The Hall D Project

The Search for Gluonic Excitations (Unusual Mesons) Using Photons

We are here to:

- Tell you about this exciting new initiative at JLab
- Discuss the physics
- Show you how far we have progressed
- Ask for your help and guidance to carry out the R & D needed to:
  - complete the design
  - prepare the Conceptual Design Report

A. Dzierba - Overview (35 min)
A. Szczepaniak - Photon polarization (10 min)
C. Meyer - Detector and R&D (15 min)
Hall D Collaboration

US Experimental Groups

Support:

DN - DOE Nuclear
DH - DOE HEP
NSF - NSF Nuclear

DN  R. Clark, P. Eugenio,
    G. Franklin, C. A. Meyer (Co-Spokesperson),
    B. Quinn, R. Schumacher
    Carnegie Mellon University (Pittsburgh, PA)

DN  H. Crannell, D. Sober
    Catholic University of America (Washington, D. C.)

DN  D. Doughty, D. Heddle
    Christopher Newport U (Newport News, VA)

DN  R. Jones *
    University of Connecticut (Storrs, CT)

DN  W. Boeglin, L. Kramer, P. Markowitz, B. Raue,
    J. Reinhold
    Florida International University (Miami, FL)

* seeking support from DOE/NSF

DN  L. Dennis, P. Dragovitsch, G. Riccardi
    Florida State University (Tallahassee, FL)

DH  A. Dzierba (Spokesperson), R. Heinz, E. Scott,
    P. Smith, C. Steffen, T. Sulanke, S. Teige
    Indiana University (Bloomington, IN)

DN  D. Abbott, I. Bird, R. Carlini, H. Fenker, G. Heyes,
    R. Macleod, C. Sinclair, E. Smith (Hall D Group
    Leader), D. Weygand, E. Wolin
    Jefferson Lab (Newport News, VA)

DN  R. Mischke, A. Palounek, J. C. Peng
    Los Alamos National Lab (Los Alamos, NM)

DN  M. Khandaker, V. Punjabi, C. Salgado
    Norfolk State University (Norfolk, VA)

DN  G. Dodge, A. Klein, S. Kuhn, P. Ulmer, L. Weinstein
    Old Dominion University (Norfolk, VA)

NSF  D. Carman, K. Hicks
     Ohio University (Athens, OH)

NSF  S. Dytman, J. Mueller
     University of Pittsburgh (Pittsburgh, PA)

NSF  G. Adams, J. Cummings, A. Empl,
     J. Napolitano, P. Stoler
     Rensselaer Polytechnic Institute (Troy, NY)
Hall D Collaboration

Theory Groups

S. Godfrey  
*Carleton U (Ottawa, Ontario, Canada)*

R. Kaminski, L. Lesniak  
*Institute of Nuclear Physics - Cracow, Poland*

J. Goity  
*Hampton U (Hampton, VA)*

C. Horowitz, T. Londergan, M. Pichowsky, A. Szczepaniak  
*Indiana U (Bloomington, IN)*

P. Page  
*Los Alamos National Lab (Los Alamos, NM)*

A. Afanasev  
*North Carolina Central U (Durham, NC)*

E. Swanson  
*University of Pittsburgh (Pittsburgh, PA)*

T. Barnes  
*U of Tennessee (Knoxville, TN)*  
*Oak Ridge National Lab (Oak Ridge, TN)*

R. Davidson, N. Mukhopadhyay  
*Rensselaer Polytechnic Institute (Troy, NY)*

Foreign Groups  -  (experimental)

S. Denisov, N. Fedyakin, A. Gorokhov, V. Samoilenko, A. Schukin  
*Institute for High Energy Physics (Protvino, Russia)*

*Moscow State U (Moscow, Russia)*

V. Druginin, V. Ivanchenko, E. Solodov  
*Budker Institute of Nuclear Physics (Novosibirsk, Russia)*

E. J. Brash, G. M. Huber, G. J. Lolos, Z. Papandreou  
*U of Regina (Regina, Saskatchewan, Canada)*

J. M. Laget, M. Garcon  
*Saclay (France)*

Additional Groups  -  (discussions in progress)

**NSF**  
J. Cameron et al  
*IUCF - Bloomington, IN*

T. Nakano et al  
*SPring8 - Osaka, Japan*

K. Helbing et al  
*Erlagen, Germany*

**NSF**  
R. Melnitchouk, A. Thomas, A. Williams  
*CSSM - Adelaide, Australia*
The Hall D Project - Overview

Collaboration History

- 80 physicists from 25 institutions
  - Spokesman (A. Dzierba), Co-Spokesman (C. Meyer) and Hall D Group Leader (E. Smith)
  - management plan being developed

- 8 workshops since July, 1997 (at 6 institutions)

- Numerous meetings with JLab - management and accelerator

- LOI presented to PAC15 in Jan, 1999 - enthusiastic response

- Design Report - ver 2 - completed in August, 1999

- Cassel Review - December 6-7, 1999 - more details will follow

- MEGA/LASS Solenoid Assessment at LANL - March 9-11, 2000

- Collaboration Meeting at Indiana U/IUCF in Bloomington - April 6-8, 2000

- Memorandum of Understanding - to be completed in April, 2000

- Design Report - ver 3 - to be completed in August, 2000
Can QCD account quantitatively for the confinement of quarks and gluons inside hadrons?

The important remaining question is this:

- Is QCD the correct theory of hadron structure?
- What testable predictions does it make that arise inevitably from its mechanism of confinement?

Confinement arises in QCD from a simple but radical postulate: the gluons themselves carry a strong interaction charge, in contrast to photons which carry no electric charge.

**Prediction:** Mesons should exist in which gluons bind to each other with no quarks present (*glueballs*). Another possibility - hybrid mesons in which a gluon binds to a quark - antiquark (*hybrids*) and these can have quantum numbers not allowed by quark - antiquark (*exotic hybrids*).

In the flux-tube picture, which is supported by lattice-gauge theory calculations, the gluons in a hadron are confined to flux-tubes. Conventional mesons arise when the flux-tube is in its ground state. Hybrid mesons arise when the flux-tube is in an excited state.
Search for QCD Mesons

- **QCD predicts mesons beyond the naive quark model**
  - glueballs and hybrids (*some with exotic J^{PC}*)
  - hard to find but *tantalizing candidates exist*
  - LGT and flux-tube *converging on masses*
  - expect to find in the mass range: 1.5 to 2.5 GeV/c^2

- **Photoproduction of light quark exotic hybrids provide a clean sector for these searches**
  - exotic hybrids do not mix with \( \bar{q}q \)
  - glueballs not likely to be photoproduced
  - photon probe (\( \bar{q}q \) in spin-1) is likely to yield exotic hybrids (flux tube in 1st excited state)
  - hybrid searches in the charm and beauty sectors very difficult
  - vector hybrids suppressed in e^+e^- collisions
  - the one area where data on light quark mesons is non-existent is precisely where you expect to find them
Search for QCD Mesons

- Photon beams are expected to yield rich results
- Optimal energy for study is 8 - 9 GeV for photons
- Requires electron energies of 12 GeV (flux and polarization)
- Hermetic detector design with excellent resolution and rate capability
- JLab is unique
- Unprecedented statistics compared to hadron data
- Guaranteed to provide important new information - independent of any theoretical model

Extensive data with $\pi$ probes exist

Little data with $\gamma$ probes exist

In the first excited state of the flux tube half of the possible $J^{PC}$ are exotic only if $S = 1$
How to Search for Exotics

• **Determination of $J^{PC}$ of Meson States requires a Partial Wave Analysis (PWA)**
  - need to kinematically identify an exclusive production process
  - provides information on the production mechanism
  - sensitivity to a variety of decay modes

Note that flux tube and other models of gluonic excitations predict the production mode and decay modes of hybrids. Also - PWA can be complicated and consistent results among various decay modes will be important in isolating hybrid states.

• **Successful application of PWA puts demands on the experiment**
  • need good acceptance - hermetic detector and good resolution
  • sensitivity to decay modes - particle ID: $\pi^\pm$, $K^\pm$, $\pi^0$, $\eta$, ..
  • identify the production mechanism - linear polarization
  • high statistics - photon flux and rate capability
  • appropriate beam energy - high enough to reach masses and have good acceptance
The Photon Beam and Linear Polarization

Linear Polarization is:
- essential in identifying the production mechanism
- is helpful in extracting decay amplitudes
- is a filter for exotics

Need for linear polarization implies:
- coherent bremsstrahlung (will deliver necessary energy and flux)
- Compton backscatter (requires high energy electrons and the required flux is not achievable)

Bremsstrahlung Spectrum for:
- 15 micron diamond radiator
- 1 μA 12 GeV electron beam

Coherent and incoherent spectrum shown

Collimation of the beam will enhance the coherent component relative to the incoherent.
Vector rest frame

**Linear Polarization**

A simple example

\[ \gamma \rightarrow V \]

\[ p \rightarrow p \]

**Photon**

**Exchange Particle**

Relative orbital angular momentum (L) cannot have projection along z axis.

Therefore, produced Vector has \( m = 1 \) if photon has \( m = 1 \) and has \( m = -1 \) if photon has \( m = -1 \).

Possible values of L are 0, 1 or 2.

**Parity Conservation**

\[ P_V = -1 = P_\gamma \cdot P_e \cdot (-1)^L \]

For our case, if the exchange particle has negative parity then \( L = 1 \) and if the exchange particle has positive parity then \( L = 0 \) or 2.

**Linear Polarization Essential**

Natural + unnatural exchange amplitudes contribute:

\[ A^N + A^U \]

\[ e_x = \frac{-1}{\sqrt{2}}(e_R - e_L) \]

\[ e_y = \frac{i}{\sqrt{2}}(e_R + e_L) \]

**Circularly polarized photons** measure the sum or differences of amplitudes whereas **linearly polarized photons** allow a separation.

**more to follow: Adam Szczepaniak**
Suppose the vector decays into two spinless particles

\[ V \rightarrow PP \Rightarrow \begin{cases} \rho \rightarrow \pi\pi \\ \phi \rightarrow KK \end{cases} \]

w.f. for the decay:

- **Circular**
  \[ Y_1^1 \propto \sin \theta \cdot e^{+i\phi} \]
  \[ \Rightarrow \frac{dN}{d\Omega} \propto \sin^2 \theta \]

- **Unpolarized**
  \[ Y_1^{-1} \propto \sin \theta \cdot e^{-i\phi} \]
  \[ \Rightarrow \frac{dN}{d\Omega} \propto \sin^2 \theta \cdot \cos^2 \phi \]

- **Linear**

**Natural Parity Exchange**

**Unnatural Parity Exchange**

\( J^p = 0^+, \ 1^+, \ 2^+, \ etc... \quad J^p = 0^-, \ 1^-, \ 2^-, \ etc... \)

in the vector rest frame
Electron Energy

Photon Flux in Coherent Peak
- endpoint energy = 12 GeV
- blue line = 11 GeV
- brown line = 10 GeV

Total Hadronic Rate Constant at approx 20 KHz

Linear Polarization
- endpoint energy = 12 GeV
- blue line = 11 GeV
- brown line = 10 GeV

Electron Energy

Linear polarization

Photon energy

Flux of photons: millions/sec
assume isotropic decay angles and a distribution: \[
\frac{dN}{dt} \propto e^{-8t}
\]

Optimal Photon Energy

Figure of Merit
Uniqueness of JLab

- **Photoproduction** - an unexplored regime - extant data are paltry
  - likely place to find exotic hybrids
    - photon is a $\bar{q}q$ with spins aligned and excitations of the flux tube leads to exotic $J^{PC}$
  - photon beams at JLab unprecedented in
    - intensity
    - flux
    - size
    - resolution
    - duty factor
    - linear polarization

- **Optimal photon energy** (8 - 9 GeV) achievable with 12 GeV electrons

- **Existing facilities cannot do the job**
  - SLAC - duty factor is $10^{-4}$ compared to 1
  - FNAL - photon beams are tertiary (backgrounds, large spot size)
  - ELFE - planned facility - uncertain future
The Hall D Detector

MEGA/LASS
Superconducting Solenoid

Target

TOF Wall

Tracking Chambers

Cerenkov Counter

Barrel Calorimeter

Lead Glass Detector
2200-elements

EXISTS!

EXISTS!

More to follow - from Curtis Meyer on the Detector Overview
Statistics Needed for PWA

• Carry out a PWA in 10 MeV mass bins for 10 equally populated bins in | t |
  - mapping out the t-dependence provides information about the production mechanism

• Take the E852 signal reported in $\rho \pi$ as a benchmark
  - exotic signal was 5% of the $a_2$ signal in that experiment

With a flux of $10^7$ photons/sec and a 30-cm LH$_2$ target and 1 year of data-taking:

Assuming an overall efficiency of 20% (data-taking, acceptance, reconstruction, etc..)

Our yield will be 200 times that collected by E852 and we would have about 1500 events in the central 10 MeV bin of the exotic signal in one | t | bin
Rates and Doing the Analysis

Rates

- at $10^7$ photons/sec we record 10 KHz (hadronic + accidental)

- pipeline electronics at the outset will eventually allow us to run at $10^8$ photons/sec with high level software trigger

Analysis

- High analysis rate capability exists at JLab

Physics Analysis

- Close collaboration of theorists/experimentalists
  - develop formalism for PWA and phenomenology
- Independent PWA teams
Costing the Experiment

**Summary**

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost ($K)</th>
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<tr>
<td>Detector Package</td>
<td>18200</td>
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<tr>
<td>Civil and Beamline</td>
<td>10000</td>
</tr>
<tr>
<td><strong>Total Cost</strong></td>
<td><strong>28200</strong></td>
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**Detector**

<table>
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<tr>
<td>Tracking</td>
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<tr>
<td>Barrel Calorimeter</td>
<td>2700</td>
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<tr>
<td>Cerenkov Counter</td>
<td>700</td>
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<tr>
<td>Forward Calorimeter</td>
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<tr>
<td>Time of Flight Wall</td>
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<tr>
<td>Start Counter</td>
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<tr>
<td>Computing</td>
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<td>Hydrogen Target</td>
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<tr>
<td>Solenoid</td>
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<td>Final Assembly</td>
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<tr>
<td>Photon Tagger</td>
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<tr>
<td><strong>Total</strong></td>
<td><strong>18200</strong></td>
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**Civil & Beamline**

**Buildings**

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<td>Utilities</td>
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<td>Crane</td>
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<td>Fire Protection</td>
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<td>Overhead</td>
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<tr>
<td><strong>Sub Total</strong></td>
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**Beamline**

<table>
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<th>Item</th>
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<tr>
<td>Diagnostics</td>
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<tr>
<td>Service Building</td>
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<tr>
<td>Elements</td>
<td>1200</td>
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<tr>
<td>Labor</td>
<td>1800</td>
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<tr>
<td><strong>Sub Total</strong></td>
<td><strong>3600</strong></td>
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**Total Civil & Beamline**

<table>
<thead>
<tr>
<th></th>
<th>Cost ($K)</th>
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<tbody>
<tr>
<td><strong>Total Civil &amp; Beamline</strong></td>
<td><strong>10000</strong></td>
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</tbody>
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**Cassel Review**

Dec 6-7, 1999

- David Cassel, Cornell (chair)
- Frank Close, Rutherford
- John Domingo, JLab
- Bill Dunwoodie, SLAC
- Don Geesaman, Argonne
- David Hitlin, Caltech
- Martin Olsson, Wisconsin
- Glenn Young, ORNL

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**From the Executive Summary**

- The experimental program proposed in the Hall D Project is well-suited for **definitive** searches of exotic states that are required according to our current understanding of QCD.

- JLab is **uniquely suited** to carry out this program of searching for exotic states.

- The **basic approach** advocated by the Hall D Collaboration is **sound**.

- The Collaboration will be ready to begin work on a Conceptual Design Report once a Project Office with a Project Director is in place.

- An **R&D program is required** to ensure that the magnet is usable, to optimize many of the detector choices, to ensure that novel designs are feasible, and to validate cost estimates.
Solenoid

Superconducting solenoid originally for LASS (SLAC) then moved to LANL for MEGA - 250 tons and 2.5 T field

Review team at LANL March 9-11, 2000

John Alcorn designers of the original
Steve St.Lorant LASS magnet
Paul Brindza JLab Systems Engineer for Experimental Equipment

Team inspected 4th coil (only 3 were used in MEGA) and the MEGA magnet, interviewed LANL staff (current and retired) involved in the transfer to LANL and operation and looked at documentation and logbooks.

Conclusions:

• Magnet and 4th coil in excellent shape

• Replacement cost: $10M

• Moving and upgrade cost: < $1M
Startup and R & D Funds

- R & D needs as per the Cassel Committee recommendations
- Needs shown below are in $K for two years
- R & D projects are of a generic nature
  - digital pipelines and digitizing for high rate experiments
  - tracking issues (e.g. sci-fi tracking)
  - calorimetry
- Solenoid and LGD moves - valuable resources for JLab

<table>
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<tr>
<th>Equipment</th>
<th>Salaries/ Travel</th>
<th>Total</th>
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<tr>
<td>Electronics</td>
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<td>TOF</td>
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<td>15</td>
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<tr>
<td>Cerenkov</td>
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<td>124</td>
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<tr>
<td>Tracking</td>
<td>195</td>
<td>260</td>
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<tr>
<td>Beam</td>
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<td>97</td>
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<tr>
<td>Barrel calorimeter</td>
<td>61</td>
<td>183</td>
</tr>
<tr>
<td>Solenoid move</td>
<td></td>
<td>500</td>
</tr>
<tr>
<td>LGD move</td>
<td></td>
<td>24</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>1948</strong></td>
</tr>
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</table>

Note: Numbers in this table for a two-year total.

Note: Indiana U has already contributed $30K and has given strong indication of an additional $280K for FY00/FY01 - This will be used to cover costs of infrastructure in the electronics lab and a processor farm and postdoc for computer simulations. This does not apply to the above table.

Note: NSERC (Regina) funding at level of C$200K for next two years likely - this will apply to the barrel calorimeter in the table above.
Other Physics

Focused Physics Goal Presented Here

• Search for exotic hybrids

General Purpose Detector Allows for Other Physics

• $K\bar{K}$ threshold and the $a_o/f_o$
  • Rare decays: $\phi$, $\eta$
  • Chiral dynamics
• Threshold Charm Production
Physics is Fundamental

Role of glue in strong QCD - Impressive strides in theory

Goal is Clear

Unambiguous identification of gluonic excitations starting with exotic hybrids

Photoproduction

Hybrids are expected to exist precisely where we have no current experimental information

Photon Beams

Needed energy, flux, duty factor and polarization are available at an energy-upgraded CEBAF

Detector

State of the art - based on several existing subsystems