The Physics of CLAS

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Jefferson Lab

20th Student Workshop on Electromagnetic Interactions
Bosen, August 31 – September 5, 2003

CEBAF at Jefferson Lab
CLAS
  technical
  physics program
  planned upgrades

CEBAF upgrade plans
Main physics programs
- nucleon electromagnetic form factors (incl. strange)
- $N \rightarrow N^*$ electromagnetic transition form factors
- spin structure functions of the nucleon
- form factors and structure of light nuclei

Superconducting recirculating electron accelerator
- max. energy 5.7 GeV
- max current 200 $\mu$A
- e polarization 80%

Experimental equipment in 3 halls (simultaneous operation)
- 2 High Resolution Spectrometers ($p_{\text{max}}=4$ GeV/c) $10^{39}$
- 2 spectrometers ($p_{\text{max}}=7$ and 1.8 GeV/c) + special equipment $10^{39}$
- Large Acceptance Spectrometer for e and $\gamma$ induced reactions $10^{34}$
CEBAF Continuous Electron Beam Accelerator Facility

- Recirculating arcs
- Accelerating structures
- RF separators

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CEBAF Site

north linac

injector

south linac

Hall C

Hall B

Hall A
Electron Beam Properties

Beam properties

- injector produces 3 separate beams via 3 pulsed (500 MHz) lasers on a common photocathode
- intensity ratio up to $10^6$:1 (100$\mu$A in A/C vs. 100pA in B)
- energies in halls need to be a multiple of common linac energy setting
- max. beam power 1MW (e.g. 200$\mu$A at 5 GeV)
- typical beam spot size 100$\mu$m, momentum spread $10^{-4}$

Polarization

- strained GaAs photocathode gives polarization up to 80%
- spin precession controlled by combination of Wien filter and linac energy setting (allows perfect spin alignment for two-hall operation, approximate for 3 halls)
Electron Beam Profile

measurement performed moving 25\(\mu\)m wire through beam
using downstream photomultipliers as radiation detectors
Areas Covered

- excitation of N* resonances (elementary and off nuclei)
- nucleon spin structure functions
- hadronic final states in electron scattering off nuclei

Common Experimental Requirements

- detection of >2 loosely correlated particles in the final state
- high counting rates for experiments that have luminosity limitations due to:
  - tagged photon beam (intensity limited by accidental coincidences)
  - polarized target operation (current limited by cooling + radiation damage)
Hall B Instrumentation

CEBAF Large Acceptance Spectrometer, CLAS
- for operation with electron and photon beams
- use missing mass technique -> good resolution for charged particles
- good particle identification
- high luminosity operation

Trigger and Data Acquisition
- programmable flexible trigger
- high-speed data acquisition system

Beam Line Equipment
- beam position, current, and polarization monitoring
- polarized photon beam and bremsstrahlung tagging system
Hall B Side View
CLAS 3-D View

Drift Chambers
35,000 wires
$\sigma_R = 350 \mu m$

Superconducting Toroidal Magnet
$\int B dl \approx 1.7 \, T \cdot m$

Cerenkov Counters
216 channels
99.5% efficient over 50 m$^2$ area

Time of Flight Counters
500+ channels, 145 ps resolution

Electromagnetic Shower Calorimeters
1700+ channels
$\sigma/E = 10\% / E^{0.5}$

electron beam direction
CLAS in Maintenance Position
Characteristics of CLAS Components

• Charged particle tracking in six independent sectors
  – 3 drift chamber packages per sector
  – 34 layers (axial and stereo)
  – drift time recorded from 35,000 sense wires

• Threshold Cerenkov counters for e identification
  – C$_4$F$_{10}$ gas radiator
  – focusing mirror system
  – 250 PMT’s, time and charge recorded

• Scintillation time-of-flight counters
  – 5 cm thick scintillators with PMT’s at both ends
  – 600 PMT’s, time and charge recorded
CLAS Components (cont’d.)

• Electromagnetic calorimeters
  – lead-scintillator sandwich construction, 39 layers
  – 1,300 PMT’s, time and charge recorded

• Beam line equipment
  – Møller polarimeter to measure electron polarization
  – bremsstrahlung tagging system with crystal radiator, 500 PMT’s
  – cryogenic (H, D, ³,⁴He) or polarized targets (H, D)

• Electronics and data acquisition
  – programmable two-level trigger system (custom design)
  – mostly commercial data conversion modules (18 FastBus, 5 VME crates)
  – parallel data readout into multi-processor on-line DAQ system
CLAS Top View

Drift Chambers
Region 1
Region 2
Region 3

Large-angle Calorimeter

Electromagnetic Calorimeter

TOF Counters

1 m

Cerenkov Counters
CLAS Rear View

Drift Chambers
Region 1
Region 2
Region 3

TOF Counters

Mini-torus Coils

Main Torus Coils

1 m
Characteristics of CLAS Components

Super-conducting toroidal magnet with six kidney-shaped coils
5 m diameter, 5 m long, 5 M-Amp-turns, max. field 2 Tesla
CLAS Lines of Constant Field
CLAS Forward Calorimeter Layout
Forward Calorimeter Hit Pattern
CLAS Single Event Display
Trajectory Reconstruction Resolution

Electrons
Monte Carlo (θ=35°)

- σ(3375 A)
- σ(2250 A) / 1.5

Monte Carlo (θ=35°)
- σ(3375 A)
- σ(2250 A)
Scintillation Counter Timing Resolution

![Graph showing resolution vs. scintillator length](image)

- **Resolution \( \sigma \) (ps)**
- **Scintillator Length (cm)**

- **15 cm**
- **22 cm**
CLAS Luminosity for $e^-$

Luminosity = $1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

$\Theta = 6^\circ - 35^\circ$

$R_1$ current/cm (nA/cm)

Mini-torus Current (kAmps)

Luminosity ($10^{34}$ nucleon cm$^{-2}$ s$^{-1}$)

A / Z

$^1$H, $^2$H, $^3$He, $^4$He, $^12$C, $^{16}$O, $^{20}$Ne, $^{27}$Al, $^{32}$S, $^{56}$Fe, $\text{NH}_3$
Missing Mass Distribution

$\gamma p \rightarrow pX$

COUNTS ($\times 10^2$)

MASS (GeV/c$^2$)
Mass Determination from p and $\beta$
vertex determination used routinely for experiments with multiple targets in the beam:

- simultaneous LH$_2$ and LD$_2$
- multiple target foils
Trajectory Reconstruction Distortions

Explored in \( e p \rightarrow e' \pi^+ (n) \)

Possible reasons

- drift chamber positions not known perfectly
- uncertainties in magnetic field

![Graphs showing before and after corrections](image-url)
Calorimeter Detection Efficiency for n

![Graph showing detection efficiency vs neutron momentum](image)

- **Forward Calorimeter**
- **Large Angle Calorimeter**

Using tagged neutrons from $e p \rightarrow e'\pi^+ (n)$
Cross Section for e-p Scattering

\[ \frac{d\sigma}{d\Omega^*} (\mu b/sr) \]

\[ \theta_{c.m.} \text{(deg)} \]

- Unradiated
- Radiated
- Inclusive Elastic

\[ \frac{(d\sigma/d\Omega^*)_{\text{data}}}{(d\sigma/d\Omega^*)_{\text{radiated}}} \]

\[ \theta_{c.m.} \text{(deg)} \]
CLAS Run and Analysis Conditions

Run

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>luminosity</td>
<td>$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$</td>
</tr>
<tr>
<td>electromagnetic rate</td>
<td>$10^9 \text{ / s}$</td>
</tr>
<tr>
<td>hadronic production rate</td>
<td>$10^6 \text{ / s}$</td>
</tr>
<tr>
<td>trigger (Level I)</td>
<td>on $e^-$ candidates (Cerenkov + calorimeter)</td>
</tr>
<tr>
<td>trigger rate (max.)</td>
<td>4,000/s</td>
</tr>
<tr>
<td>data rate to disk (max.)</td>
<td>25 MB/s (~BaBar, CLEO, $\frac{1}{2}$ RHIC STAR)</td>
</tr>
<tr>
<td>data volume to silo (max.)</td>
<td>1 TeraByte/day</td>
</tr>
<tr>
<td>personnel</td>
<td>2 on shift, on call: 7 system experts + engineering-on-call</td>
</tr>
</tbody>
</table>

Analysis

- first-pass analysis: at JLab compute farm
- physics analysis: at JLab for full data set at outside institutions for filtered data
W-Dependence of Selected Channels at 4 GeV

$W$

$p(e,e')X$
(trigger)

$p(e,e'p)X$

$p(e,e'\pi^+)X$

$p(e,e'\pi^+)X$

$p(e,e'p\pi^+)X$

$p(e,e'p\pi^+)X$
N* Program Physics Goals

- Understand QCD in the strong coupling regime
  - example: bound qqq systems
  - mass spectrum, quantum numbers of nucleon excited states
  - what are the relevant degrees-of-freedom
  - wave function and interaction of the constituents

- Source of information
  - dominated by pion-induced reactions (mostly $\pi N \rightarrow \pi N$)
  - advantage:
    - strong coupling $\rightarrow$ large cross sections
    - simple spin structure
    - good quality beams
  - disadvantage: no structure information
    insensitive to states with weak $\pi N$ coupling
Quark Model Classification of N*

Lowest Baryon Supermultiplets
SU(6)×O(3) Symmetry

Particle Data Group
- ****
- ***
- **

“Missing”
P_{13}(1870)
Capstick and Roberts

D_{13}(1520)
S_{11}(1535)

D_{13}(1895)
Mart and Bennhold

"Missing"
P_{13}(1870)
Capstick and Roberts

Roper P_{11}(1440)
Non-quark Model State

S_{11}(1790)
Non-quark Model State

Δ(1232)

L_{3q}

0
(1135 MeV)

1
(1545 MeV)

2
(1839 MeV)

3
(2130 MeV)

N
(Mass)
Theoretical Models for N* Resonances

• Constituent quark model
  – 3 constituent quarks
  – all 3 contribute to number of states
  – non-relativistic treatment (typically)

• Refinements of the constituent quark model
  – restore relativity
  – hadronic form factors
  – coupling between decay channels

• Lattice gauge calculations
Electromagnetic Excitation

- Helicity amplitudes very sensitive to the difference in wave functions of $N$ and $N^*$
- Can separate electric and magnetic parts of the transition amplitude
- Varying $Q^2$ allows to change the spatial resolution and enhances different multipoles
- Sensitive to missing resonance states
N* Program Requirements

Experiment

large high-quality data set for N* excitation covering
- a broad kinematical range in $Q^2$, $W$, decay angles
- multiple decay modes ($\pi$, $\pi\pi$, $\eta$, $\rho$, $\omega$, $K$)
- polarization information (sensitive to interference terms)

Analysis

$\Delta(1232)$: full Partial Wave Analysis possible
(isolated resonance, Watson theorem)

higher resonances
- need to incorporate Born terms, unitarity, channel coupling
- full PWA presently not possible due to lack of data (polarization)
  (substitute by assuming energy dependence of resonance)
- skills required at the boundary between experiment and theory
Kinematics and Cross Sections

example:
$e\, p \rightarrow e'\, p\, \pi^0$

$$\frac{d\sigma}{d\Omega_e dE' e d\Omega_{\pi}} = \Gamma_t \left( \sigma_t + \varepsilon \sigma_l + \varepsilon \sigma_{tt} \cos 2\phi_\pi + \sqrt{2\varepsilon (\varepsilon + 1)} \cdot \sigma_{tl} \cos \phi_\pi \right)$$
Standard Analysis Approach

known resonance parameters
(mass, width, quantum numbers, hadronic couplings)

photo- and electro-production data base
(mostly differential cross sections)

Analysis

electromagnetic transition form factors
$e \, p \rightarrow e \, X$ at 4 GeV

Clas
CLAS Coverage for $e\ p \rightarrow e'\ X$

$p(e,e')X$
$E=4\,GeV$

Deep inelastic

$Q^2(\text{GeV}^2)$

$W(\text{GeV})$

Missing states

$N(940)$
$\Delta(1232)$
$N(1520)$
$N(1680)$

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CLAS Coverage for $e p \rightarrow e' p X$, $E=4$ GeV
$N \rightarrow \Delta(1232)$ Transition Form Factors

SU(6): $E_{1+} = S_{1+} = 0$

(A. Buchmann, E. Henley, 2000)
Multipoles $E_{1+}/M_{1+}$, $S_{1+}/M_{1+}$ (before 2001)
CLAS

\[ Q^2 = 0.40 \text{(GeV/c)}^2, \quad \Delta Q^2 = 0.100 \text{(GeV/c)}^2 \]

\[ d\sigma/d(\Omega_{\pi^0}, \mu\text{b/sr}) \]

\[ \cos(\theta^*) \]

\[ \Phi \]

\[ W, \text{ GeV/c}^2 \]
Multipole Analysis for $\gamma^* p \rightarrow p \pi^0$

$Q^2 = 0.9 \text{ GeV}^2$

$|M_{1+}|^2$

$\text{Re}(E_{1+}M_{1+}^*)$

$|M_{1+}|^2$

$\text{Re}(S_{1+}M_{1+}^*)$
Multipoles $E_{1+}/M_{1+}, S_{1+}/M_{1+}$ (2002)
Theoretical Interpretation of $E_{1+}/M_{1+}$, $S_{1+}/M_{1+}$
N→Δ Transition, what’s next?

- systematic uncertainties in extraction of $E_{1+}/M_{1+}$ from $ep \rightarrow e'p \pi^0$ around 0.5%
  - differences in treatment of background terms (models not constrained)
  - will become more severe for higher $Q^2$ ($\Delta$ dropping faster)

- more experimental information in hand (analysis in progress)
  - cross sections $ep \rightarrow e'p(\pi^0)$ $Q^2 = (1.5 – 5.5)$ GeV$^2$
  - single-spin asymmetry $\sigma_{TL}$, for $e^- p \rightarrow e'p(\pi^0)$ and $e^- p \rightarrow e' \pi^+(n)$
  - polarization transfer in $e^- p \rightarrow e' p (\pi^0)$
  - differential cross sections for $e^- p \rightarrow e' \pi^+ n$ ($\Delta$ less important)

- experiments in the near future
  - extend $Q^2$ range to 0.05 GeV$^2$ (end of 2002)
  - extend $Q^2$ range to ~7 GeV$^2$ (1st half of 2003)
Polarized Beam Observables

CLAS

$\sigma_{LT^\prime}$ response function for

$\vec{e} \, p \rightarrow e \, p \, \pi^0$

$\sigma_{LT^\prime} = 0$ if only a single diagram contributes (sensitive to the interference between $\Delta$ and background)
$\pi^+$ Electroproduction

[Graph showing data points and curves with labels $\mu$ b / sr and $\theta^*$, deg]
“Missing” Resonances, where are they?

Problem: symmetric CQM predicts many more states than have been observed (in $\pi N$ scattering)

Two possible solutions:

1. di-quark model
   - fewer degrees-of-freedom
   - open question: mechanism for $q^2$ formation?

2. not all states have been found
   - possible reason: decouple from $\pi N$-channel
   - model calculations: missing states couple to $N\pi\pi$ ($\Delta\pi$, $N\rho$), $N\eta$, $N\omega$, KY

   $\gamma$ coupling not suppressed $\rightarrow$ electromagnetic excitation is ideal
Resonances in $\gamma^* p \rightarrow p \pi^+ \pi^-$

Analysis performed by Genova-Moscow collaboration

step #1:
use the best information presently available

$\Gamma_{N\pi\pi}$ from PDG
$\Gamma_{N\gamma}$ AO/SQTM

extra strength
Attempts to fit observed extra strength

Analysis step #2:
- vary parameters of known $D_{13}$
- or
- introduce new $P_{13}$

![Graph showing $\sigma (\mu b)$ vs. $W(\text{GeV})$ for different $Q^2$ values.](Image)
Summary of $\gamma^* p \rightarrow p \pi^+ \pi^-$ Analysis

CLAS data at variance with N* information in PDG

Describing data requires

- major modifications of the parameters of known resonances, or
- introduction of new $P_{13}$ resonance with

(consistent with “missing” $P_{13}$ state, but mass lower than predicted)

Next steps:

- more experimental data already in hand
- combined analysis with other decay channels: $\pi N$, $\eta N$, $K \Lambda$
Resonance Contributions to $\gamma^* p \rightarrow p \omega$?

CLAS

Above resonance region

In resonance region

$\sigma$

$\gamma$

$p$

$p$

$\omega$

$N^*$

$\omega$

$\gamma$

$p$

$p$

$\cos \theta_{\omega}$

$\frac{d\sigma}{d\cos \theta}$ [ub/rad]

$2.05 < W < 2.15$ GeV

$1.0 < Q^2 < 1.5$ GeV$^2$

$1.5 < Q^2 < 2.0$ GeV$^2$

$1.85 < W < 1.95$ GeV

$1.0 < Q^2 < 1.5$ GeV$^2$

$1.5 < Q^2 < 2.0$ GeV$^2$
Resonances in $\omega$ Photoproduction?

- Old data only showed forward angle peaking (Regge)
- PDG lists no $N^* \rightarrow \omega p$ decays
- Strong signal with $e, \gamma$ beam
- Vector particle provides interesting observables with polarized beam/target
- Calculations from Y. Oh- ‘good’ representation of $t$-chan+res.
- Results preliminary: strong resonance contribution, but no single signature for a single state
Hyperon Photoproduction off the Proton

Goal: $\Lambda$ and $\Sigma$ differential cross sections for $1.6 \text{ GeV} < W < 2.3 \text{ GeV}$

Technique: $K$ identified by time-of-flight, hyperons via missing mass

$\Lambda$ and $\Sigma$ polarization measured via self-analyzing weak decay and proton detection
Λ Photoproduction off the Proton

Dominant resonances

$S_{11}(1650)$
$P_{11}(1710)$
$P_{13}(1720)$

Bump at 1.9 GeV
$D_{13}(1895)$?
Polarization of Photoproduced $\Lambda$

**Model-s (hadrodynamic)**
Resonances, plus
$K$ and $K^*$ exchange

**Model-t (Regge)** has $K$ and $K^*$ interference, misses at back angles
Resonances in Hyperon Electroproduction?

\[
\gamma^* p \rightarrow K^+ Y
\]

CLAS

forward hemisphere

backward hemisphere

\[
0. < \cos(\Theta_K) < 1., \quad Q^2 = 0.7 \text{ (GeV/c)}^2
\]

\[
-1. < \cos(\Theta_K) < 0., \quad Q^2 = 0.7 \text{ (GeV/c)}^2
\]

\[\sigma_T + \epsilon_L \sigma_L\]
Next Steps in Missing Resonance Search

• Needed: a coherent, consistent analysis of the data from a broad variety of channels, from photo- and electro-production, and for the available values of $Q^2$

• Important to incorporate consistently available data obtained using hadronic beams

• JLab has requested support for an analysis center to be created as part of the theory group
Integrals over Spin Structure Functions

**Bjorken Sum Rule** ($Q^2 \to \infty$):

**Basic assumptions:**
- Isospin symmetry,
- Current algebra or Operator Product Expansion within QCD

\[
\int_0^1 \left[ g_1^p(x) - g_1^n(x) \right] dx = \frac{1}{6} |g_A/g_V|
\]

**GDH Sum Rule** ($Q^2 \to 0$):

**Basic assumptions:**
- Lorentz invariance, gauge invariance, unitarity,
- Dispersion relation applied to forward Compton amplitude

\[
\int_{k_{\text{thres}}}^{\infty} \left[ \sigma_{3/2}(k) - \sigma_{1/2}(k) \right] \frac{dk}{k} = \frac{2\pi^2\alpha}{m^2} \kappa
\]

$\kappa = $ nucleon anomalous magnetic moment
Q^2 Dependence of the Moments

\[ Q^2 = \infty \]

- single partons (Bjorken SR)
- multiple partons
- constituent quarks, N^*
- pions, nucleon
- magnetic moment (GDH SR)

\[ Q^2 = 0 \]

DIS, pQCD

\[ Q^2 \ (\text{GeV}^2) \]

ChPT ?

GDH sum rule

twist expansion ?

quark models LQCD ?
Polarized Solid State Target for CLAS

dynamically polarized NH$_3$ and ND$_3$
CLAS: First Moment \( \Gamma_{1p} = \int g_{1}(x,Q^2)dx \)

**VERY PRELIMINARY**

- \( Q^2 \) evolution of \( G_{1p} \) reveals the importance of nucleon resonances.
- Resonances are needed to explain:
  - fall-off for \( Q^2 < 1.5 \) GeV\(^2\)
  - zero-crossing

The graph shows various models and data points, indicating the trend of the \( Q^2 \) dependence of the first moment. The graph includes labels for different models and data sets, such as EG1b(Data+DIS), EG1a(Data+DIS), Burkert-Ioffe, Soffer-Teryaev, GDH slope, and pQCD DIS.
Generalized Parton Distributions (GPDs)


Proton form factors, transverse charge & current densities

Correlated quark momentum and helicity distributions in transverse space - GPDs

Structure functions, quark longitudinal momentum & helicity distributions
e.g.: Deeply Virtual Compton Scattering (DVCS)

\[ H(x, \xi, t), E(x, \xi, t), \ldots \]
Universality of Generalized Parton Distributions

- Elastic form factors
- Real Compton scattering at high t
- Single Spin Asymmetries
- Deeply Virtual Compton Scattering
- Deeply Virtual Meson production
- Parton momentum distributions

GPDs
Experimental Access to GPDs

DIS only measures at x=0
Quark distribution q(x)
-\overline{q(-x)}

Accessed by beam/target spin asymmetry
Accessed by cross sections

H(x, ξ, 0)
Access GPDs through DVCS

\[
\frac{d^4 \sigma}{dQ^2 dx_B dt d\phi} \sim |T_{DVCS} + T_{BH}|^2
\]

**DVCS**

**BH**

\( T_{BH} \): determined by Dirac & Pauli form factors

\( T_{DVCS} \): determined by GPDs

Helicity difference:

\[
\Delta \sigma \sim \sin \phi |\text{Im}\{(F_1 H(\xi, \xi, t) + k_1 (F_1 + F_2) H(\xi, \xi, t) + k_2 F_2 E(\xi, \xi, t)}\}|d\phi
\]
ep → e'pX - Missing Mass Analysis

Calibrate missing mass using radiative elastic and exclusive ep → e'pγγ events

\[ \text{ep} \rightarrow e'p(\gamma) \]

\[ \text{ep} \rightarrow e'p\pi^0 \]

exclusive ep → e'pγ
Measurement of exclusive DVCS

1999 data, $E=4.2\text{GeV}$, $\langle Q^2 \rangle = 1.3\text{GeV}^2$

\[ \alpha(\phi) = \alpha \sin \phi + \beta \sin 2 \phi \]

- $\alpha = 0.202 \pm 0.028^{\text{stat}} \pm 0.013^{\text{sys}}$
- $\beta = -0.024 \pm 0.021^{\text{stat}} \pm 0.009^{\text{sys}}$

2001 data, $E=5.75\text{GeV}$, $\langle Q^2 \rangle = 2.5\text{GeV}^2$

- Higher energy increases kinematics range.
- Higher statistics allows binning in $Q^2$, $t$, $\xi$

S. Stepanyan et al. PRL 87, 2001
Goal: Determine quark content of colorless hadrons

Expectation from the quark model is that the properties of baryons are determined by three valence quarks (qqq)
Hadron Multiplets

Mesons $\bar{q}q$

\[ 3 \otimes \bar{3} = 8 \oplus 1 \]

Baryons $qqq$

\[ 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1 \]

Baryons built from meson-baryon basis

\[ 8 \otimes 8 = 27 \oplus 10 \oplus \bar{10} \oplus 8 \oplus 8 \oplus 1 \]
What are Penta-Quarks?

- Minimum quark content is 5-quarks.
- Anti-quark has different flavor than any of 4-quarks ($qqqq\bar{q}$).
- Quantum numbers can not be defined by 3-quarks.

- General idea of a five-quark states has been around since late 60’s.
- However, searches did not give any conclusive results.
- PDG dropped the discussion on pentaquark searches after 1988.
Exotic Baryon Search

The chiral soliton model by D. Diakonov, M. Petrov, M. Polyakov predicts an anti-decuplet of penta-quark baryons.

The lightest state is predicted to be a baryon state with exotic quantum number S=+1, and M=1.53GeV, $\Gamma=15\text{MeV}$.
$\Theta^+ \text{ Photoproduction and Competing Reactions}$

\[ \gamma n (p) \rightarrow \Theta^+ K^- (p) \]
\[ \Theta^+ \rightarrow K^+ n \]

\[ \gamma p (n) \rightarrow \Lambda^* (1520) K^+ (n) \]
\[ \Lambda^* (1520) \rightarrow K^- p \]

\[ \gamma N \rightarrow \phi (1020) N \rightarrow K^+ K^- N \]
Exclusive $\gamma d$ Measurement

CLAS Collaboration
(S. Stepanyan, K. Hicks, et al.),
hep-ex/0307018
requires FSI – both nucleons involved
- no Fermi motion correction necessary
- FSI puts $K^-$ at larger lab angles: better CLAS acceptance
- FSI not rare: in ~50% of $\Lambda^*(1520)$ events both nucleons detected with $p > 0.15$ GeV/c
Kaon start times relative to the proton

\[ \Delta t_K = t - \frac{R}{\beta_c \cdot c}; \beta_c = \frac{p}{\sqrt{p^2 + m_K^2}} \]

\[ \Delta t(p-K^-) \text{ (ns)} \]

\[ \Delta t(p-K^+) \text{ (ns)} \]

pp\(\pi^-\)

p\(\pi^+\)\(\pi^-\)

pK\(^+\)K\(^-\)
Reaction $\gamma d \rightarrow pK^+K^-(X)$

- Clear peak at neutron mass
- 15% non-pKK events within $\pm 3\sigma$ of the peak
- Background under the neutron peak can be further reduced by tight timing cut

![Graph showing reconstructed neutrons](image)
Removal of known resonances

Cuts

- remove events with $IM(K^+K^-) \rightarrow \phi(1020)$ by $IM > 1.07$ GeV
- remove events with $IM(pK^-) \rightarrow \Lambda(1520)$
- limit $K^+$ momentum due to $\gamma d \rightarrow p K^- \Theta^+$ phase space $p_{K^+} < 1.0 \text{GeV/c}$
(nK\(^+\)) Invariant Mass Distribution

\[ F(M) = G_{\Theta^+} + G_{Bg} + P_0 \]

- \( N_{\Theta} = 43 \)
- \( M_{\Theta} = 1.542 \text{ GeV} \)
- \( \sigma_{\Theta} = 0.009 \text{ GeV} \)
- \( N_{\Theta}/\sqrt{N_{Bg}} = 5.8\sigma \)

distribution of \( \Lambda(1520) \) events
Θ⁺ Experimental Status

Experimental evidence for Θ⁺ has been reported by four groups:

- LEPS at Spring-8 (Japan), January 2003 - peak in the invariant mass of the nK⁺ at 1.54 GeV with statistical significance of 4.6σ
- DIANA at ITEP (Moscow), April 2003 – peak in the invariant mass of pK⁰ at 1.538 GeV, statistical significance 4.4σ
- CLAS at JLAB, July 2003 – peak in the invariant mass of the nK⁺ at 1.542 GeV, statistical significance 5.3σ
- SAPHIR at ELSA, August 2003 – peak in the invariant mass of the nK⁺ at 1.54 GeV, statistical significance 4.8σ

All experiments observe a narrow width

Penta-Quark 2003 Workshop at JLab
November 6-8, 2003
Nucleon-Nucleon Correlations

Observable: NN-pair with
• large relative momentum
• small total momentum
→ need to distinguish between Correlations and Currents

Correlations | Currents
---|---
\[ \gamma \]
\[ \gamma \]
\[ \gamma \]
\[ \gamma \]

Two-Body Currents (MEC + IC)
• not a Correlation
• strongly enhance effect of correlation
Three-Body Break-up of $^3\text{He}$

$^3\text{He}(e,e'pp)n$

Two protons detected with $p > 250$ MeV/c $> p_{\text{Fermi}}$

Reconstruct neutron via missing mass

Select proton/neutron with almost all transferred energy ($TN/\omega \approx 1$)

Clear evidence of back-to-back excess over three-body absorption followed by phase-space decay simulation
Angular Distribution of Emitted NN-Pair

Cut on leading nucleon $P_{\text{perp}} < 300 \text{ MeV/c}$ to select quasifree knockout (reduce FSI)

Preliminary

Isotropic Fast Pairs

$\rightarrow$ Pair not involved in REACTION!

Preliminary
Conclusions from $^3\text{He}(e,e'pp)n$ Experiment

If one selects a fast leading nucleon in $^3\text{He}(e,e'pp)n$ then the remaining (fast) NN pair:

- is back-to-back
- is isotropic with respect to momentum transfer $q$
- has small momentum along $q$

Fast NN pair is not involved in the reaction

Total and relative momentum distributions similar for:

- pp and pn pairs
- $0.5 < Q^2 < 1$ and $1 < Q^2 < 2$ (GeV/c)$^2$

- WE ARE OBSERVING BOUND-STATE CORRELATIONS!
Setup for Deeply Virtual Compton Scattering

**Physics Goal**
measure $\xi$, $t$, $Q^2$ - dependence of $ep \rightarrow e'p \gamma$ in a wide kinematics range to constrain GPD models.

**Technical Problem**
- need to detect all final state particles to identify process
- double luminosity to $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

**Technical solution**
- add forward calorimeter (436 lead tungstate crystals)
- readout via avalanche photodiodes (APD)
- SC 5Tesla solenoid Moller shield
Bound Nucleon Structure (B O N U S)

Physics issue:
tag process off a neutron bound in deuterium by
detecting the spectator proton in coincidence with
the scattered e’

Technical problem:
spectator protons have
- low momentum and low range
- isotropic angular distribution (no correlation)
- high rate

Solution:
- high pressure gas target
- surrounded by radial drift chamber
- GasElectronMultiplier gap
Frozen Spin Target for CLAS

Technical problem:
build polarized target for tagged photon beam
  - minimum obstruction of CLAS solid angle
  - low distortion of particle trajectories in magnetic field

Solution:
- frozen spin target
- temperature 50mK
- magnetic field 5kG

Status:
- design in progress at JLab
- procurement started for polarizing magnet
Physics Drivers for CEBAF Upgrade

• New capabilities
  – search for origin of confinement ($J^{PC}$ exotic mesons)
  – determine parton distributions (high $Q^2$ and $W$) via
    • polarized and unpolarized inclusive scattering
    • semi-inclusive (tagged) structure functions
    • exclusive processes (DVCS, meson production)

• Push present program to higher $Q^2$
  – form factors of mesons, nucleons, and light nuclei
CEBAF Upgrade Plan

• Upgrade accelerator to 12 GeV max. energy
  – maintain 100% duty cycle
  – keep beam power constant (1MW) → max. current 80µA

• Build new experimental hall for meson spectroscopy (Hall D)
  – polarized tagged photon beam (coherent bremsstrahlung)
  – large acceptance detector for real photons only

• Upgrade existing 3 halls for higher beam energy
CEBAF Accelerator Upgrade

• keep present accelerating system

• add ten new cryomodules at 100MeV energy gain
  – present cryomodules provide ~30 MeV
  – increased performance can be achieved by
    • increased effective cavity length (5-cell ⇒ 7-cell)
    • Increased average gradient (7.5 MV/m ⇒ 17.5 MV/m)

• double cryogenic system capacity
• upgrade recirculating arcs
• add new beam line to Hall D
Upgrade magnets and power supplies

Add 5 cryomodules

20 cryomodules

CHL-2

Enhance equipment in existing halls

Add arc

Add Hall D (and beam line)
CLAS Physics Program at 12 GeV

- **Quark-Gluon Dynamics and Nucleon Tomography**
  - Deeply Virtual Compton Scattering (DVCS)
  - Deeply Virtual Meson Production (DVMP)
  - High-t DVCS and $\pi^0/\eta$ production

- **Valence Quark Distributions**
  - Proton and Neutron Spin Structure
  - Neutron Structure Function $F_{2n}(x, Q^2)$
  - Tagged Quark Distribution Functions
  - Novel Quark Distribution Functions (tranversity, $e(x)$,..)

- **Form Factors and Resonance Excitations**
  - The Magnetic Structure of the Neutron
  - Resonance Excitation Dynamics

- **Hadrons in the Nuclear Medium**
  - Space-Time Characteristics of Hadronization
  - Color transparency

- **Physics with quasi-real Photons**
Upgraded CLAS (CLAS++)

- Forward Cerenkov
- Forward DC
- Inner Cerenkov
- Central Detector
- Torus Cold Ring
- Forward TOF
- Preshower EC
- Forward EC
- Coil Calorimeter
CLAS++ - 2-dimensional Cut
12 GeV Upgrade Project Status

• Developed by User Community in collaboration with JLab

• Nuclear Science Advisory Committee, NSAC
  – plan presented during last 5-year Long Range Plan
  – recommended by NSAC for new construction

• Plan presented to Department of Energy
  – presently waiting for CD-0 (determination of ‘mission need’)

• Construction
  – estimated costs: $158M (in FY02$)
  – construction start expected in FY2007 (October 2006)
  – 3 year construction project
Study underway for an electron-light ion collider at JLab to investigate

inclusive and semi-inclusive DIS
deep exclusive reactions (GPD’s)

Parameters

- electrons
- ions (p, d, $^3\text{He}$)
- luminosity

3 - 5 GeV
30-50 GeV
≤ $6 \times 10^{34}$ cm$^{-2}$ s$^{-1}$

Design maintains fixed target capability with

- 25 GeV external beam
- luminosity $\sim 10^{38}$ cm$^{-2}$ s$^{-1}$
Electron-Light Ion Collider Layout

5 GeV electrons

100 MV cryomodules

50 GeV light ions

5 GeV CEBAF with Energy Recovery

Lia Merminga at EIC Workshop, BNL

02/27/2002