Study of light nuclei by polarization observables in electron scattering

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Guildford, 6 Sep 2019
Unpolarized electron scattering

\[ Q^2 = \vec{q}^2 - \omega^2 \]

\[ \vec{q} = \vec{p}_e - \vec{p}'_e \]

\[ \omega = \vec{E}_e - \vec{E}'_e \]

\[ \vec{p}_m = \vec{q} - \vec{p}_x \]

\[ \frac{d\sigma}{dE_e' d\Omega_e' dE_x d\Omega_x} = \sigma_0 [\nu_{LL} R_L + \nu_{TT} R_T + \nu_{LT} R_{LT} + \nu_{TT} R_{TT}] \]
Electron scattering with beam and target polarization

\[ A = \frac{\sigma(h_+, \vec{S}) - \sigma(h_-, \vec{S})}{\sigma(h_+, \vec{S}) + \sigma(h_-, \vec{S})} \propto \nu_{T'}R_{T'} + \nu_{LT'}R_{LT'} \]
Electron scattering with beam and recoil polarization

\[ P'_z = P'_\ell \propto \nu_{LT}' R_{LT}' + \nu_{TT}' R_{TT}' \]
\[ P_n \propto \nu_L R_L^n + \nu_T R_T^n + \nu_{LT} R_{LT}^n + \nu_{TT} R_{TT}^n \]
\[ P'_x = P'_t \propto \nu_{LT}' R_{LT}' + \nu_{TT}' R_{TT}' \]
Experiments covered in this talk

\(^3\text{He}\)

- JLab E05–102
  Double-spin asymmetries in quasi-elastic \(^3\text{He}(\vec{e}, e'd)p\)
  \(^3\text{He}(\vec{e}, e'p)d\)
  \(^3\text{He}(\vec{e}, e'p)pn\)

- JLab E05–015
  Target single-spin asymmetry in quasi-elastic \(^3\text{He}^\uparrow(e, e')\)

- JLab E08–005
  Target single-spin asymmetry in quasi-elastic \(^3\text{He}(\vec{e}, e'n)\)
  Double-spin asymmetries in quasi-elastic \(^3\text{He}(\vec{e}, e'n)\)

- MAMI (Mainz) Project ‘N’
  *Triple*-polarized \(^3\text{He}(\vec{e}, e'\vec{p})\)

\(^2\text{H and } ^{12}\text{C}\)

- MAMI (Mainz)
  Single-spin asymmetries in \(^{12}\text{C}(e'^\uparrow, e')\)

- MAMI (Mainz + TAU) joint recoil-polarimetry effort
  Double-spin asymmetries in \(^2\text{H}(\vec{e}, e'\vec{p})\) and \(^{12}\text{C}(\vec{e}, e'\vec{p})\)
Physics motivation for studying processes on $^3$He

- Knowledge of ground-state structure of $^3$He needed to extract information on the neutron from $^3$He($\vec{e}, \vec{e}'X$) or $^3$He($\vec{e}, \vec{e}'$).
  Examples: $G^n_E$, $G^n_M$, $A^1_1$, $g^1_1$, $g^2_2$, GDH.

- Complications: protons in $^3$He partly polarized due to presence of $S'$- and $D$-state components.

- Addressing differences in $\sqrt{\langle r^2 \rangle}$ ($^3$H, $^3$He).

- Understanding (iso)spin dependence of reaction mechanisms (MEC, IC).

- Understanding role of $D$ and $S'$ states is one of key issues in "Standard Model" of few-body theory.

- Persistent discrepancies among theories regarding double-polarization observables most sensitive to $^3$He ground-state structure.
Polarized $^3$He: it is easy to draw the cartoon ...

- $S$: spatially symmetric
  $\approx 90\%$ of spin-averaged WF; “polarized neutron”
- $D$: generated by tensor part of NN force, $\approx 8.5\%$
- $S'$: mixed symmetry component; (spin-isospin)-space correlations, $\approx 1.5\%$. $P_{S'} \approx E_p^{-2.1}$
- $P_{\text{eff}} \approx +0.86$, $P_{\text{eff}} \approx -0.03$

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Schiavilla++ PRC 58 (1998) 1263
TM = Tucson-Melbourne $\pi$-$\pi$ exchange 3NF
UIX = Urbana 3NF
... supported e. g. by data on $^3\text{He}(\vec{e}, \vec{e'})d/pn$ ...

- quasi-elastic ($Q^2 = 0.31$, $\omega = 135$, $q = 570$)
- 3NF, MEC negligible, FSI small in 2bbu, large in 3bbu

\[ A_{pd} \]
\[ A_1 \]
\[ A_2 \]

\begin{itemize}
  \item 2bbu
    \[ A_{\text{PWIA}} \approx A_{\text{PWIA+FSI}} \]
    $\parallel$ kinematics + small $p_d$
    $\Rightarrow$ polarized p target, $P_p \approx -\frac{1}{3}P_{\text{He}}$
  \item 3bbu
    \[ A_{\text{PWIA}} \approx 0 \ (p \uparrow p \downarrow) \]
    $A_{\text{PWIA+FSI}}$ large & negative
    not a polarized p target
\end{itemize}

PRC \textbf{72} (2005) 054005, EPJA \textbf{25} (2005) 177
... and which has a nice analogue in the deuteron ...

\[ \tilde{d}(\tilde{e}, e^'p) \]

\[ \sigma = \sigma_0 \left( 1 + hP_1^d A_{ed}^V \right) \]

\[ P_{2}^P = \sqrt{\frac{2}{3}} \left( P_S - \frac{1}{2} P_D \right) P_1^d \]

Passchier++ PRL 82 (1999) 4988
Passchier++ PRL 88 (2002) 102302
... but the true ground state of $^3$He is like lace

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<th>Channel number</th>
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Blankleider, Woloshyn PRC 29 (1984) 538
The E05–102 and E08–005 experiments at JLab

- **Benchmark measurement** of $A'_x$ and $A'_z$ asymmetries in $^3\text{He}(\bar{e}, e'd)$, $^3\text{He}(\bar{e}, e'p)$, and $^3\text{He}(\bar{e}, e'n)$.

- **Better understanding of ground-state spin structure of polarized $^3\text{He}$** — $S$, $S'$, $D$ wave-function components. Improve knowledge of $^3\text{He}$ rather than using it as an effective neutron target. **Direct consequences for all polarized $^3\text{He}$ experiments.**

- Distinct manifestations of $S$, $D$, $S'$ with changing $p_{\text{miss}}$ in (e, e'\{p/d/n\}).

- Data at (almost) identical $Q^2$ for $(\bar{e}, e'd)$, $(\bar{e}, e'p)$, and $(\bar{e}, e'n)$ simultaneously over a broad range of $p_{\text{miss}}$ poses **strong constraints on state-of-the-art calculations.**
What is so special about $^3\text{He}(e, e'd)$ and $^3\bar{\text{He}}(\bar{e}, e'd)$?

**Unique isoscalar-isovector interference in $(e, e'd)$**

Tripp++ PRL 76 (1996) 885

**in $(e, e'p)$ the $D/S'$ effects seen only at high $p_{miss}$**

Laget PLB 276 (1992) 398
Exploiting state-of-the-art calculations

**Bochum/Krakow** (full Faddeev)
- AV18 NN-potential (+ Urbana IX 3NF, work in progress)
- Complete treatment of FSI, MEC

**Hannover/Lisbon** (full Faddeev)
- CC extension and refit of CD-Bonn NN-potential
- Includes FSI, MEC
- $\Delta$ as active degree-of-freedom providing effective 3NF and 2-body currents
- Coulomb interaction for outgoing charged baryons

**Pisa**
- AV18 + Urbana IX (or IL7)
- Inclusion of FSI by means of the variational PHH expansion and MEC
- Not Faddeev, but accuracy completely equivalent to it

**Trento**
- Coming up
Basic machinery: Faddeev calculations

Nuclear transition current for breakup of $^3\text{He}$: \[ J^\mu = \langle \Psi_f | \hat{O}^\mu | \Psi_{^3\text{He}}(\theta^*, \phi^*) \rangle \]

Photon absorption operator: \[ \hat{O}^\mu = \sum_{i=1}^{3} \left[ \hat{J}_{\text{SN}}(i) + \hat{J}_{\text{MEC}}(i) \right] \]

Final-state interactions (auxiliary states): \[ \langle \Psi_f | \hat{O}^\mu | \Psi_{^3\text{He}}(\theta^*, \phi^*) \rangle \rightarrow \langle \Psi_f | U_f^\mu \rangle \]

Golak++ Phys Rep 415 (2005) 89
Indication of $D$ and $S'$ components in $^3\text{He}(\bar{e}, e')$

Inclusive $A_T' (= A_Z)$ and $A_{LT}' (= A_x)$

- $A_{LT}'$ receives contributions from ingredients which go beyond most simplistic picture [$F_1^{(n)} = 0$]
- sensitive to replacement PWIA(PS) → PWIA.
- $S'$- and $D$-state pieces contribute very strongly to $A_{LT}'$

Ishikawa++ PRC 57 (1998) 39
$^3\text{He}(\vec{e}, e'd)$ vs. $^3\text{He}(\vec{e}, e'p)$

- **KRAKOW/BOCHUM CALC.**

- $S'$ state relevant at small $p_r$ (= $p_{\text{miss}}$)
- $D$ state governs variation of $A_z$ at large $p_r$
Cannot disentangle effects of WF components \((S, D, S')\) by measurement of cross-sections alone: need polarization observables

\[
\frac{d\sigma(h, \vec{S})}{d\Omega_e dE_e d\Omega_d dp_d} = \frac{d\sigma_0}{\ldots} \left[ 1 + \vec{S} \cdot \vec{A}^0 + h(A_e + \vec{S} \cdot \vec{A}) \right]
\]

\[
A(\theta^*, \phi^*) = \vec{S}(\theta^*, \phi^*) \cdot \vec{A} = \frac{[d\sigma_{++} + d\sigma_{--}] - [d\sigma_{+-} + d\sigma_{-+}]}{[d\sigma_{++} + d\sigma_{--}] + [d\sigma_{+-} + d\sigma_{-+}]}
\]

Access to [effects of] small WF components \((D, S')\)

E05–102: simultaneous measurement of all break-up channels:
\(3\text{He}(\vec{e}, e'\text{d})\text{p}, 3\text{He}(\vec{e}, e'\text{p})\text{d}, 3\text{He}(\vec{e}, e'\text{p})\text{pn} \ldots\) and also \(3\text{He}(\vec{e}, e'\text{n})\text{pp}\)
Experimental Setup

**All Channels**

- **Hall A**
  - **BigBite**
  - **Left HRS**
  - **Right HRS**


\[
E_e = 2.425 \text{ GeV} \quad \theta_e = 12.5^\circ \quad \theta_{d,p} = 75^\circ \quad Q^2 = 0.25 \text{ GeV}^2
\]

\[
\ldots \quad \theta_e = 14.5^\circ \quad \theta_{d,p} = 82^\circ \quad Q^2 = 0.35 \text{ GeV}^2
\]

\[
\ldots \quad \theta_e = 17^\circ \quad \theta_n = 62.5^\circ \quad Q^2 = 0.46 \text{ GeV}^2
\]

\[
E_e = 3.605 \text{ GeV} \quad \theta_e = 17^\circ \quad \theta_n = 54^\circ \quad Q^2 = 0.96 \text{ GeV}^2
\]

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Results on $^3$He(\(\bar{e}, e'd\))p

- Asymmetries are small (typically a few %), thus hard to reproduce theoretically (cancellations)
- Good agreement on the transverse asymmetry (71°)
- Worse for the longitudinal asymmetry (160°) ... but it improves when \(\omega\) is restricted to QE peak
- Discrepancy due to
  — incomplete treatment of FSI (?)
  — unaccounted for 3NF (?)
  — underestimated \(S'\) component of g.s. WF (?)

\[ \begin{align*}
    &|E05-102 (JLab 2009) \rangle \\
    &\text{same, } \omega < 140 \text{ MeV} \\
    &\text{Hannover/Lisbon} \\
    &\text{same, } \omega < 140 \text{ MeV} \\
    &\text{Bochum/Krakow} \\
    &\text{Pisa}
\end{align*} \]

Mihovilović++ PRL 113 (2014) 232505
Results on $^3\text{He}(\bar{e}, e'd)p$ \(\omega\)-dependence

\[ A(71^\circ, 0^\circ) \]

\[ A(160^\circ, 0^\circ) \]

Mihovilović++ PRL 113 (2014) 232505
Attempt to evaluate $P_Z$ and $P_{ZZ}$

$^3\text{He}(\vec{e}, e^\prime \vec{d})p$

- Assume $^3\text{He}(\vec{e}, e^\prime \vec{d})p$ at low $p_{\text{miss}}$ is like elastic scattering off polarized d
- Use $A_x(^3\text{He}), A_z(^3\text{He})$ as if they were $A_x^{(\text{ed})}, A_z^{(\text{ed})}$ with appropriate deuteron FFs, and extract $P_Z$ and $P_{ZZ}$
- Toy model $|^3\text{He}\rangle = |d\rangle + |p\rangle$
- Spin decomposition $|^3\text{He}\rangle = \frac{1}{\sqrt{2}} |\frac{1}{2}, \frac{1}{2}\rangle + \frac{1}{\sqrt{3}} |1, 1\rangle + \frac{1}{\sqrt{3}} |1, 0\rangle + \frac{1}{\sqrt{2}} |\frac{1}{2}, -\frac{1}{2}\rangle$
gives $P_Z = \langle I_z \rangle_{^3\text{He}} = \frac{2}{3}, P_{ZZ} = \langle 3I_z^2 - 2 \rangle_{^3\text{He}} = 0$

\[ \text{PRL 113 (2014) 232505} \]
Results on $^3\text{He}(\bar{e}, e'p)$

$p_m$-dependence

- No 2bbu/3bbu separation possible; rely on MC to disentangle $A_{2\text{bbu}}/A_{3\text{bbu}}$
  - Unpolarized 2bbu and 3bbu XS as well as $A_{2\text{bbu}}$ well established
- Only qualitative agreement of data with theory. Issues:
  - Cancellation of 2bbu and 3bbu contributions
  - 3bbu asymmetry dominant — possibly too much so
  - Pertinent ingredients: Coulomb, RC, FSI, 3NF (?)
Simple interpretation of \( ^3\text{He}(\bar{e}, e'p) \)

- Valid for \( p_m \approx 0 \)
- Assume PWIA
- \( S \)-state dominates
- Missing energy: 
  \( E_m = \omega - T_p - T_d \)
- Low-\( E_m \) region dominated by 2bbu: \( A \approx A(\bar{e} - \bar{p} \text{ elastic}) \)
- High-\( E_m \) region dominated by 3bbu: \( A \approx 0 \)
- Non-zero asymmetry in 3bbu probably caused by FSI
Extraction of 2bbu and 3bbu asymmetries in $^3\text{He}(e, e'p)$
Message on 2bbu and 3bbu asymmetries in $^{3}\text{He}(\bar{e}, e^{'p})$

$A(p_m \approx 0)/A(\vec{e}\vec{p})$

$2\text{bbu}$

$3\text{bbu}$

Mihovilović++ PLB 788 (2019) 117
More $^3\text{He}(e, e'd)$ and $^3\text{He}(e, e'p)$ ...

- High-statistics data also available at $Q^2 \approx 0.35 \text{ GeV}^2$ in all channels

- Opportunity to study $Q^2$-dependence of asymmetries
- Theoretical calculations pending
Single-spin asymmetry in QE $^3\text{He} \uparrow (e, e')$

**Motivation**

$$A_y = \frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \propto \vec{s} \cdot (\vec{k} \times \vec{k}')$$

- $A_y = 0$ in Born approximation ($T$-invariance)
- $A_y \neq 0$ indicative of $2\gamma$ effects, $\propto \text{Im}\{T_{1\gamma}T_{2\gamma}^*\}$ interference; relevant for $G_E^p/G_M^p$, GPDs
- no measurement of comparable precision on neutron
Single-spin asymmetry in QE $^3\text{He}↑(e,e')$

$$A_y(-\theta) = -A_y(\theta)$$

| $E_0$ [GeV] | $E'$ [GeV] | $\theta_{lab}$ [Deg] | $Q^2$ [GeV$^2$] | $|q|$ [GeV] | $\theta_q$ [Deg] |
|-------------|-------------|----------------------|-----------------|-------------|-----------------|
| 1.25        | 1.22        | 17                   | 0.13            | 0.359       | 71              |
| 2.43        | 2.18        | 17                   | 0.46            | 0.681       | 62              |
| 3.61        | 3.09        | 17                   | 0.98            | 0.988       | 54              |

Figure & table courtesy of Yawei Zhang, Rutgers
Single-spin asymmetry in QE $^3\text{He}^\uparrow(e, e')$  

- First measurement of $A_y^n$ (extracted from transversely polarized $A_{3\text{He}}$)
- Uncertainty several times better than previous proton data
- Asymmetry clearly non-zero and negative

Zhang++ PRL 115 (2015) 172502
Single-spin asymmetries in $^{12}\text{C}(e^\uparrow, e')$  

- Several calculations for $A_\gamma$ in p(e$^\uparrow$, e), very few on nuclei
- Generalization of forward inclusive model to nuclear targets:

$$A_\gamma \sim C_0 \log \left( \frac{Q^2}{m_e^2 c^2} \right) \frac{F_{\text{Compton}}(Q^2)}{F_{\text{charge}}(Q^2)}$$
Single-spin asymmetries in QE $^3$He($\bar{e}$, e$'$n)

- Ideal probe of FSI and MEC
- Should be zero in PWIA and should die out at high $Q^2$
- Difficult calculations at high $Q^2$
Single-spin asymmetries in QE $^3\text{He}(\vec{e}, e'\text{n})$

![Graph showing single-spin asymmetries](image)

$\Rightarrow$ PWIA good enough for high-$Q^2$ experiments at JLab 12 GeV!
Double-spin asymmetries in QE $^3\text{He}(\bar{e}, e'n)$

$Q^2 \approx 0.5$

$Q^2 \approx 0.95$

- Calculations?

*** PRELIMINARY *** Figures courtesy of Elena Long, UNH
Triple-polarized $^3\text{He}(\vec{e}, e'\vec{p})$

- PWIA: $\sigma_L$, $\sigma_T$, $\sigma_{T'}$ yield spin-dependent momentum distribution
- FSI, MEC preclude direct access except at $p_d \lesssim 2\text{ fm}^{-1}$
- Rich interplay $\triangleright$ **final-state symmetrization**: large effect in $C_3$
  $\triangleright$ **FSI**: largest in $C_2$
  $\triangleright$ **MEC**: most prominent in $C_1$

![Diagram showing $C_1$, $C_2$, and $C_3$ with vectors and arrows indicating $\vec{p}_d$, $\vec{p}_N$, and $\vec{Q}$ relationships.]

Fig. courtesy of M. Distler, JGU Mainz
Triple-polarized $^3\text{He}(\vec{e}, e'\vec{p})$

- Spin-dependent momentum distributions of $\vec{p}\vec{d}$ clusters in polarized $^3\text{He}$
  
  Golak++ PRC 65 (2002) 064004

$$N_{\mu} = \langle \Psi_{pd}^{(-)} M_d m | \hat{j}_{\mu}(\vec{q}) | \Psi M \rangle$$

$$y \left( M = \frac{1}{2}, M_d = 0, m = \frac{1}{2} \right) \propto \left| N_{-1}^{\text{spin PWIA}} \left( \frac{1}{2}, 0, -\frac{1}{2} \right) \right|^2$$

$$y \left( M = \frac{1}{2}, M_d = 1, m = -\frac{1}{2} \right) \propto \left| N_{+1}^{\text{spin PWIA}} \left( \frac{1}{2}, 1, +\frac{1}{2} \right) \right|^2$$

$$A = \frac{y(1/2, 0, 1/2) - y(1/2, 1, -1/2)}{y(1/2, 0, 1/2) + y(1/2, 1, -1/2)}$$

$$\sigma_L \propto |N_0|^2$$

$$\sigma_T \propto |N_{+1}|^2 + |N_{-1}|^2$$

$$\sigma_{T'} \propto |N_{+1}|^2 - |N_{-1}|^2$$
Form-factor modification in medium

\[ A \frac{X(\vec{e}, e' \vec{p})}{A^{-1} X} \]

- Observable \( Q^2 \)– and \( \rho \)-dependent effects predicted by various models
- Exploit polarization-transfer technique in \( \approx \) QE proton knock-out:

\[
\frac{G_E^p}{G_M^p} = -\frac{P'_x E_e + E'_e}{P'_z 2M_p} \tan \frac{\theta_e}{2} \quad \Rightarrow \quad \left( \frac{P'_x}{P'_z} \right)_A / \left( \frac{P'_x}{P'_z} \right)_p
\]
Form-factor modification: calculations for $^{12}$C

- Different shells $\Leftrightarrow$ different local densities // Ron++ PRC 87 (2013) 028202
- Disentangle via $E_m$ cuts
- Need to explore $\pm p_m$ and $\pm \nu$ regions (no a priori symmetry)
Form-factor modification in medium: “universality”

- Virtuality: $\nu = p^2 - m_p^2$ or, better, $\nu = (m_A - \sqrt{m_A^2 - (P_m^2 + P_p^2)})^2 - P_m^2 - m_p^2$
- Relevant variable: $\nu$. No $A$-dependence ("universality")
- Largest effects due to FSI and WF of proton in nucleus, not due to FF modification — hard to disentangle $\Rightarrow$ new JLab proposal at higher $Q^2$
Preliminary results on $^{12}\text{C}$ $P'_x$ and $P'_z$ (not ratios)

Figs courtesy of T. Kolar
Any Questions?
Acceptance-averaging of $^3\text{He}(\bar{e}, e'p)$ and $^3\text{He}(\bar{e}, e'd)p$

- Calculations available only on a discrete kinematic mesh acceptance averaging needed
- Decision: Manipulate calculations — not data
- Asymmetry for each $(E', \theta_e)$ at each $(p_m, \theta_{xq})$ determined by calculating the weighted mean of the nearest points
- Weak dependence on cell size
- Data at $Q^2 = 0.25$ and 0.35 GeV$^2$, only first set published:
  PRL 113 (2014) 232505
“Fine-tuning” the calculations for $^3\text{He}(\bar{e}, e^{'p})$

- **Rescale 3bbu calculations** to roughly match magnitude and zero-crossing of $A$
  
  - $A = \frac{\sigma_2 A_2 + \sigma_3 A_3}{\sigma_2 + \sigma_3} = \frac{A_2 + A_3 R_{32}}{1 + R_{32}}$
  
  - $\approx$ 30–40% reduction needed
Extraction of $A^n_\gamma$ from $A^{3\text{He}}_{\gamma}$ — effective polarization approximation:

$$A^{3\text{He}}_{\gamma} = P_n f_n A^n_\gamma + P_p (1 - f_n) A^p_\gamma$$

$$f_n = \frac{\sigma^n}{\sigma^{3\text{He}}} = \frac{\sigma^n}{2\sigma^p + \sigma^n}$$

$$P_n = 0.86 \pm \cdots \quad P_p = -0.028 \pm \cdots$$

high $Q^2$: $f_n$ computed with Kelly’s parameterization of nucleon FFs

low $Q^2$: theoretical estimate (due to FSI): $f_n = 0.042$ (A. Deltuva)

$A^p_\gamma$ computed by Afanasev et al.