Weak Interaction Studies with
\[ \vec{e} + {}_3^3\text{He} \rightarrow {}_3^3\text{H} + \nu \]

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Weak Currents and QCD

• One of the main goals of QCD is to understand nucleons and nuclei in terms of quarks and the forces of QCD.

• We believe that the spontaneous breaking of chiral symmetry of QCD is responsible for the large effective mass of quarks confined in nucleons and nuclei.

• The best way to study these effects is to measure the weak currents in nucleons and nuclei. The axial current is of primary importance.

• However, the axial form factor of light nuclei such as $^3\text{He}$ has never been measured.

• Weak interaction measurements will also provide information about axial two-body currents.

• Weak capture of polarized electrons in $^3\text{He}$ has great potential to fill this gap and also help test for 2nd class currents.

• Complementary to e-capture in proton discussed by A. Deur.
Second Class Currents

Introduced by Weinberg  
Phys. Rev. 112, 1375 (1958)

Represent the properties of strangeness conserving ($\Delta S=0$) Vector and Axial currents under G-parity transformation

First class:

$$GV_{\mu}^{(I)\pm} G^{-1} = V_{\mu}^{(I)\pm}, \quad GA_{\mu}^{(I)\pm} G^{-1} = -A_{\mu}^{(I)\pm}$$

Second class:

$$GV_{\mu}^{(II)\pm} G^{-1} = -V_{\mu}^{(II)\pm}, \quad GA_{\mu}^{(II)\pm} G^{-1} = A_{\mu}^{(II)\pm}$$

Experimentally, so far there is no evidence for or against the existence of second class currents
The $e + ^3\text{He} \rightarrow ^3\text{H} + \nu$ Reaction

Neglecting lepton masses

$$\frac{d\sigma}{d\Omega_n} = K(E_e, E_\nu, \theta_\nu)\sigma_0(f_E, f_M, f_A)$$

$q = k-k'$, $P = p_1-p_2$

$f_E$, $f_M$, $f_A$ are the electric, magnetic and axial formfactors of $^3\text{He}$

Neglecting electron mass, there are no contributions from $2^{nd}$ class currents and no spin-momentum correlations.

Small cross section $\sim 10^{-40}$ cm$^2$/sr
Spin Dependent e-Capture

If the mass of the electron is not neglected (relevant for the low energies proposed here)

\[ \frac{d\sigma}{d\Omega_n} = K(E_e, E_\nu, \theta_\nu)\sigma_0 \left[ 1 + \frac{m_e}{\sigma_0} [(k' \cdot s)g_1(W_1, W_2, W_5) + (P \cdot s)g_2(W_2, W_5) + (q \cdot s)g_3(W_5, W_6)] \right] \]

\[ q = k - k'; \quad P = p_1 - p_2; \quad s = \text{electron spin vector} \]

\[ W_1 - W_6 \] are functions of the nuclear form factors with \( W_5 \) and \( W_6 \) entirely due to second class currents
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\( q = k - k' \); \( P = p_1 - p_2 \); \( s = \) electron spin vector

\( W_1 \) - \( W_6 \) are functions of the nuclear form factors with \( W_5 \) and \( W_6 \) entirely due to second class currents

Observation of a non-zero correlation between q-vector and electron spin direction would be sufficient to verify the existence of second-class currents.
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\]

\[ q = k - k'; P = p_1 - p_2; s = \text{electron spin vector} \]

\( W_1 - 6 \) are functions of the nuclear form factors with \( W_5 \) and \( W_6 \) entirely due to second class currents.

Observation of a non-zero correlation between q-vector and electron spin direction would be sufficient to verify the existence of second-class currents.

Also relevant for the \( \vec{e} + p \rightarrow \nu + n \) reactions discussed in the previous talk.
If the mass of the electron is not neglected (relevant for the low energies proposed here)

Ignoring second class currents and for \( q^2 \ll M_{\text{Targ}}^2 \)

\[
\frac{d\sigma}{d\Omega_n} = K(E_e, E_\nu, \theta_\nu)\sigma_0[1 + A_1 + \gamma h m_e A_2 \cos \theta_n (1 + \frac{|f_A(q^2)|^2}{|f_V(q^2)|^2})],
\]

\( h \) is electron helicity, \( f_A \) and \( f_V \) are axial and vector formfactors of \(^3\text{He}\)
Spin Dependent e-Capture

If the mass of the electron is not neglected (relevant for the low energies proposed here)

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$h$ is electron helicity, $f_A$ and $f_V$ are axial and vector formfactors of $^3\text{He}$

The coefficient of the $\cos\theta_n$ moment of the longitudinal asymmetry can give us the ratio of the axial to vector formfactor
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Implies that $\vec{e} + p \rightarrow \nu + n$ reaction will allow access to $|g_A(Q^2)/g_V(Q^2)|$

via a new method unlike the ones traditionally used to measure this ratio.
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$q = k-k'$, $P = p_1-p_2$

Want to measure a small cross section buried under electromagnetic background to extract the axial formfactor of $^3\text{He}$

Strategy:

- Detect $^3\text{H}$ in backward lepton kinematics to enhance Weak/EM cross sections
- Detect elastic backward going electrons in coincidence to reduce backgrounds
- Use high intensity low energy beam with a thin target
- Use polarization degrees of freedom to cleanup parity conserving backgrounds
Spin Dependent e-Capture

Only left-handed neutrinos exist in the Standard Model with massless neutrinos.

If polarized electrons are used

\[ e + ^3\text{He} \rightarrow ^3\text{H} + \nu \]

cross section is non-zero only for left handed electrons

For a symmetric detector any parity conserving (electromagnetic) background would cancel in:

\[ \sigma (h=+1) - \sigma (h=-1) \]
Backgrounds

- Elastic scattering from $^3$He and $^3$H (cross sections 8 - 9 orders of magnitude larger)
  Elastic rates $\sim 10^5 - 10^6$ Hz compared to $10^{-3}$ Hz for signal
  Target must be ultra-pure with $^3$H contamination at $10^{-9}$ level
  Elastic background can be reduced by detecting the scattered $e^-$ in coincidence

- Elastically scattered $^3$He undergoes charge exchange with cell wall to yield $^3$H
  Detect scattered $e^-$ in coincidence

- Elastically scattered $^3$He picking up an $e^-$ to become indistinguishable from $^3$H
  Charge sensitive detector
  Detect scattered $e^-$ in coincidence

Use longitudinally polarized electrons with high polarization
Weak Charged Current Cross Sections

Using $<r_c^{3\text{He}}>$ = 1.87 fm; $<r_m^{3\text{He}}>$ = 1.74 fm
$<r_c^{3\text{H}}>$ = 1.70 fm; $<r_m^{3\text{H}}>$ = 1.70 fm

\[ \frac{d\sigma}{dq^2} \text{ (\mu B/GeV)} \]
Windowless Target

under development at JLab for the
Proton Charge Radius Experiment (PRAD)
A. Gasparian (NCA&T), D. D(Miss. State), H. Gao (Duke) and M. Khandakar (Idaho State)

Similar target also being developed for the DarkLight experiment at the JLab FEL
Detector Design

Large acceptance (2\pi polar angle and 20° - 160° azimuthal) with a solenoidal/toroidal field

- **Avalanche Chambers**: $r = 4 \& 8 \text{ cm}$, $\sigma \sim 100 \text{ ps}/200 \mu\text{m}$
- **Chamber Gas**: 2-10 Torr Isobutane
- **Chamber Windows**: 40-50 $\mu\text{g/cm}^2$ Polypropylene
- **Silicon Micro-strip**: $r = 10 \text{ cm}$, $t \sim 100 \& 400 \mu\text{m}$, $\sigma \sim 100\mu\text{m}$
- **Scintillator**: $r = 15 \text{ cm}$, $t \sim 2 \text{ cm}$

Low Energy Recoil Detector under development by K. Hafidi (ANL), R. Dupré (Saclay) and S. Stepanyan (JLab)
Detector Design

Momentum range of $^3$H 80 - 550 MeV/c

- × through tracks
- ☒ stopped tracks

Low Energy Recoil Detector under development
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Projected Rates

I_\text{e} = 600 \ \mu\text{A}, \ \text{polarized beam}

Target density \sim 10^{19} \ \text{atoms/cm}^2

Luminosity \sim 4 \times 10^{34} \ /\text{cm}^2

Rates @ E_\text{e} = 0.08 \ \text{GeV} \sim 8 \times 10^{-4} \ /\text{sec}

\Rightarrow \sim 3\% \ \text{statistics in 350 hrs

3\% \ \text{systematic uncertainty assumed for all settings.

Stat. and total error shown for each point}
Summary of Experiment

1. 0.08 - 0.12 GeV, highly polarized beam with 600 µA current

2. Windowless gas flow/jet target with ultra-pure $^3$He

3. Solenoidal magnet (low energy/warm)

4. Large acceptance recoil detector with excellent PID
detect recoil $^3$H
and elastically scattered electrons in coincidence (to reduce backgrounds)

5. Eliminate parity conserving EM backgrounds using
   \[
   (\sigma (h=+1) - \sigma (h=-1))
   \]

6. Use electron scattering data on $f_M^{^3\text{He}}(Q^2)$ to extract $f_A^{^3\text{He}}(Q^2)$

7. Look for spin correlations in search of second class currents

8. Use spin correlations to measure $f_A/f_V$ of $^3$He
Conclusions

- Weak capture of electrons on the proton and $^3$He can provide unique opportunities to measure the axial formfactor.

- Backgrounds can be controlled using polarized electrons and well designed detectors.

- Several ideal detectors and targets already under development for other experiments.

- At very low energies measurement of spin correlations can test for 2$^{\text{nd}}$ class currents.
- On protons one can measure $|g_A/g_V|$ with completely different systematics compared to neutron beta decay.

- Weak capture of electrons would be complementary to the traditional neutrino scattering experiments and less resource intensive.

- Will help launch a new program to measure the charge changing weak current. The next reaction to attempt $e + p \rightarrow \Lambda + \nu$ (cross section 1/25 of capture cross section on p)