclear theorists save us?!
$6\text{He}$: 
“forbidden” components

$$C_v \int \vec{\alpha} \times \vec{r} \to \frac{f_v}{M} \left[ \int \tau^+ \vec{\sigma} + \int \tau^+ \vec{r} \times \vec{p} \right] - 2 f_{WM} \int \tau^+ \vec{\sigma}$$

$$C_A i \int \gamma_5 \vec{r} \to g_A i \int \tau^+ \vec{\sigma} \times \vec{l}$$

Small: why?
1) First element is multiplied by a kinematic factor that integrates to zero in the limit of zero Coulomb corrections.
2) LS-scheme wave fn for $6\text{He} \to 6\text{Li}$

$$\begin{align*}
\left| ^6\text{He} \right> & \approx 0.95 \left| ^1S_0 \right> - 0.31 \left| ^3P_0 \right> \\
\left| ^6\text{Li} \right> & \approx 0.99 \left| ^3S_1 \right> - 0.10 \left| ^1P_1 \right> + 0.10 \left| ^3D_1 \right>
\end{align*}$$

Little room for orbital ang. mom. in wave fn.

... and radiative corrections.

Can nuclear theorists save us?
6He collaboration

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LPC, CAEN, France

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NSCL, Michigan State University

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• Simple decay (~100% to ground state)
• Pure Gamow-Teller decay
• Half-life appropriate for trapping (~1 sec)
• Large Q-value, good for seeing effects of ν
• Noble gas → no worries about chemistry
• Simple nuclear structure

\[ ^{6}\text{He} \rightarrow ^{6}\text{Li} \]
Production of $^6$He at Seattle via $^7$Li(d,$^3$He)$^6$He

Now have a reliable source of $^6$He yielding $\sim 4 \times 10^9$ atoms/s in a clean room!

*A High-Intensity Source of 6He Atoms for Fundamental Research*

A. Knecht et al.

*NIM A. 660, 43 (2011)*
$g_A / g_V$ for free neutrons is determined by measurements of the Beta Asymmetry (PERKEO, UCNA)
Fermi’s Golden rule

\[
\frac{K}{f t} = B(GT) = g_A^2 \left| \langle \Psi_f | \sigma \tau | \Psi_i \rangle \right|^2
\]

\[
f \approx \int F(Z, E_e) d^3 p_e d^3 p_v
\]

`Phase space`

Problem: when comparing calculations with experiment found less strength than predicted: `quenching of \( g_A \`).

\[g_A \text{ from neutron} \sim 1.27\]

\[g_A \text{ for (sd-shell) nuclei} \sim 1.00\]
`quenching of $g_A$`.

Two alternative explanations

Calculations are performed in a reduced shell-model space

$$\langle \Psi_f P^{-1} | P \sigma \tau P^{-1} | P \Psi_i \rangle$$

$p = \text{projection operator into the reduced space.}$

Need to $\text{renormalize}$ to account for the reduced config. space.

Vector current protected by CVC, but Axial current is not. Meson Exchange Currents yield a mechanism for a different effective $g_A$. 
$^6$He and $^3$H: very simple transitions; light enough for ab-initio calculations.

The decay of $^3$H is used to determine the Nucleon-Delta excitation effect and it turns out to be small (2% correction). Several `ab-initio’ calculations show agreement at the few percent level:

Schiavilla & Wiringa PRC 65, 054302 (2002)
Previn et al., PRC 76, 064319 (2007)
Veintraub et al., PRC 79, 065501 (2009)

However, experimental situation was somewhat unclear.

Veintraub et al.
…our accuracy in estimating the GT matrix element is at the level of per mil… validates the use of the $^6$He $\beta$-decay as a testing ground for an axial MEC model.
Extracting $g_A$ from the lifetime of $^6\text{He}$

**Experimental Setup**

- Stainless steel measuring volume with insert to check for diffusion
- Scaler based DAQ
Extracting $g_A$ from the lifetime of $^6$He

- Two previous experiments disagreed by 9 ms. Resolved the discrepancy.
- Our results in combination with ab-initio calculations shows that quenching is at most about 2%.

Overview of Calculations

  - Argonne $v_{18}$ two-nucleon and Urbana-IX three nucleon interaction
  - Including meson-exchange current fixed to $^3$H
  - Variational Monte Carlo calculation

  - Argonne V8’ two-nucleon and Tucson-Melbourne TM’(99) three nucleon interaction
  - Ab-initio shell model calculation

  - Argonne $v_{18}$ two-nucleon and Illinois-2 three nucleon interaction
  - Variational and Green’s function Monte Carlo calculation

  - J-matrix inverse scattering (JISP16) two-nucleon potential for wave functions
  - Including meson-exchange current fixed to $^3$H
  - Chiral perturbation theory calculation
The Influence of MEC

<table>
<thead>
<tr>
<th>Calculation</th>
<th>$MGT$ (no MEC)</th>
<th>Change from $gA(n)$</th>
<th>$MGT$ (incl. MEC)</th>
<th>Change from $gA(n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schiavilla/Wiringa</td>
<td>2.254(5) ($\Psi_T I$) 2.246(10) ($\Psi_T II$)</td>
<td>-3.9%</td>
<td>2.284(5) ($\Psi_T I$) 2.278(10) ($\Psi_T II$)</td>
<td>-5.2%</td>
</tr>
<tr>
<td>Vaintraub/Barnea/Gazit</td>
<td>2.225(2)</td>
<td>-2.7 %</td>
<td>2.198(7)</td>
<td>-1.5 %</td>
</tr>
</tbody>
</table>

- Free low-energy constant in calculation of meson-exchange currents: → fixed by $^3$H half-life
- Influence of MEC different in the two calculations
- Vaintraub et al. argue that this is an effect of the correct modeling of the underlying currents in $\chi$PT
Searches for Scalar and Tensor currents.

Are weak decays carried only by W’s?

Or is there something new?

Searches for Tensor Currents in spin flip decays

\[ \begin{array}{c}
\text{u} \quad \text{d} \quad \text{e}^+ \quad \nu_e \\
\text{W} \end{array} \]
Searches for Tensor currents: Helicities in the Standard Model

\[ \mathcal{H} = \frac{\vec{p} \cdot \vec{J}}{|\vec{p}| J_{\text{max}}} \]

Example: photons have \( \mathcal{H} = \pm 1 \).

The electro-weak interactions are mediated by VECTOR (Spin=1) particles (Photon, Z0, Ws).

A consequence is that the interactions don’t flip helicities.

Or equivalently (notice anti nu):

All the particles that couple to the Weak interactions are left handed;

Particles \( \rightarrow \) Left handed

Anti particles \( \rightarrow \) Right handed
Helicities in the Standard Model

If the nuclear spins don’t flip then the leptons have total $J_z=0$

\[
\begin{align*}
J^e_z &\quad \rightarrow \quad p^e_z \\
J^\nu_z &\quad \rightarrow \quad p^\nu_z 
\end{align*}
\]

Consequence: e-antinu correlation

\[
\frac{d\Gamma}{d\Omega_{e\nu}} = 1 + \frac{\vec{p}^e}{E_e} \cdot \frac{\vec{p}^\nu}{E_\nu}
\]

If the nuclear spins flip then the leptons have total $J_z=1$

\[
\begin{align*}
J^e_z &\quad \rightarrow \quad p^e_z \\
J^\nu_z &\quad \rightarrow \quad p^\nu_z 
\end{align*}
\]

Consequence: e-antinu correlation

\[
\frac{d\Gamma}{d\Omega_{e\nu}} = 1 - \frac{\vec{p}^e}{E_e} \cdot \frac{\vec{p}^\nu}{E_\nu}
\]
Helicities with **Scalar or Tensor Currents**

If the nuclear spins don’t flip then the leptons have total \( J_z = 0 \)

\[
\begin{align*}
J_z^e &\quad \leftrightarrow \quad p^e \\
J_z^\nu &\quad \leftrightarrow \quad p^\nu
\end{align*}
\]

Consequence: e-antinu correlation

\[
\frac{d\Gamma}{d\Omega_{ev}} = 1 - \frac{\vec{p}^e}{E_e} \cdot \frac{\vec{p}^\nu}{E_\nu}
\]

If the nuclear spins flip then the leptons have total \( J_z = 1 \)

\[
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J_z^e &\quad \leftrightarrow \quad p^e \\
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\[
\frac{d\Gamma}{d\Omega_{ev}} = 1 + \frac{\vec{p}^e}{E_e} \cdot \frac{\vec{p}^\nu}{E_\nu}
\]
Searching for tensor currents in $^6\text{He}$

Instead of detecting the neutrino, determine momentum of electron and $^6\text{Li}$

Problem: slow $^6\text{Li}$, will loose momentum in ANY supporting layer.

Solution: hold $^6\text{He}$ with light!
Magneto-Optical Trap

- Six orthogonal, counter-propagating beams of opposite circular polarization are red-detuned as in the Doppler cooling configuration.
- Anti-Helmholtz coils introduce a quadrupole field with zero magnetic field at the center and linearly increasing field in the directions of the lasers.
Trapping of $^6\text{He}$

- RF discharge in xenon/krypton to excite into metastable state
- Cycling on 1083 nm transition to transversely cool, slow down and trap magneto-optically
- Trapped atoms transferred to detection chamber with dipole trap
- Based on experience from $^6\text{He}$, $^8\text{He}$ charge radius measurements by ANL collaborators:
  L.-B. Wang et al., PRL 93, 142501 (2004)
$^6$He Little a, detection

- Electron and $^6$Li recoil nucleus detected in coincidence

- $\Delta E-E$ scintillator system for electron detection (energy, start of time-of-flight)

- Micro-channel plate detector for detection of recoil nucleus (position,
So far we have managed to trap 500-1000 $^6$He atoms.

But only for periods of $\frac{1}{2}$ hour. Need more stability.

Presently working on many developments.

First physics run likely early 2013.
Interaction for GT transitions

\[ H = \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_i \ 2C_A \overline{e}^L \gamma_\mu \gamma_5 \nu_e^L + \]
\[ \overline{\Psi}_f \gamma^\mu \gamma^\nu \Psi_i \left[ (C_T - C_T') \overline{e}^L \gamma_\mu \gamma_\nu \nu_e^R + (C_T + C_T') \overline{e}^R \gamma_\mu \gamma_\nu \nu_e^L \right] \]

Decay rate:

\[ dw = dw_0 \left[ 1 + a \frac{p_e}{E_e} \cdot \frac{p_\nu}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right] \]

\[ b \approx \text{Re} \left[ \frac{2C_A (C_T + C_T')}{{2|C_A|^2 + |C_T|^2 + |C_T'|^2}} \right] \]

\[ a \approx \frac{-1}{3} \frac{2|C_A|^2 - |C_T|^2 + |C_T'|^2} {{2|C_A|^2 + |C_T|^2 + |C_T'|^2}} \]
We have already trapped ~500 atoms of $^6$He at UW!
6He: measuring the spectrum in search of the `Fierz interference'

- Use MWPC
  - Identify backscattering
  - Veto non-contained events, backgrounds,

Calibration of line shapes very important.
Follow Tseung, Kaspar, Tolich, arXiv:1105.2100v1:
Use $^{12}$C$(p,p')$ to generate 4.4 MeV photons and then scatter in TPC to generate Compton electrons.

Ongoing simulations to understand the limits of our methods