Spectator Tagging - Quo Vadis?

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Overview

• Neutron Structure and Binding Effects (C.K.)
• Spectator Tagging as a Tool
• The “Deeps” Experiment with CLAS
• The “BoNuS” Experiment with CLAS (C.K.)
• New Experiments with the “BoNuS” RTPC (EG6 with a $^{4}\text{He}$ target)
• The Data Mining Initiative
• The 11 GeV Future of Spectator Tagging
Structure Functions and Moments

\[ \frac{d\sigma}{d\Omega dE'} = \sigma_{\text{Mott}} \left( \frac{F_2(x)}{\nu} + 2\tan^2\frac{\theta_e}{2} \frac{F_1(x)}{M} \right) ; \quad F_2(x,Q^2) = x \sum_{f=\text{up,down,...}} z_f^2 \left( q_f(x,Q^2) + \bar{q}_f(x,Q^2) \right) \]

- \( q_{\text{down}}/q_{\text{up}}(x\rightarrow1) \) is a crucial test of valence quark models
  - SU(6) breaking, pQCD,…

- Precise PDFs at large \( x \) needed as input for LHC, neutrino experiments…
  - Large \( x \), medium \( Q^2 \) evolves to medium \( x \), large \( Q^2 \)

- Moments can be directly compared with OPE (twist expansion), Lattice QCD and Sum Rules
  - All higher moments are weighted towards large \( x \)

\[ M_n^{\text{CN}}(Q^2) = \int_0^\infty dx x^{(n-2)} F_2(x,Q^2) = \sum_{\tau=2k}^{\infty} E_{n\tau}(\mu,Q^2) O_{n\tau}(\mu) \left( \frac{\mu^2}{Q^2} \right)^{\frac{1}{2}(\tau-2)} + \text{TM corr.} \]
Structure Functions and Resonances

- Precise structure functions in Resonance Region constrain nucleon models
  [Separate resonant from non-resonant background; isospin decomposition]

- Needed as input for spin structure function data, radiative corrections,…

- Compare with DIS structure functions to test duality
Large $x$ - Large Nuclear Effects

- Even simple “Fermi Smearing” leads to significant dependence on D wave function
- Different models for off-shell and “EMC” effects lead to large additional variations
- Contributions from MEC, $\Delta(1232)$ and “exotic” degrees of freedom unknown
- FSI?
Present Knowledge of d/u ($x \rightarrow 1$)

\[ \frac{F_{2n}}{F_{2p}} \approx \frac{1 + 4d/u}{4 + d/u} \Rightarrow \]

\[ \frac{d}{u} \approx \frac{4F_{2n}/F_{2p} - 1}{4 - F_{2n}/F_{2p}} \]

\[ F_{2n}/F_{2p} = F_{2d}/F_{2p} - 1 \]

• Limited by “Nuclear Binding Uncertainties”
Bound Neutron Structure Functions -
2 Questions:

1) How can we explore the structure of the neutron if all we have are neutrons bound in nuclei?
   • In many cases, a neutron bound in deuterium can be considered “nearly free”.
   • BUT: For certain kinematics (large $x > 0.5$, resonance region $W < 2$) the high-momentum (short-distance tail) of the deuteron wave function plays a large role and might distort the result.

2) Can we learn something about what happens to a nucleon if it is part of a short-distance pair?
   • Many ideas: Off-shell modifications of on-shell structure functions, color delocalization, suppression of point-like components, $\Delta\Delta$ components, extra mesons or 6-quark bags
   • Fundamental question about QCD in bound hadron systems that we haven’t understood yet. Relevant for QCD phase diagram (high baryon density, neutron stars, color superconductivity?)
Our Tool: “Spectator Tagging”

\[ p_n = (M_D - E_S, -\vec{p}_S); \]
\[ \alpha_n = 2 - \alpha_S \]
\[ p_S = (E_S, \vec{p}_S); \quad \alpha_S = \frac{E_S - \vec{p}_S \cdot \vec{q}}{M_D / 2} \]

\[ W^2 = M^2 + 2M\nu - Q^2 \]

\[ W^* = (p_n + q)^2 = p_{n\mu} p_{n\mu} + 2(M_D - E_S)\nu - \vec{p}_n \cdot \vec{q} - Q^2 \]
\[ \approx M^* + 2M\nu(2 - \alpha_S) - Q^2 \]

\[ x^* = \frac{Q^2}{2p_{n\mu} q_{\mu}} \approx \frac{Q^2}{2M\nu(2 - \alpha_S)} \]

\[ E = 4.223 \text{ GeV} \]
\[ \langle Q^2 \rangle = 1.19 \text{ (GeV/c)}^2 \]
Modifications to Simple Spectator Picture

Final State Interactions

Binding Effects

High spectator momenta (0.25 - 0.7 GeV/c): “Deeps”
Results from “Deeps”: Momentum Distribution

Vertical axis: Number of events
Horizontal axis: Proton momenta from 250 to 700 MeV/c

**Left: Angular range > 107.5°**
**Right: Angular range 72.5° - 107.5°**

3 different ranges in the final state mass W of the unobserved struck neutrons

PWIA model with “light cone”-wave function for deuterium
Deviations from free structure function:

*Off-shell Effects [should depend on $\alpha (p_s), x, Q^2]$*

\[ \frac{F_{2N}^{\text{eff}} (x = 0.6, Q^2, \alpha)}{F_{2N}^{\text{eff}} (x = 0.2, Q^2, \alpha)} \]

Modification of the off-shell scattering amplitude (Thomas, Melnitchouk et al.)

*Color delocalization*

Close et al.

*Suppression of “point-like configurations”*

Frankfurt, Strikman et al.

… plus 6-quark bags, $\Delta\Delta$, MEC…

“Off-shell” mass of the nucleon $M^*$

\[ p_T = 0 \quad Q^2 = 5 \text{ GeV}^2 \]

\[ 939 \text{ MeV} \quad 905 \text{ MeV} \quad 823 \text{ MeV} \quad 694 \text{ MeV} \]

\[ P_s = 0 \quad 0.09 \quad 0.17 \quad 0.25 \quad 0.32 \quad 0.39 \text{ GeV/c} \]
Results from “Deeps”: Ratio Method

Ratio =
\[
\frac{\sigma(x^* = 0.55, \alpha_s)}{\sigma(x^* = 0.25, \alpha_s)} (\text{bound n})
\]
\[
\frac{\sigma(x = 0.55)}{\sigma(x = 0.25)} (\text{free n})
\]

- Independent of deuteron WF, acceptance, kinematic factors
- Should be sensitive to off-shell effects at large x, but also influenced by FSI and target fragmentation
- Fixed $p_T = 0.3$ GeV/c - TOO LARGE!
Results from “Deeps”: Comparison w/ FSI model (CdA et al.)

\[ W^* = 1.25 \text{ GeV}, \ ps = 0.3 \text{ GeV/c} \]

\[ M^* = 0.84 \text{ GeV} \]

\[ Q^2 = 1.8 \text{ GeV}^2 \]

\[ W^* = 1.25 \text{ GeV}, \ ps = 0.39 \text{ GeV/c} \]

\[ M^* = 0.77 \text{ GeV} \]

\[ W^* = 1.25 \text{ GeV, } ps = 0.56 \text{ GeV/c} \]

\[ M^* = 0.54 \]

\[ W^* = 2 \text{ GeV, } ps = 0.56 \text{ GeV/c} \]

\[ M^* = 0.54 \]
Low Spectator Momenta - Nearly Free Neutrons?

The Experiment

BoNuS = Barely off-shell Nucleon Scattering

RTPC = Radial Time Projection Chamber
BoNuS RTPC

Gas
Electron
Multiplier

3 GEMs
Readout pads and electronics

7 atm \( D_2 \) gas

\( \frac{dE}{dx} \) from charge along track (particle ID)

Møller el.
\( e^- \) (to CLAS)

BoNuS in CLAS
RTPC Performance

e⁻ reconstructed in CLAS & RTPC

$\sigma = 8\text{mm}$

$\sigma = 1.4^\circ$

$\sigma = 4^\circ$

Particle ID (after gain calibration of each channel)

Out-of-time track suppression
Kinematic Coverage - 2.1, 4.2 & 5.3 GeV

Kinematics coverage, $D(e,e'\pi^-p)$, $E = 5.3$ GeV

VIPs
Preliminary Results from BoNuS

- Measured tagged n / inclusive d
- Corrected for e- acceptance and normalized to “known” ratio at high $W$
- Multiplied with known $F_{2d}$ to get bottom row.
Preliminary Results from BoNuS (ii)

“Free” neutron structure function compared with a model by P. Bosted
Preliminary Results from BoNuS (iii)

- model, $Q^2$ between 1.10 & 2.23 (GeV/c)$^2$
- model, $Q^2$ between 2.23 & 4.52 (GeV/c)$^2$
- experiment, $Q^2$ between 1.10 & 2.23 (GeV/c)$^2$
- experiment, $Q^2$ between 2.23 & 4.52 (GeV/c)$^2$

Cut on $W > 1.8$

5 GeV Data
Preliminary Results from BoNuS (iv)

Testing the Spectator Assumption - dependence on $p_s$

- Data have radiative elastic tail subtracted
- Simulation uses simple spectator model, radiative effects, full model of RTPC and CLAS

<table>
<thead>
<tr>
<th>$W^*$ [GeV]</th>
<th>80 MeV/c</th>
<th>100 MeV/c</th>
<th>120 MeV/c</th>
<th>140 MeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio Data/Model</td>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
<td><img src="image4.png" alt="Graph" /></td>
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</tr>
<tr>
<td>Extracted “effective structure function” $F_{2n}$</td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
<td><img src="image7.png" alt="Graph" /></td>
<td><img src="image8.png" alt="Graph" /></td>
</tr>
</tbody>
</table>
Preliminary Results from BoNuS (v)

So far, no strong deviations from naïve PWIA spectator picture at lower spectator momenta.

Possible indication of $\theta$-dependence at higher $p_s$.

Have systematics for a wide range in $Q^2$, $W^*$ and beam energies.

$W^* = 1.73$ GeV
$Q^2 = 1.66$ (GeV/c)$^2$
Deeply Virtual Compton Scattering from Helium: $^4\text{He}(e,e'\gamma\,^4\text{He})$

Search for exotic mesons in $\gamma^* + ^4\text{He} \rightarrow M + ^4\text{He} \rightarrow 4\,\gamma$’s + $^4\text{He}$

Slightly modified (improved!) RTPC

Significantly increased data rate

Ran in Fall 2009

Can be used to extract data on spectator $^3\text{He}$ and compare to spectator $^3\text{H}$ (struck proton with known structure function!)
2nd RTPC Experiment - EG6

Detector calibration, 1st step analysis under way
1st results maybe in 1 year
CLAS data mining

• Joint effort of a large group of people (many of them here) to re-analyze existing nuclear target data from CLAS
• Proposal to DOE for funding (mostly for a dedicated postdoc) - presently “in limbo”
• Relevant for spectator physics:
  – E6 data, d(e,e’p_s)X : extend Q^2 range, lower p momentum threshold
  – E6 data: Look for d(e,e’Δ_s)Δ and other “exotic” final states
  – EG1/EG4/EG1-DVCS: study ̃d(̃e,e’p)n vs. missing momentum to learn more about spin effects and FSI
• Discussion Friday afternoon
Plans for Jefferson Lab at 11-12 GeV

- CLAS12 will have central detector for medium-low momentum large angle particles
- Can be replaced by “BoNuS” type RTPC for much lower spectator momenta
- Can insert polarized target inside Central Detector - study tagged pol. SFs? (Polarized EMC effect LOI [Brooks] approved by PAC35)
Expected Results -

**Neutron/Proton structure function**

- **Data taking of 35 days on D\textsubscript{2} and 5 days on H\textsubscript{2} with \( \mathcal{L} = 2 \cdot 10^{34} \) cm\(^{-2}\) sec\(^{-1}\)**

**BoNuS12**

**E12-06-113**

- **DIS region with**
  - \( Q^2 > 1 \text{ GeV}^2/\text{c}^2 \)
  - \( W^* > 2 \text{ GeV} \)
  - \( p_s > 70 \text{ MeV}/\text{c} \)
  - \( -10^\circ < \theta_{pq} < 170^\circ \)

- **Dark Symbols:** \( W^* > 2 \text{ GeV} \Rightarrow x^* \) up to 0.8, (bin centered \( x^* = 0.76 \))
- **Open Symbols:** "Relaxed cut" \( W^* > 1.8 \text{ GeV} \) (\( x^* \) up to 0.83)

\[
F_{2n} / F_{2p}
\]

\[
\frac{d}{u}
\]

\[
\text{SU}(6) \rightarrow
\]

\[
d/u = 1/5
\]

\[
d/u = 0
\]
Expected Results - Deeps12

$D(e,e'p_s)$

LOI 12-07-102

- Significantly increase kinematic coverage in $x$, $Q^2$ while remaining in DIS and “backward spectator” kinematics
- Can augment $\alpha_s = 1$, small $p_T$ region with data from BoNuS12 - can get closer to “ideal” kinematics
- Possibly combination with n detector for a comparison of $d(e,e'p_s)X$ with $d(e,e'n_s)X$
- Requires a new, full proposal and significant simulation work
- EG6 will also be continued at higher energy - two LOIs (Milner, Hafidi) approved by most recent PAC35

\[ \theta_{pq} > 110^\circ \quad Q^2 > 1.5, \ W > 2 \]
Conclusion - Status of Spectator Experiments

- Lots of data with coincident spectator detection already exist, many have been (partially) analyzed
  - FSI seems very important in perpendicular and forward kinematics
  - Simple spectator picture with LC wave functions seems to work reasonably in some kinematic regions
  - Possible modifications of internal nucleon structure (dependent on spectator momentum) still an open question
- New data from EG6 will extend this study to $^4$He target
- Data mining initiative will unlock much more information from all nuclear data taken with CLAS
- Lots more exciting experiments after JLab energy upgrade!
- Requires theory-experiment interaction: Agree on definition of “reduced cross section”; need predictions of this cross section including FSI over large kinematic range (not only for $p_T = 0$ ;-
- ULTIMATE GOAL: EIC - can smoothly map out $p_{\text{spect.}}$ from 0 to 1 GeV/c
Happy Birthday (belated), Mark