Photodisintegration of the deuteron, and 3He

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Exclusive Reactions at High Momentum Transfer
Jefferson Lab
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Motivation / Introduction

- 2007 Long Range Plan: “We recommend completion of the 12 GeV Upgrade at Jefferson Lab. The Upgrade will enable new insights into the structure of the nucleon, the transition between the hadronic and quark/gluon descriptions of nuclei, and the nature of confinement.”
Are nucleons made up of hadrons or of quarks and gluons?
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- Yes, both.
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- Yes, both.
- The issue is under what conditions we are better off with a theory based on hadrons vs. a theory based on quarks and gluons.
Hadrons rule!

- Generally, exclusive reactions are well understood with hadronic theories based on the NN and photopion nucleon interactions, etc.:
  - $A(e,e')$ elastic scattering
  - $A(e,e'p)$ reactions, particularly quasifree kinematics
- Whatever the quark effects are, they appear to be effectively incorporated into the hadronic theory
Hadrons rule!

- $d(e,e')d$ elastic scattering described well as $A(Q)$ falls $>8$ orders of magnitude
Elastic ed $T_{20}$ Data

- Improved low $Q$ data were measured at Bates BLAST. (Figure from Tsentalovich, Nucleon05.)
- Data well described by several theories.
Quarks and gluons

- Some reactions are simply understood with quarks and gluons, or at least we have no good hadronic theory for them:
  - $A(e,e')$ deep inelastic scattering
  - High $E_{\gamma}$ photodisintegration reactions
- Both these reactions probe nuclei at high $Q^2$ (or $-t$) and high $W$
The Past
Hard Scattering Regime Experiments

- SLAC NE8, NE17
- JLab Hall C E89-012, E96-003
- Yerevan (Σ)
- JLab Hall A E89-019, E00-007 ($C_{x'}, p_y, C_{z'}$), E99-008
- JLab Hall B E93-017
- JLab Hall B: $^3$He [S. Strauch]
90° Excitation Functions

- Cross sections fall by a factor of 30,000 from 1 - 4 GeV, ~following ``expected'' quark scaling, \( \frac{d\sigma}{dt} \sim s^{11} \)
- Hadronic theories not satisfactory and not shown
- Most quark models normalized
The Quark Models

- **QGS**: Regge phenomenology to evaluate 3-quark exchange, justified by dominance of planar diagrams

- **RNA, HRM, TQC, CQM**: Photon absorbed and quarks exchanged; might be related to NN elastic scattering - all use hard scattering approximations
Onset of Scaling

- Scaling needs $p_T > 1.1 \text{ GeV/c}$
Some Observables in $d(\gamma,p)n$

- $d\sigma/d\Omega$, $\Sigma$, $T$, $C_{x'}$, $p_y$, $C_{z'}$.
HHC - Hadron Helicity
Conservation - leads to $\Sigma = -1$

Adamian et al. showed $\Sigma$ heads away from HHC, with increasing energy

Grishina et al. pointed out iso-vector (scalar) limit is $\Sigma = 1$ (-1)
Induced Polarization $p_y$

- Hadronic prediction, that $D_{13} + D_{15}$ leads to large resonance peak, falsified.
- HHC leads to $p_y = 0$, and $p_y$ vanishes above 1 GeV.
- HRM predicts $p_y$ small, $<0$.
Polarization Transfer

- Schwamb & Arenhövel prediction good at low energies
- $C_x$ small, but not vanishing, so no HHC
- Cannot rule out or strongly support HRM / QGS / approach to HHC
Recent / Future Present

- JLab E00-007: X Jiang et al., PRL 98, 182302 (2007)
  - Recoil polarization angular distribution at 2 GeV

- Novosibirsk $t_{2i}$ data: I Rachek et al., PRL 98, 182303 (2007)
  - Tensor polarizations up to ~600 MeV

- JLab E05-103: J Glister et al.
  - Ran July-Sep 2006
  - Angular distribution for recoil polarizations from 280 - 360 MeV

- JLab Hall B $^3$He($\gamma$,pp)n: S. Strauch et al. preliminary data, and Brodsky et al. theory article
- $E_\gamma \sim 2 \text{ GeV}$
- $C_z$ large at forward angles, like QGS + HR
- $C_x$ and $p_y$ cross 0 near $90^\circ$: in HR, if isovector photon dominance, these $\approx \phi_5$, which vanishes at $90^\circ$
- Perhaps similar to $\Sigma$?
Novosibirsk $t_{2i}$

- I Rachek et al., PRL 98, 182303 (2007)
- Calculations from Levchuk, Arenhovel, Schwamb
Hall A E05-103: J Glister et al.

- $E_\gamma \sim 280 - 360$ MeV
- Map out region in which calculations diverge from $p_\gamma$ data
- Determine $C_{x'}$ and $C_{z'}$ to further test breakdown
- Note that cross sections, $\Sigma$, ... are okay here
Hall A E05-103: J Glister et al.

- Near on-line preliminary results
- Calculations from Schwamb: original (solid) and latest (dash)
- Data from 20-110°, 280-360 MeV
\(^3\text{He} \text{ (pp) Disintegration}\)

- At low energy, \(\sigma(\gamma_{pp}) / \sigma(\gamma_{pn}) \sim 0.1\): pp dipole moment vanishes: JM Laget.
- Quark models predict larger ratio: slow 2\textsuperscript{nd} order or fast 1\textsuperscript{st} order phase transition?
$^3\text{He} \ (pp) \ \alpha_n$ Distribution

- Light cone momentum fraction, $\alpha = (E-p_z)/m$, is conserved:
  $\alpha_{\gamma} + \alpha_{\He} = 0 + 3 = \alpha_{p1} + \alpha_{p2} + \alpha_n$

- Soft FSI “do not” affect $\alpha$, so $\alpha_n$ reflects neutron spectator wave function

- RNA short range/broad, HRM long range/narrow

- Model-independent check of long vs short range dynamics
$^3\text{He (pp) Oscillations}$

- Prominent oscillations in pp cross section, as opposed to flatter pn cross section, reflected in oscillations in $\gamma_{pp}$, as opposed to flatter energy dependence in $\gamma_d$?

- To match $s$ and $t$, compare $60^\circ$ pp to $90^\circ$ $\gamma_{pp}$
$^3$He(γ,pp)n Measured!

- Hall B experiment, analyzed by S. Strauch, GWU (now SC)
- PRELIMINARY

\[ \begin{align*}
\gamma & \quad \theta_{cm} \\
p & \quad n \\
\text{pp c.m. frame} \end{align*} \]
$^3\text{He}(\gamma,pp)n$ Neutron Spectator?

- Is the neutron a spectator? Cut at 0.1 - 0.25 GeV/c
$^3\text{He}(\gamma,pp)n$ Cross Sections

- **Red**: "γpp→pp", symmetric about 90°
- **Blue**: γd→pn x $\frac{1}{4}$, asymmetric about 90°
- **Cross sections for γpp like back-angle γd**, near 1 GeV
$^3\text{He}(\gamma,pp)n$ Cross Sections

- Theory has 100 MeV/c cut
- Data small compared to $\gamma d$, 10 – 25 % as large
- Scaling of $\sigma$ by $E_\gamma \sim 1.3$ GeV in $\gamma d$, $p_\gamma$ vanished by $\sim 1$ GeV, $C'_{x',z'}$ slowly vanishing $\Rightarrow$ I would expect a transition by 1 or 1.3 GeV
- Hint of a phase transition starting at 1.4 GeV -or- perhaps QGS or TQC is the right approach?
$^3\text{He}(\gamma,pp)n\ \alpha_n$ Distribution

- Hard distribution from short-range physics, evidence for TQC?
- 1 GeV/c nucleons in c.m. are too low in energy: lots of rescattering broadens distribution
Future Perfect

- Hall A E03-101: $^3\text{He}(\gamma,pp)n$
Is pp disintegration much smaller than, about equal to, or much larger than deuteron disintegration?

Is there a sudden change in the ratio (phase transition)?

Is the process long or short range ($\alpha_n$)?

Scheduled to start in $\sim 2 \frac{1}{2}$ weeks
Future Perfect

- Hall A E03-101: $^3$He(γ,pp)n
- The results of the $^3$He experiment that is about to start will clearly influence any future work, but we can examine what is possible:
  - Study issue of iso-scalar vs iso-vector by measuring $\Sigma$ asymmetry in Hall B up to ~3 GeV
  - If SRC are determined to be underlying physics, expand study to selected heavier targets as part of the SRC program
  - If there is a “phase transition” in $^3$He/d, study it
  - Continue to higher energies with 12 GeV upgrade
Summary

- Hadronic d.o.f. describe few-body elastic and QF scattering well; going to high $Q^2$ is insufficient to guarantee large quark effects.
- We know lots of details in $\gamma d \rightarrow pn$ – it is clear that detailed models like those used at low energy do not work – but the underlying quark dynamics is unclear.
- $^3$He photo-disintegration will help sort out if any of the existing quark models represents the underlying physics.