JLab: Probing Hadronic Physics with Electrons and Photons

Elton S. Smith
Jefferson Lab

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Introduction to JLab
The shape of the proton
Pentaquarks
Why use electron and photon probes?

Electromagnetic interaction is well-known

F(Q^2)

Elastic Form Factors

Inelastic transitions

Size probed \sim \frac{1}{\sqrt{Q^2}}
CEBAF @ JLab Today

- **Main physics programs**
  - nucleon electromagnetic form factors (including strange form factors)
  - \( N \rightarrow N^* \) 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%

- **Simultaneous operation in 3 halls**
  - A: Two High Resolution Spectrometers (\( p_{\text{max}} = 4 \) GeV/c) \( 10^{39} \)
  - B: Large Acceptance Spectrometer for e and \( \gamma \) induced reactions \( 10^{34} \)
  - C: Two spectrometers (\( p_{\text{max}} = 7 \) and 1.8 GeV/c) + special equipment \( 10^{39} \)
CEBAF accelerator site
Three Experimental End-Stations

**HALL A**
Pair of identical High Resolution Spectrometers (HRS$^2$)

**HALL B**
CEBAF's Large Acceptance Spectrometer (CLAS) and Bremsstrahlung Photon Tagger

**HALL C**
High Momentum Spectrometer (HMS) and Short Orbit Spectrometer (SOS)
**G_{Ep}: Electric form factor of the proton**

**Goal:** Determine the charge and current distributions inside the proton

NY Times “Is a proton round?”

Naïve expectation is that the charge and currents are determined from the spatial distribution of quark charges and spins.

from G.A. Miller
Charge distribution and Form Factors

\[ \rho(r) = \int d^3 q \ F(q^2) \ e^{-i \vec{q} \cdot \vec{r}} \]

\[ \rho(r) = \frac{\Lambda^3}{8 \pi} \ e^{-\Lambda r} \]

\[ F(Q^2) = \left( \frac{1}{1 + Q^2 / \Lambda^2} \right)^2 \]

\[ \Lambda = 0.94 \text{ GeV} \]
\[ \Lambda = 0.84 \text{ GeV} \]
\[ \Lambda = 0.74 \text{ GeV} \]
Charge Distributions and Form Factors

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Function</th>
<th>Form Factor</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point</td>
<td>$f(r) = \delta(r - r_o)$</td>
<td>$F(Q^2) = 1$</td>
<td>unity</td>
</tr>
<tr>
<td>Exponential</td>
<td>$f(r) = \frac{\Lambda^3}{8\pi} e^{-\Lambda r}$</td>
<td>$F(Q^2) = \left(\frac{1}{1 + Q^2 / \Lambda^2}\right)^2$</td>
<td>dipole</td>
</tr>
<tr>
<td>Yukawa</td>
<td>$f(r) = \frac{\Lambda^2}{4\pi r} e^{-\Lambda r}$</td>
<td>$F(Q^2) = \frac{1}{1 + Q^2 / \Lambda^2}$</td>
<td>pole</td>
</tr>
<tr>
<td>Gaussian</td>
<td>$f(r) = \left(\frac{\Lambda^2}{2\pi}\right) e^{-\left(\frac{1}{2} \Lambda^2 r^2\right)}$</td>
<td>$F(Q^2) = e^{-\frac{1}{2}\left(\frac{Q^2}{\Lambda^2}\right)}$</td>
<td>Gaussian</td>
</tr>
</tbody>
</table>
Decomposition of the elastic cross section

\[ \frac{d \sigma}{d \Omega} = \sigma_{ns} \left( \frac{G_{Ep}^2}{1 + \tau} + \tau G_{Mp}^2 \tan^2 \left( \frac{\vartheta_e}{2} \right) \right) \]

\[ \sigma_{ns} = \frac{\alpha^2 \cos^2 \left( \frac{\vartheta_e}{2} \right) E'}{4E^2 \sin^4 \left( \frac{\vartheta_e}{2} \right) E} \]

\[ \tau = \frac{Q^2}{4M_p^2} \]

\[ \sigma_R = \frac{d \sigma}{d \Omega} \frac{(1 + \tau) \varepsilon}{\sigma_{ns} \tau} = \frac{\varepsilon G_{Ep}^2 (Q^2) + G_{Mp}^2 (Q^2)}{\tau} \]

\[ \varepsilon = \left\{ 1 + 2(1 + \tau) \tan^2 \left( \frac{\vartheta_e}{2} \right) \right\}^{-1} \]
Proton Form Factors pre-1998

\[ G_{Ep} \sim \frac{G_{Mp}}{\mu} \sim G_D \]

\[ G_D = \frac{1}{\left(1 + \frac{Q^2}{0.71}\right)^2} \]
Spin transfer reaction $\vec{e} \vec{p} \rightarrow e \vec{p}$

\[
\frac{G_{Ep}}{G_{Mp}} = - \frac{P_l}{P_t} \frac{E_e + E_e'}{2M} \tan(\vartheta_e / 2)
\]
Transport through magnet

\[ \chi = \gamma \theta_B (\mu_p - 1) \]

\[ P^t_{fpp} = P^t \]

\[ P^t'_{fpp} = P^t \sin \chi \]
Azimuthal asymmetry in the polarimeter

\[ Q^2 = 5.6 \text{ GeV}^2 \]
$G_{Ep}$ from polarization transfer

$\frac{\mu_p G_{Ep}}{G_{Ep}}$ vs $Q^2$ in $\text{GeV}^2$

JLab 1998
JLab 2000
Belitsky, Ji, Yuan, 2003
Brodsky 2002

E93-027, E99-007
Perdrisat, Punjabi, Jones, Brash
World data for $G_{Ep}$

\[ \mu G_{Ep} / \mu_{mp} \]

\[ Q^2 \text{ in GeV}^2 \]

- JLab 1998
- JLab 2000
- SLAC 1993
- World Data
Interpretation of new data

F₂(Q²) is a spin-flip transition

\[ \langle P' \uparrow | J^\mu | P \downarrow \rangle \sim F_2(Q^2)\bar{u}_{\uparrow}(P') \frac{i\sigma^{\mu\nu} q_\alpha}{2M} u_{\downarrow}(P) \]

In the absence of quark angular momentum

\[ Q^2 \frac{F_2}{F_1} \sim m_q M \quad \frac{m_q \rightarrow 0}{m_q \rightarrow 0} \rightarrow 0 \]

Quark orbital angular momentum essential to describe data

\[ Q \frac{F_2}{F_1} \sim \frac{1}{Q} \log^2 \left( \frac{Q^2}{\Lambda^2} \right) \sim \text{const} \]
Pentaquark: Baryon with five quarks

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** $q\bar{q}$

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

**Baryons** $qqq$

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

**Baryons built from meson-baryon basis**

\[ 8 \otimes 8 = 27 \oplus 10 \oplus 1 \bar{10} \oplus 8 \oplus 8 \oplus 1 \]
Production and decay of $\Omega^- \rightarrow \Xi^0 \pi^-$

FIG. 2. Photograph and line diagram of event showing decay of $\Omega^-$. 
What are pentaquarks?

- Minimum quark content is 5-quarks.
- Anti-quark has different flavor than any of 4-quarks \((qqqq\overline{Q})\).
- 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.
The Anti-decuplet predicted by Diakonov et al.

\[ uudd\bar{s} \]
\[ \Theta^+(1530) \]

\[ udd(uu + ss) \]

\[ uud(d\bar{d} + ss) \]
\[ N(1710) \]

\[ dds(uu + ss) \]

\[ uus(d\bar{d} + ss) \]
\[ \Sigma(1890) \]

\[ dss(uu + d\bar{d}) \]

\[ uuss(d\bar{d}) \]
\[ \Xi(2070) \]

\[ ddss\bar{u} \]

\[ uuss\bar{d} \]
Reactions on deuterium

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

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

\[ \gamma N \rightarrow \phi (1020) N \rightarrow K^+ K^- N \]
CEBAF Large Acceptance Spectrometer

**Torus magnet**
6 superconducting coils

**Liquid D₂ (H₂)target +**
γ start counter; e minitorus

**Drift chambers**
argon/CO₂ gas, 35,000 cells

**Electromagnetic calorimeters**
Lead/scintillator, 1296 photomultipliers

**Time-of-flight counters**
plastic scintillators, 684 photomultipliers

**Gas Cherenkov counters**
e/π separation, 256 PMTs
Exclusive measurement using $\gamma d$ reactions

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
$\gamma d \rightarrow p K^+ K^- (n)$ in CLAS
Kaon times relative to proton

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

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

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

- $pp\pi^-$
- $p\pi^+\pi^-$
- $pK^+K^-$
Reaction $\gamma d \rightarrow pK^+K^-(n)$

- Clear peak at neutron mass.
- 15% non pKK events within $\pm 3\sigma$ of the peak.
- Almost no background under the neutron peak after event selection with tight timing cut.
Identification of known resonances

- Remove events with $\text{IM}(K^+K^-) \rightarrow \phi(1020)$ by $\text{IM} > 1.07$ GeV
- Remove events with $\text{IM}(pK^-) \rightarrow \Lambda(1520)$
- Limit $K^+$ momentum due to $\gamma d \rightarrow p K^- \Theta^+$ phase space $p_{K^+} < 1.0\text{GeV/c}$
- C. Meyer (CLAS note 03-009): checked narrow structure impossible in $\gamma d \rightarrow K^+Y*N \rightarrow K^+(K-N)N, + KN$ rescattering
nK\(^+\) invariant mass distribution

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

\[ \begin{align*}
N_\Theta &= 43 \\
M_\Theta &= 1.542 \text{ GeV} \\
\sigma_\Theta &= 0.009 \text{ GeV} \\
N_\Theta/\sqrt{N_{Bg}} &= 5.8\sigma
\end{align*} \]

Distribution of \( \Lambda(1520) \) events
**Θ⁺: experimental status**

- Experimental evidence for Θ⁺ have been reported at four laboratories.
  - LEPS collaboration 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 collaboration at ITEP (Moscow), April 2003 – peak in the invariant mass of pK⁰ at 1.538 GeV, statistical significance 4.4σ.
  - CLAS collaboration at JLAB, July 2003 – peak in the invariant mass of the nK⁺ at 1.542 GeV, statistical significance 5.3σ.
  - SAPHIR collaboration at ELSA (Bonn), August 2003 – peak in the invariant mass of the nK⁺ at 1.54 GeV, statistical significance 4.8σ.

- All experiments observe a narrow width.
- Spin, isospin and parity not yet established.
- Subject of intense interest and research.
  - Penta-Quark 2003 Workshop at JLab in November.
Summary

- We have presented two examples which highlight the physics program at Jefferson Lab.
- The electromagnetic interaction can be used to probe deep into the structure of nucleons.
  - From measurements of $G_{Ep}$ up to a $Q^2 = 5.6$ GeV$^2$ we have gained new insights into the shape of the proton.
  - Orbital angular momentum of quarks is a key ingredient in our understanding of proton structure.
- A key question in non-perturbative QCD is the structure of hadrons
  - We have presented evidence for an exotic baryon with $S = +1$, which would have a minimal quark content of five quarks (uudd$\bar{s}$).
  - This baryon represents a new class of colorless hadrons.
Scaled $F_2/F_1$ ratio

SLAC, Andivahis et al.
JLab Jones e.a.
JLab Gayou e.a.

1 VMD Lomon 2002
2 soliton
3 Franck et al. 1996
4 CQ, G. Miller, 2002
5 di-quark
6 cloudy bag

$q^2$ in GeV$^2$