The Search for Glueballs and Hybrids

Ulrich Wiedner
Ruhr-University Bochum

Sarajevo, February 4, 2013
QCD

Meson ($q\bar{q}$)

Baryon ($qqq$)

Glueball ($gg$)

Hybrid ($q\bar{q}g$)
Like social elephants, quarks only exist in groups with other quarks and are never found alone. Composite particles made of quarks are called hadrons.

Although individual quarks have fractional electrical charges, they combine such that hadrons have a net integer electric charge. Another property of hadrons is that they have no net color charge even though the quarks themselves carry color charge (we will talk more about this later).

There are two classes of hadrons (try putting your mouse on the elephants):

**Baryons**

...are any hadron which is made of three quarks (qqq).

Because they are made of two up quarks and one down quark (uud), **protons** are baryons. So are **neutrons** (udd).

**Mesons**

...contain one quark (q) and one antiquark (\(\bar{q}\)).

One example of a meson is a pion (\(\pi^+\)), which is made of an up quark and a down antiquark. The antiparticle of a meson just has its quark and antiquark switched, so an antipion (\(\pi^-\)) is made up a down quark and an up antiquark.

Because a meson consists of a particle and an antiparticle, it is very unstable. The kaon (K) meson lives much longer than most mesons, which is why it was called "strange" and gave this name to the strange quark, one of its components.

A weird thing about hadrons is that only a very very very small part of the mass of a hadron is due to the quarks in it.
A few % of the proton mass is generated due to the Higgs mechanism.

Most of the proton mass is created by the strong interaction.

Glueballs gain their mass solely by the strong interaction and are therefore an unique approach to the mass creation by the strong interaction.
Crystal Barrel

\[ \bar{p}p \rightarrow \pi^0\pi^0\pi^0 \text{ Dalitz plot} \]

700000 events = 6×700000 entries
100,000 events
The $X(4140)$

$$ M = 4143.4^{+2.9}_{-3.0} \text{(stat.)} \pm 1.2 \text{ MeV/c}^2 $$

$$ \Gamma = 11.7^{+8.3}_{-5.0} \text{(stat.)} \pm 3.7 \text{ MeV/c}^2 $$

CDF/DOC/BOTTOM/PUBLIC/10244;

Test for glueball properties

<table>
<thead>
<tr>
<th></th>
<th>$f_0(1500)$</th>
<th>$\eta_L(1410)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seen in antiproton annihilations</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Seen in radiative $J/\psi$ decays</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Seen in central production</td>
<td>✔</td>
<td>❌*</td>
</tr>
<tr>
<td>Not seen in $\gamma\gamma$ collisions</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Supernumerous to the nonet</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

* maybe due to kinematical suppression
The $\eta_L(1410)$ has strong affinity for glue and all signatures of a glueball.


**Problem:**

Lattice calculations put the pseudoscalar glueball at $\sim 2.3$ GeV.

**Exotic interpretation:**

gluino-gluino bound state

Claim:

The $\eta_L(1410)$ appears naturally as the pseudoscalar glueball if glueballs are closed gluonic fluxtubes.

GLUEBALLS, FLUXTUBES AND $\eta(1440)$.
L. Fadeev, A. Niemi and U. Wiedner
Phys.Rev.D70:114033, 2004
Are glueballs configurations of twisted or knotted colored flux?

Ulrich Wiedner
Twist can be left-handed or right-handed:

\[ |\pm\rangle = \frac{1}{\sqrt{2}} (|L\rangle \pm |R\rangle) \]

Glueballs could appear as mass degenerate parity doublets and should be produced with similar production rates.

This is the case for the \( f_0(1500) \) and the \( \eta_L(1410) \).
Production rates

Antiproton reactions:

\[
\text{BF}(p\bar{p} \to f_0(1500)) = (7.7 \pm 3.8) \times 10^{-3}
\]

\[
\text{BF}(p\bar{p} \to \eta_L(1410)\pi\pi) = (5.3 \pm 1.7) \times 10^{-3}
\]

Radiative J/ψ decays:

\[
\text{BF}(J/ψ \to \gamma f_0(1500)) = (1.3 \pm 0.3) \times 10^{-3}
\]

\[
\text{BF}(J/ψ \to \gamma \eta_L(1410)) = (1.0 \pm 0.46) \times 10^{-3}
\]
Isospin violating decays of $\eta(1440)$

$\eta(1440) \to f_0(980) \pi^0$

η(1440) produced in different processes from ongoing analysis

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Do gluonic excitations look like …

Glueball (gg)  Hybrid (q\bar{q}g)
The glueball spectrum
K.A. Meissner:

- strongly coupled bound states (glueballs with $0^{++}$ etc.) could be described by gravitational solutions but...
Open Strings

representing gauge theories

Closed Strings

representing gravitation

String World

Hadron World

meson

glueball

Ulrich Wiedner
Summary

PANDA physics

\[\uparrow\]

LHC physics

\[\downarrow\]

sub-Planck physics
In fact, his work led to two sets of very useful results. The first, purely pedagogical, is embodied in the *Feynman Lectures on Gravitation* (publication [123]). In those lectures, Feynman develops the quantum field theory of a neutral massless spin 2 particle (the *graviton*), emphasizing the special features that arise, in comparison to theories of spin 0 and spin 1 particles, as well as the complications that result for a zero-mass particle in trying to create a self-consistent theory. As in the case of spin 1, masslessness results in redundant degrees of freedom, since Lorentz invariance requires that a *massless* particle can spin only along or opposite to its direction of momentum (positive or negative *chirality*), while a massive spin 2 particle may take up five different orientations relative to any arbitrary quantization direction. Eliminating the unwanted degrees of freedom is achieved by imposing certain “gauge conditions,” which in the gravitational case brings about nonlinearity in the form of *graviton–graviton interaction*. Feynman shows that the classical limit of a properly gauged massless spin 2 theory is described by the Einstein gravitational field equations.\(^3\)
How to Calculate Meson Spectra from String Theory

Johanna Erdmenger

Max-Planck-Institut für Physik, München

work in collaboration with J. Babington, Z. Guralnik, I. Kirsch (HU Berlin),
R. Apreda, J. Große (HU Berlin/MPI München), N. Evans (Southampton)

AdS/CFT Correspondence

(Maldacena 1997, AdS: Anti de Sitter space, CFT: conformal field theory)

- Duality Quantum Field Theory ⇔ Gravity Theory
- Arises from String Theory in a particular low-energy limit
  - Duality: Quantum field theory at strong coupling
    ⇔ Gravity theory at weak coupling
  - Works for large $N$ gauge theories at large ’t Hooft coupling $\lambda$

Conformal field theory in four dimensions
  ⇔ Supergravity Theory on $AdS_5 \times S^5$
Comparison with experimental results

D4/D8/D8 brane model – spontaneous breaking of $SU(N_f) \times SU(N_f)$  

Sakai+Sugimoto 12/2004

vector and axial vector mesons  
(obtained from gauge field fluctuations as described by the DBI action)

meson mass ratio:

<table>
<thead>
<tr>
<th>Experiment:</th>
<th>$\frac{m_{a_1}^2}{m_\rho^2} = \frac{(1230\text{MeV})^2}{(776\text{MeV})^2} = 2.51$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stringy model:</td>
<td>$\frac{m_{a_1}^2}{m_\rho^2} = 2.4$</td>
</tr>
</tbody>
</table>

($\rho : C = -1, a_1 : C = +1$)

In the model of Sakai+Sugimoto, it is also possible to have $N_f > 1$.  

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Glueball Mass Spectrum from Supergravity

Csaba Csáki† and John Terning
Theoretical Physics Group
Ernest Orlando Lawrence Berkeley National Laboratory
University of California, Berkeley, CA 94720

and
Department of Physics
University of California, Berkeley, CA 94720

TABLE III. Masses of the first few $0^{++}$ glueballs in QCD$_4$, in GeV, from supergravity compared to the available lattice results. The first column gives the lattice result [7,16,17], the second the supergravity result for $a = 0$ while the third the supergravity result in the $a \to \infty$ limit. The change from $a = 0$ to $a = \infty$ in the supergravity predictions is tiny. Note, that for the excited state the supergravity calculation came before the lattice results.

<table>
<thead>
<tr>
<th>state</th>
<th>lattice, $N = 3$</th>
<th>supergravity $a = 0$</th>
<th>supergravity $a \to \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^{++}$</td>
<td>$1.61 \pm 0.15$</td>
<td>1.61 (input)</td>
<td>1.61 (input)</td>
</tr>
<tr>
<td>$0^{+++}$</td>
<td>$2.48 \pm 0.18$</td>
<td>2.55</td>
<td>2.56</td>
</tr>
<tr>
<td>$0^{++++}$</td>
<td>-</td>
<td>3.46</td>
<td>3.48</td>
</tr>
<tr>
<td>$0^{+++++}$</td>
<td>-</td>
<td>4.36</td>
<td>4.40</td>
</tr>
</tbody>
</table>
Crystal Barrel

\[ \bar{p}d \rightarrow \pi^+ \pi^- \eta + p \]

spectator
(<100 MeV/c)

\[ (\text{MeV}/c^2)^2 \]

\[ m^2(\eta \pi^-) \]

\[ m^2(\eta \pi^-) \rightarrow [ (\text{MeV}/c^2)^2 ] \]

\[ a_2(1320) \]

\[ a_2(1320) \quad \rho^-(770) \]

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Difference data-fit with “standard” resonances
$\chi^2 / \text{d.o.f} = 3.07$

Fit exceeds data

Data exceed fit

Include exotic $J^{PC} = 1^{+} \pi_1(1400)$ in fit
$\chi^2 / \text{d.o.f} = 1.29$
Properties of the $\pi_1(1400)$

Decay: $(\eta\pi)_L = 1$
Mass: $1400 \pm 30$ MeV
Width: $310 \pm 70$ MeV
Quantum numbers: $J^{PC} = 1^{-+}$ not possible from $\bar{q}q$

\[ \bar{J} = \bar{L} + \bar{S} \]
\[ P = (-1)^{L+1} \]
\[ C = (-1)^{L+S} \]

Previous indications of this resonance:

$\pi^- p \rightarrow (\pi^0 \eta)n$ (GAMS/CERN, 100 GeV/c, 1988)
$\pi^- p \rightarrow (\pi^0 \eta)n$ (VES/Serpukhov, 100 GeV/c, 1993)
$\pi^- p \rightarrow (\pi^0 \eta)n$ (E852/Brookhaven, 18 GeV/c, 1997))

$M: 1300 - 1400$ MeV/c$^2$, $\Gamma: 150 - 400$ MeV
Crystal Barrel

Exotic production in $\bar{p}p$: 

![Graph showing production of particles in $\bar{p}p$ collisions]
$J^{PC}=1^{-+}$ – Pb vs H Target

- Peak at 1.67 GeV/c² for both targets
- Phase motion indicates resonant behavior
- Structure at 1.2 GeV/c² unstable w.r.t. fit model
- No fit to spin-density matrix yet for H target
- Production of $M=1$ states enhanced for heavy target
- Non-resonant background to be understood

[Ulrich Wiedner]


X and Y mesons

\[ \text{X(3872)} \]

\[ B \rightarrow K \pi^- \pi^- J/\psi \]

\[ M(\pi^- \pi^- J/\psi) - M(J/\psi) \]

\[ \text{Y(3940)} \]

\[ B \rightarrow K \omega J/\psi \]

\[ M(\omega J/\psi) \]

\[ \text{Y(3940)} \rightarrow \text{X(3872)} \]

\[ \text{Y(4260)} \]

\[ e^+ e^- \rightarrow \gamma_{\text{ISR}} \pi^+ \pi^- J/\psi \]

\[ M(\pi^+ \pi^- J/\psi) \]

\[ \text{Y(4350)} \rightarrow \text{Y(4660)} \]

\[ e^+ e^- \rightarrow \gamma_{\text{ISR}} \pi^+ \pi^- \psi' \]

\[ M(\pi^+ \pi^- \psi') \]

\[ \text{X(4160)} \]

\[ e^+ e^- \rightarrow D^* D^* J/\psi \]

\[ M(D D^*) \]

\[ \text{Y(4140)} \]

\[ B \rightarrow K \phi J/\psi \]

\[ M(\phi J/\psi) \]

\[ \text{Y(4630)} \rightarrow \Lambda_c \Lambda_c \]

\[ e^+ e^- \rightarrow \gamma_{\text{ISR}} \Lambda_c \Lambda_c \]

\[ M(\Lambda_c \Lambda_c) \]
\[ \text{DD}^* \text{ molecule} \]

\[ \text{threshold effect} \]

\[ \text{tetraquark} \]
Transition from color forces to colorless nuclear forces?
Decay of charmonium hybrids
Lattice results*

Decay of charmonium provides a clean "tag".


Ulrich Wiedner
Proton-Antiproton contains already a 4-Quark-System

Idea: Dilepton-Tag from Drell-Yan-Production

Advantages

- Trigger
- less JPC-Ambiguities
- 1200 E./day @ 12 GeV
- 300 E./day @ 5-8 GeV antiproton-Beam (for L=10^{32} cm^{-2}s^{-1})
Exotics

*What we know:*

\[ \pi_1(1400) \]

- **Mass:** $1400 \pm 30$ MeV
- **Width:** $310 \pm 70$ MeV
- **Decay:** $(\eta \pi)$
- **JPC:** $1^{--}$

\[ \eta(1660) \]

- **Mass:** $1660 \pm 10 \pm 64$ MeV/$c^2$
- **Width:** $269 \pm 21 \pm 42$ MeV/$c^2$
- **Decay:** $(\rho \pi)$
- **JPC:** $1^{++}$


JLAB@12 GeV

PANDA

M.G. Alekseev et al., *PRL 104* (2010) 241803
\[ L = 2 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}, \]
\[ p_F = 1.5 - 15 \text{GeV}/c \]
\[ \Delta p/p = 10^{-4} - 10^{-5} \]

Ulrich Wiedner
PANDA Collaboration

At present a group of 500 physicists from 62 institutions and 16 countries


http://www.gsi.de/panda
Layout of the detector (top view)
# Further Preparatory Work

<table>
<thead>
<tr>
<th>Date</th>
<th>Stripping of topsoil (area tree felling)</th>
<th>Site roads (Messeler Parkstr.)</th>
<th>Site roads (southern traffic link)</th>
<th>Site roads (northern traffic link)</th>
</tr>
</thead>
<tbody>
<tr>
<td>01 / 12</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>02 / 12</td>
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<td>03 / 12</td>
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<tr>
<td>04 / 12</td>
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</tbody>
</table>

![Günter Rosner](Günter_Rosner.jpg)  ![PANDA Meeting, Darmstadt, 7/3/12](PANDA_Meeting_Darmstadt_7_3_12.jpg)
Experimental Site 2012
Timeline

- 2011
  - Building permits
- 2012
  - Site preparation
- 2013
  - Civil construction contracts
- 2014
  - Building of accelerator & detector components
- 2015
  - Completion of civil construction work
- 2016
  - Installation & commissioning of accelerators and detectors
- 2017
  - Start Data taking
Thank you!