Theoretical Physics at Jefferson Lab

Anthony W Thomas
Outline

• Staff: focus on changes

• Expertise & Recent Achievements

• New Initiatives:
  - Expanded visitor program (focus for hadron physics)
  - Expanded initiative in lattice QCD
  - Excited Baryon Analysis Center (& PWA Hall D)
Role of Theory at Jefferson Lab

• Contribute to Intellectual Leadership of Lab

• Phenomenological Support of Experimental Program
  - development/analysis of proposals
  - provision of essential support in interpretation of data

• Projects of scope/duration appropriate to a national laboratory
JLab Theory Group: Senior Staff

• 4.5 full-time staff (4.5 FTE)
  Robert Edwards  (lattice gauge theory)
  Franz Gross  (0.5 time)
  Wally Melnitchouk  (from Feb 04)
  David Richards  (lattice gauge theory)
  Christian Weiss  (from Aug 04)

Distinguished Visiting Fellow: Stan Brodsky (SLAC), Jan 03-Jun 03
                      Barry Holstein (UMass), Jan 04-Jun 04

Chief Scientist / Group Leader: Anthony Thomas (from April 04)

• 7 staff with joint appointments (3.5 FTE)
  Ian Balitsky (ODU)  Winston Roberts (ODU)
  Jose Goity (Hampton)  Rocco Schiavilla (ODU)
  Anatoly Radyushkin (ODU)  Marc Vanderhaeghen (W&M)
                              Wally Van Orden (ODU)
JLab Theory Group: Junior Staff

• 5 JLab postdoctoral fellows (5 FTE)

  Jozef Dudek (PhD 04, Oxford, UK) – from Oct 04
  George Fleming (Ph.D. 00, Columbia) – Oct 02 to Sep 05
  Renato Higa (Ph.D. 03, São Paulo, Brazil) - from Oct 03
  Mark Paris (Ph.D. 01, UIUC) – from Nov 03
  Ross Young (PhD 04, Adelaide, Australia) – from Oct 04

• Isgur Distinguished Postdoctoral Fellow (funded by SURA and JLab)
  Evgeny Epelbaum (Ph.D. 00, Bochum) – from Oct 03
JLab Theory Group: Associate Staff

• 4 senior staff (100% university support)
  Carl Carlson (W&M)          Marc Sher (W&M)
  Chris Carone (W&M)          Peter Agbakpe (NSU)

• Numerous sabbatical visitors (supported by JLab)
  D. Diakanov (Nordita) - from Apr 04 (9 months)
  J. Tjon (Utrecht) - from Aug 03 (6 months)
  J. Laget (Saclay) – from May 04 (4 months)
  D. Leinweber (CSSM) – from Aug 04 (2 months)

• 1 postdoctoral fellow (external funding)
  Vladimir Pascalutsa (W&M, Gross DOE) - from Oct 03

• 8 graduate students:
  3 supported by JLab + 2 LSU (one LSU support, one SURA Fellowship)
  + 3 Adelaide University (with AWT)
$G_E^p/G_M^p$ as Measured by $(e, e' p)$: Critical Data for Understanding Proton Structure

The combination of high intensity e beams and proton polarimetry has dramatically improved our knowledge of this fundamental system and raised important theoretical challenges.
Estimate of 2-photon Exchange Effects

\[ \frac{\mu_p G_E}{G_M} \]

vs.

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

Blunden, Melnitchouk, Tjon, PRL (2003)

N only... so far
Partially Quenched DWF Form Factor

- DWF $F_\pi(Q^2,t)$: LHPC (Edwards, Richards ….)
  - Smaller mass close to experimental VMD.

- Charge radius (crude analysis):
  - Exp. $h r^2_i = 0.439(8)\text{fm}^2$, VMD $0.405\text{fm}^2$
  - Statistical: $0.156(5)\text{fm}^2$, $0.310(6)\text{fm}^2$ strong mass dependence

\[
\frac{\partial F(Q^2)}{\partial Q^2} \bigg|_{Q^2=0} = \frac{1}{6} \langle r^2 \rangle \quad \rightarrow \quad \langle r^2 \rangle = \frac{6}{m_V^2}
\]
Octet Magnetic Moments

Leinweber, AWT, Young, hep-lat/0406003
$s_\ell$ may be estimated from the Kaon loop integrals

- Regulated by a dipole form factor with $\Lambda = 0.8 \text{ GeV}$

\[
\ell R_d^s = \frac{s_\ell}{d_\ell} = \frac{-0.036}{-0.258} = 0.140
\]

- Repeating the calculation for $\Lambda = 0.8 \pm 0.2 \text{ GeV}$ provides

\[
\ell R_d^s = \frac{s_\ell}{d_\ell} = 0.140 \pm 0.040
\]

Hence $G_M^s = -0.051 \pm 0.021 \mu_N$

(dots are steps of 0.01 $\mu_N$)

Non-trivial that intersection lies on constraint line!
Generalized Parton Distributions

• Off-forward matrix elements related to moments of $H, E$

• Lowest moments give form factors: $A_{10}(t) = F_1(t), B_{10}(t) = F_2(t)$

$$A_{n0} = \int dx \ x^{n-1} H(x, 0, t); \quad B_{n0} = \int dx \ x^{n-1} E(x, 0, t)$$

• Asymptotic behavior of $F_2/F_1$ (Belitsky, Ji, Yuan)

$$\frac{Q^2 F_2(Q^2)}{\log^2 (Q^2 / \Lambda^2) F_1(Q^2)} \sim \text{const}$$

LHPC/SESAM, hep-lat/0404009
(Edwards, Fleming, Richards at JLab)
New Theory Initiatives at JLab

• Make JLab international focus of theoretical work in hadron physics; expanded visitor & sabbatical program

• Expand LQCD effort to world-class computational capability

• Strengthen support of the experimental program through the establishment of the Excited Baryon Analysis Center (EBAC) (linked to PWA/Hall D initiative) at JLab
Lattice QCD Initiative – Software and Hardware

• Software developments:
  — **QCD-API**: portable programming interface for diverse computational platforms. Development of QDP++, a C++ implementation, led by Edwards
  — Implementation of LHPC physics program being performed by Edwards, Fleming and Richards

• Hardware developments:
  — 128-node Pentium IV cluster **connected by Myrinet** commissioned in Sep 02; tackling key problems including moments of structure functions and GPD’s
  — 256-node Pentium IV grid-based machine **connected by GigE**; aggregate computational capability of around 400 Gflops
  — Prototype machines for envisioned multi-Tflops facility
Clusters at Jefferson Laboratory - SciDAC

128-node P4 Xeon, with Myrinet

256-node P4 Xeon, with 3d gigE torus
Performance per Dollar for Typical LQCD Applications

**Optimized LQCD Clusters**
- Commodity compute nodes (leverage marketplace & Moore’s law)
- Large enough to exploit cache boost
- Low latency, high bandwidth network to exploit full I/O capability (& keep up with cache performance)

**Future clusters** will significantly extend scientific reach

JLab SciDAC Prototype Clusters
- Anticipated boost due to SciDAC funded software
  - (2004)
- QCDSP
- Japanese Earth Simulator

Vector Supercomputers, including the Japanese Earth Simulator

JLab SciDAC will deliver significant capabilities in early 2005

Future clusters will significantly extend scientific reach
Jefferson Lab Teraflops for 3 Funding Scenarios

- $8M/yr
- $2M/yr
- $6M/yr

Electromagnetic and transition form factors at high $Q^2$

Lowest $S=1$ pentaquark states

Teraflops

2002 2003 2004 2005 2006 2007 2008 2009
# LQCD Hadron Physics Roadmap

<table>
<thead>
<tr>
<th>Tflops-yrs</th>
<th>Description</th>
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<tbody>
<tr>
<td>1-5</td>
<td>QQCD: N* spectroscopy; pentaquarks; valence PDFs &amp; GPDs</td>
</tr>
<tr>
<td>5-10</td>
<td>Lighter quark (large volume): GPDs; (transition) form factors; spectroscopy</td>
</tr>
<tr>
<td>10-50</td>
<td>Flavor singlet distributions; high-Q^2 form factors; gluon structure</td>
</tr>
<tr>
<td>50-500</td>
<td>Fully consistent valence &amp; sea computations; decay widths…..</td>
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<tr>
<td>Open problems</td>
<td>Functional form of PDFs &amp; GPDs; light nuclei…</td>
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N* Spectrum

- First generation calculations – largely for quarks masses around that of **strange quark**

Zanotti et al, PRD68, 054506

• Spectrum in accord with naïve **oscillator quark model** at large \( m_q \)

\[ M_N < M_{N\frac{1}{2}^-} < M_{N^*\frac{1}{2}^+} \]

• Development of tools to extract radial excitations LHPC, hep-lat/0312003

Nature of Roper, \( \Lambda(1405), \ldots ?? \)
Roper Resonance

- Roper resonance at light quark masses
  S.J. Dong et al, hep-ph/0306199
- Bayesian statistics and constrained curve fitting?
- Roper predominantly a three-quark state?

Physics at physical values of the pion mass very different from the heavy-quark regime
Pentaquarks

- First tentative lattice results (Csikor et al, Sasaki), $l = 0$, spin $\frac{1}{2}$.
- Need to isolate “resonance” from two-body spectrum
- Require study of full spectrum – & various interpolating fields…

**Bottom line dependent on χ’al extrapolation**

- Higher spin states require construction of operators in IR of cubic symmetry of lattice
- Method developed for fermionic states in hep-lat/0312003 (Richards, Edwards .. at JLab)
- Computations of baryon operators in $G_1$, $G_2$ and $H$ IR’s in progress

<table>
<thead>
<tr>
<th>$J$</th>
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<th>$n_{G_2}^{J}$</th>
<th>$n_H^{J}$</th>
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<td>9/2</td>
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</table>
Chiral Extrapolation of $G_E^p$

Lattice data:
Göckeler et al. (QCDSF), hep-lat/0303019 – Wilson fermions

Chiral Extrapolation:
Ashley et al. (CSSM), Nucl. Phys. A721 (2003) 915
Chiral Extrapolation of $G_M^p$

Finest lattice $a \approx 0.05$ fm
DIS – Chiral Extrapolations

Physics of pion cloud crucial for making contact with experiment.

Lowest moment of unpolarized Structure function – momentum carried by valence quarks in Nucleon

Different symbols \$ quenched/full

“Light” pion masses

• Physics of pion cloud… Detmold et al., hep-lat/0103006

$$\langle x^n \rangle_u - \langle x^n \rangle_d \sim a_n \left[ 1 - \frac{(3g_A^2 + 1)m^2}{(4\pi f_\pi)^2} \ln \left( \frac{m^2}{m^2 + \mu^2} \right) \right] + b_n m^2$$
Shape…

- Calculations give moments of distributions
- Higher moments harder - hypercubic symmetry…
- Can we recover shape from knowledge of, say, first three moments?

Detmold, Melnitchouk, Thomas

Employs parametrization strongly motivated by experiment

\[ x(u_v(x) - d_v(x)) = a x^b (1 - x)^c (1 + \varepsilon \sqrt{x} + \gamma x) \]

Model dependence
Proton Properties Measured in Different Experiments

- **Elastic Scattering**
  - transverse quark distribution in Coordinate space

- **DIS**
  - longitudinal quark distribution in momentum space

- **DES (GPDs)**
  - Fully-correlated quark distribution in both coordinate and momentum space
Generalized form factors…

\[ A_{10}, A_{20}, A_{30} \]

\[ m_\pi = 0.740 \text{ GeV} \]

\[ A_{n0}^{u-d} \]

\[ \pm \]

Decrease slope : decreasing transverse size as \( x \to 1 \)

Burkardt

LHPC (Edwards et al.)
The Search for “Missing States” in the Quark Model Classification of N*
Excited-Baryon Analysis Center

A proposal for the establishment of an excited-baryon analysis center at JLab

• **Role:** To develop theoretical tools (e.g. coupled channel; EFT) to analyze existing & future CLAS data

• **Scientific relevance:**
  1. identify new baryon resonances
  2. measure couplings & transition form factors
  3. comparison with LQCD
  4. deepen understanding of how QCD is realized

• **Critical theoretical issues:**
  1. background-resonance separation
  2. incorporation of multi-particle final states
  3. importance of unitarity, analyticity…
Proposed Structure of EBAC

- Senior theorist with a broad knowledge of hadronic and electromagnetic interactions, reaction theory, and the methods used in phenomenological analysis

- Mid- and junior-level staff positions and term/visiting positions for theorists and experimentalists to advance the program and to interface with relevant groups. Strong workshop/visitor program.

- Independent, Expert Scientific Advisory Board

- Total budget ~ $ 700k per year (+overhead)

S&T Review 2003: “A critical need in the overall JLab program is to have a systematic effort dedicated to analysis of photo- and electro-production of baryons and mesons. The theory group, in concert with the needs of the experimental collaborations, has begun to formulate a plan to establish an N* Analysis Center. We applaud this long-needed initiative.”
Close Working Link Between Baryon and Meson Analysis

PHYSICAL REVIEW D 68, 036003 (2003)

Meson model for $f_0(980)$ production in peripheral pion-nucleon reactions

F. P. Sassen, S. Krewald, and J. Speth
Institut für Kernphysik, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

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Special Research Centre for the Subatomic Structure of Matter, University of Adelaide, Adelaide 5005, Australia
(Received 3 December 2002; published 25 August 2003)

The Jülich model for $\pi\pi$ scattering, based on an effective meson-meson Lagrangian, is applied to the analysis of the $S$-wave production amplitudes derived from the BNL E852 experiment $\pi^- p \rightarrow \pi^0 \pi^0 n$ for a pion momentum of 18.3 GeV and the GAMS experiments performed at 38 GeV and 100 GeV. The unexpected strong dependence of the $S$-wave partial wave amplitude on the momentum transfer between the proton and neutron in the vicinity of the $f_0(980)$ resonance is explained in our analysis as an interference effect between the resonance and the nonresonant background.
Conclusion

Further development of Theory at JLab is vital to:

• Success of present experimental program

• Design and implementation of the 12 GeV Upgrade

• Development of the case for Hadron Physics Beyond 12 GeV