Glueballs and Light-Meson Spectroscopy

V. Credé

Florida State University, Tallahassee, Florida

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Outline

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The Quark Model of Hadrons

- Mesons ($q\bar{q}$) $\quad q \otimes \bar{q} = 3 \otimes \bar{3} = 8 \oplus 1$

- Baryons (qqq) $\quad q \otimes q \otimes q = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

Ordinary matter ...

The Quark Model of Hadrons

- **Mesons** ($q\bar{q}$) $\quad q \otimes \bar{q} = 3 \otimes \bar{3} = 8 \oplus 1$

- **Baryons** (qqq) $\quad q \otimes q \otimes q = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$

However, QCD also predicts so-called exotic states

➜ simplest possibility: $\underbrace{q \otimes \bar{q} \otimes q = 15 \oplus 6 \oplus 3 \oplus 3}$ *"SU(3) Color"*

Does not work: color singlets needed !

➜ multiple of (qqq) and ($q\bar{q}$) necessary

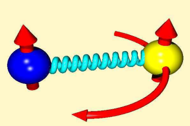
- **Glueballs:** $g \otimes g = 8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus \boxed{1}$
- **Hybrids:** $q \otimes \bar{q} \otimes g = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 8 \oplus \boxed{1}$ ➜ $\boxed{(q\bar{q})^l((q)^3)^m(g)^n}$,

$l + m \geq 1$ for n = 1

Ordinary Mesons

$J^{PC} \equiv {}^{2S+1}L_J$

- Parity $P = (-1)^{L+1}$
- Charge Conjugation (defined for neutral mesons) $C = (-1)^{L+S}$
- G parity $G = C(-1)^I$

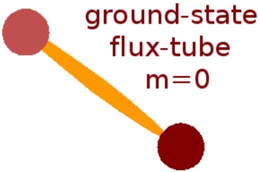


$L = 0,\ S = 1:$

$\rho,\ \omega,\ \phi\ (J^{PC} = 1^{--})$

$L = 0,\ S = 0:$

e.g. $\pi\ (J^{PC} = 0^{-+})$



Ordinary and Exotic Mesons

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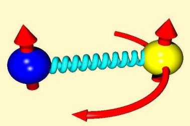

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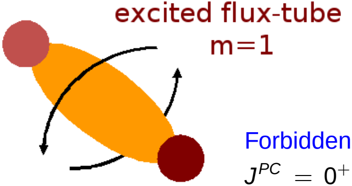

12 GeV CEBAF upgrade has high priority (DOE Office of Science, Long Range Plan) "[key area] is experimental verification of the powerful force fields *(flux tubes)* believed to be responsible for quark confinement."

Forbidden States (Exotics):

$J^{PC} = 0^{+-},\ 0^{--},\ 1^{-+},\ \cdots$

Mesons and their Quantum Numbers

		J^{PC}	$^{2S+1}L_J$	$I=1$	$I=0\ (n\bar{n})$	$I=0\ (s\bar{s})$	Strange
$L=0$	$S=0$	0^{-+}	$^1S_0$	π	η	η'	K
	$S=1$	1^{--}	$^3S_1$	ρ	ω	ϕ	K^*
$L=1$	$S=0$	1^{+-}	$^1P_1$	b_1	h_1	h'_1	K_1
	$S=1$	0^{++}	$^3P_0$	a_0	f_0	f'_0	K^*_0
	$S=1$	1^{++}	$^3P_1$	a_1	f_1	f'_1	K_1
	$S=1$	2^{++}	$^3P_2$	a_2	f_2	f'_2	K^*_2

Notation

1. J^{PC} s are measured quantities.
2. $^{2S+1}L_J$ s are internal quantum numbers in a non-relativistic quark model.

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	$S=1$	2^{++}	$^3P_2$	a_2	f_2	f'_2	K^*_2

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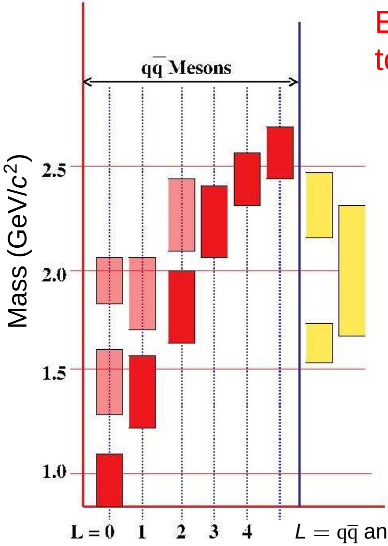
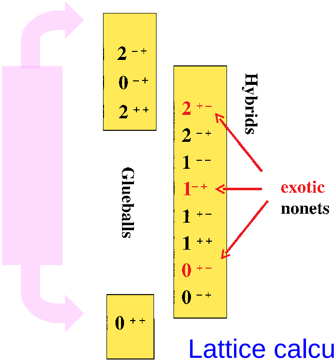


Each box corresponds to 4 nonets (2 nonets for $L = 0$)

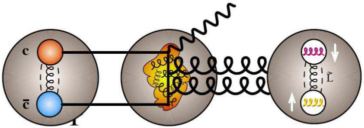


Lattice calculations:
(lightest) $M_{0^{++}} \approx 1.55$ GeV/c^2

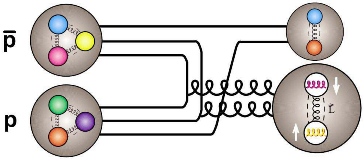
Outline

Glue-Rich Environments

Pictures: Ulrich Wiedner



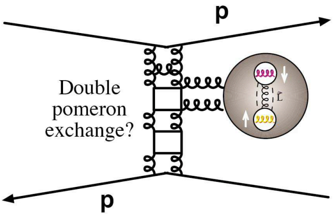
Mark III, DM 2, BES



Asterix, Obelix, Crystal Barrel

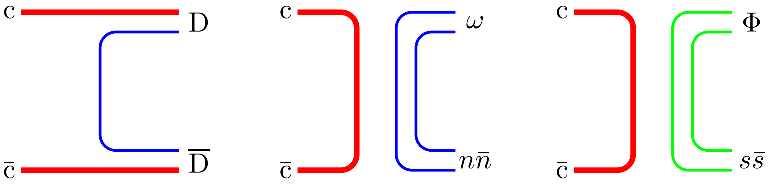
Different Production Mechanisms

1. J/ψ may convert into 2 gluons and a photon.
2. In $p\bar{p}$ annihilation, $q\bar{q}$ pairs annihilate into gluons forming glueballs.
3. Central production: two hadrons scatter diffractively, no exchange of valence quarks.



WA 79, WA 102

The OZI Rule and Flavor-Tagging Approach



The decay of J/ψ into mesons with open charm (left) is forbidden due to energy conservation.

The two right diagrams require annihilation of $c\bar{c}$ into gluons:

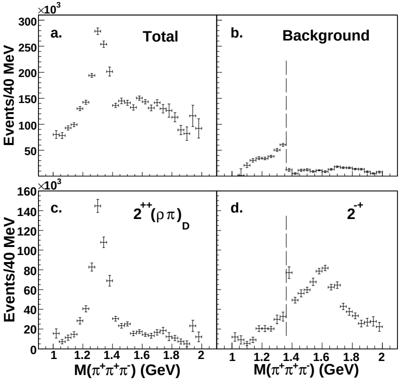
- Recoiling against ω, mesons with $n\bar{n}$ quark structure are expected.
- If a ϕ is observed, we expect mesons with hidden strangeness $s\bar{s}$.

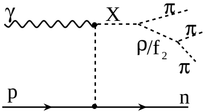
➜ OZI rule, e.g. ratio $\phi\eta'/\omega\eta' \sim$ ratio of $s\bar{s}/n\bar{n}$ in η' w.f.

Meson Spectroscopy in Photoinduced Reactions

Results on light mesons from CLAS at Jefferson Lab

1. Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system
(M. Nozar *et al.*, Phys. Rev. Lett. **102**, 102002 (2009))





charge exchange

CLAS

The authors don't observe a resonant structure in the 1^{-+} $(\rho\pi)_P$ partial wave.

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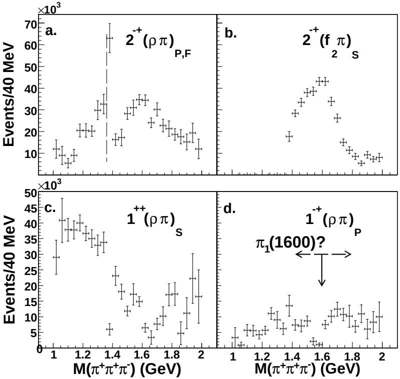

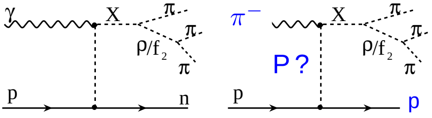

charge exchange — CLAS

neutral exchange — E852

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Meson Spectroscopy in Photoinduced Reactions

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1. Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system
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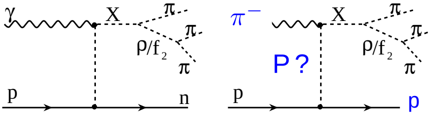
A $J^{PC} = 1^{-+}$ gluonic hybrid should be photo-produced at the same rate as the $a_2(1320)$, whereas in pion production it should be suppressed by a factor of 10.
(Close & Page, Phys. Rev. D **52**, 1706 (1995))



charge exchange — CLAS
neutral exchange — E852

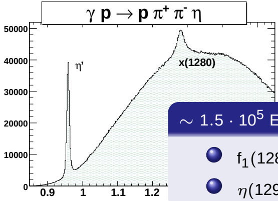
- Upper limit for the $\pi_1(1600)$ of 13.5 nb, less than 2 % of the $a_2(1320)$.

- New HyCLAS data have an order of magnitude more statistics.
  ➜ e.g. $\gamma p \to p\,\pi^+\pi^+\pi^-$, $\gamma p \to p\,\pi^+\pi^-\pi^0$ ($J^{PC} = 1^{-+}$ isoscalar production?)
- GlueX proposed to map out the light exotic spectrum.

Meson Spectroscopy in Photoinduced Reactions

Results on light mesons from CLAS at Jefferson Lab

1. Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system
   (M. Nozar *et al.*, Phys. Rev. Lett. **102**, 102002 (2009))
2. First measurement of direct $f_0(980)$ photoproduction on the proton
   (M. Battaglieri *et al.*, Phys. Rev. Lett. **102**, 102001 (2009))
3. Production and decay of the $f_1/\eta\,(1285)$ [*in the g11 data set*]
   (R. Dickson *et al.*, Ph.D. thesis)



$\sim 1.5 \cdot 10^5$ Events, PDG Properties

- $f_1(1285)\ 1^{++}$, $\Gamma = 24$ MeV
- $\eta(1295)\ 0^{-+}$, $\Gamma = 55$ MeV

Channel	Measurements
$\eta\pi\pi$	dσ/dΩ, mass, and Γ
$a_0\pi$	Dalitz plot analysis
$KK\pi$	dσ/dΩ, B. F.
$\rho^0\gamma$	B. F. (upper limit)

Outline

The $I = 0$, $J^{PC} = 0^{-+}$ (Pseudoscalar) Mesons

Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$\eta(548)$ *	547.51 ± 0.18	$1.30 \pm .07$ keV	$\gamma\gamma$, 3π
$\eta'(958)$ *	957.78 ± 0.14	0.203 ± 0.016	$\eta\pi\pi$, $\rho\gamma$, $\omega\gamma$, $\gamma\gamma$
$\eta(1295)$ *	1294 ± 4	55 ± 5	$\eta\pi\pi$, $a_0\pi$, $\gamma\gamma$, $\eta\sigma$, $K\bar{K}\pi$
$\eta(1405)$ *	1409.8 ± 2.5	51.1 ± 3.4	$K\bar{K}\pi$, $\eta\pi\pi$, $a_0\pi$, $f_0\eta$, 4π
$\eta(1475)$ *	1476 ± 4	87 ± 9	$K\bar{K}\pi$, $K\bar{K}^* + cc$, $a_0\pi$, $\gamma\gamma$
$\eta(1760)$	1760 ± 11	60 ± 16	$\omega\omega$, 4π
$\eta(2225)$	2220 ± 18	$150^{+300}_{-60} \pm 60$	$K\bar{K}K\bar{K}$

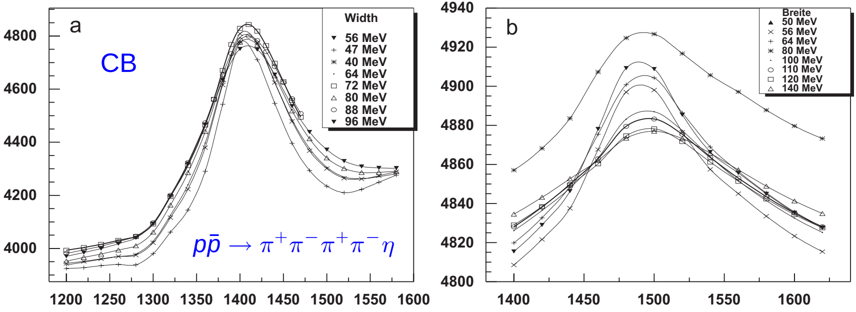
Five pseudoscalar states < 1500 MeV/c^2 listed in the PDG summary table

➜ Too many for two nonets!!

The Search for the Lightest Pseudoscalar Glueball

In 1990, Mark III reported two pseudoscalar states in the 1400 MeV/c^2 region in radiative J/ψ decays (with $J/\psi \to a_0(980)\pi$ and $J/\psi \to K^*K$).

- Both states confirmed by Crystal Barrel and Obelix at LEAR
- But: CB did NOT observe the $\eta(1295)$



The Search for the Lightest Pseudoscalar Glueball

In 2001, L3 observed $\eta(1475) \to K\bar{K}\pi$ in two-photon collisions.

- No observation by L3 of the second state, the $\eta(1405)$ ➜ Glueball?

The Search for the Lightest Pseudoscalar Glueball

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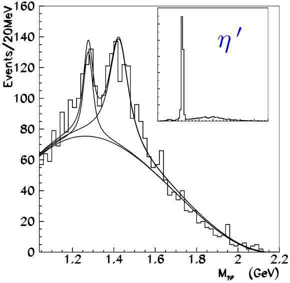
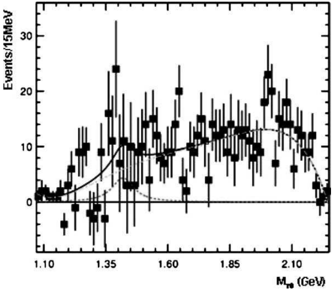
- No observation by L3 of the second state, the $\eta(1405)$ ➜ Glueball?
- In 2005, CLEO published (high-statistics) negative results on both states.

The Flavor Filter in the Decay $J/\psi \to \gamma[\gamma V]$

BES-II studied $J/\psi \to \gamma\gamma V(\rho, \phi)$

- Clear observation of peak at $M \approx 1424$ MeV/c^2 in $X(1424) \to \gamma\rho$ (left)
- No observation of $X(1424) \to \gamma\phi$ (right)!
  ➜ Glueball should decay to both final states.

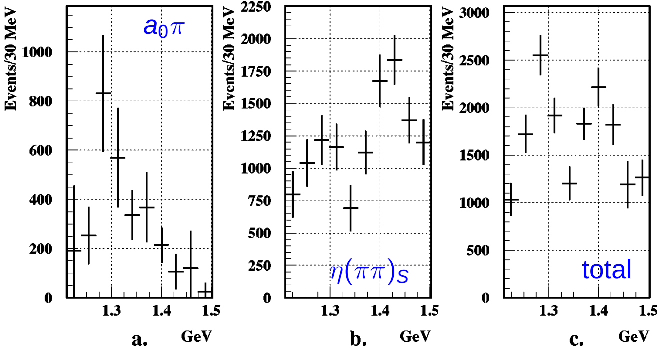




What about the $\eta(1295)$?

Often interpreted as first radial excitation of the η meson.

- Ideal mixing: degenerate in mass with $\pi(1300)$
- Problem: only observed in pion-induced reactions!



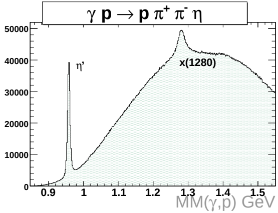
E852

$\eta \rightarrow a_0(980)\pi$

Study of the $\eta(1295)$ in Photoproduction at CLAS

First photoproduction measurements of $x(1280)$
(Preliminary conclusions from talk at APS Spring Meeting 2009)

- Mass and width of the state consistent with the PDG values for $f_1(1285)$, not the $\eta(1295)$
- Cross sections being compared to models for both 0^- and 1^+
- Dalitz plot analysis of $\eta\pi\pi$ final state shows clear $a_0(980)$ intermediate state, with no charge asymmetry
- $KK\pi$ and $\eta\pi\pi$ final states measured; no $\rho^0\gamma$ final state seen
  - ➜ inconsistent with $f_1(1285)$ (PDG: $(5.5 \pm 1.3)\,\%$ for $f_1 \to \gamma\rho^0$)



The 2^{++} Tensor Glueball

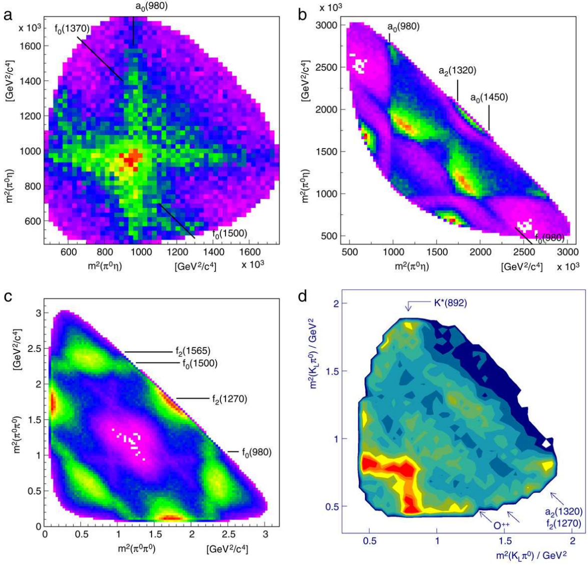
Evidence essentially non-existent!

- Two quark configurations yield 2^{++}:
  1. $L = 1,\ S = 1,\ J = 2:\ {}^3P_2$ ➜
  2. $L = 3,\ S = 1,\ J = 2:\ {}^3F_2$
- For both nonets, radial excitations are expected.
- Situation premature: none of the states can be assigned definitely to any of the above nonets.

Name	Mass [MeV/c^2]
$f_2(1270)$ *	1275.4 ± 1.1
$f_2(1430)$	1430
$f_2'(1525)$ *	1525 ± 5
$f_2(1565)$	1546 ± 12
$f_2(1640)$	1638 ± 6
$f_2(1810)$	1815 ± 12
$f_2(1910)$	1915 ± 7
$f_2(1950)$ *	1944 ± 12
$f_2(2010)$ *	2011^{+60}_{-80}
$f_2(2150)$	2156 ± 11
$f_2(2300)$ *	2297 ± 28
$f_2(2340)$ *	2339 ± 60

The $I = 0$, $J^{PC} = 0^{++}$ (Scalar) Mesons

Name	Mass [MeV/c^2]	Width [MeV/c^2]	Decays
$f_0(600)$ $*$	$400 - 1200$	$600 - 1000$	$\pi\pi$, $\gamma\gamma$
$f_0(980)$ $*$	980 ± 10	$40 - 100$	$\pi\pi$, $K\bar{K}$, $\gamma\gamma$
$f_0(1370)$ $*$	$1200 - 1500$	$200 - 500$	$\pi\pi$, $\rho\rho$, $\sigma\sigma$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $K\bar{K}$
$f_0(1500)$ $*$	1507 ± 5	109 ± 7	$\pi\pi$, $\sigma\sigma$, $\rho\rho$, $\pi(1300)\pi$, $a_1\pi$, $\eta\eta$, $\eta\eta'$ $K\bar{K}$, $\gamma\gamma$
$f_0(1710)$ $*$	1718 ± 6	137 ± 8	$\pi\pi$, $K\bar{K}$, $\eta\eta$, $\omega\omega$, $\gamma\gamma$
$f_0(1790)$			
$f_0(2020)$	1992 ± 16	442 ± 60	$\rho\pi\pi$, $\pi\pi$, $\rho\rho$, $\omega\omega$, $\eta\eta$
$f_0(2100)$	2103 ± 7	206 ± 15	$\eta\pi\pi$, $\pi\pi$, $\pi\pi\pi\pi$, $\eta\eta$, $\eta\eta'$
$f_0(2200)$	2189 ± 13	238 ± 50	$\pi\pi$, $K\bar{K}$, $\eta\eta$



Crystal Barrel

a	$p\bar{p} \to \pi^0\eta\eta$
b	$p\bar{p} \to \pi^0\pi^0\eta$
c	$p\bar{p} \to \pi^0\pi^0\pi^0$
d	$p\bar{p} \to \pi^0 K_L K_L$

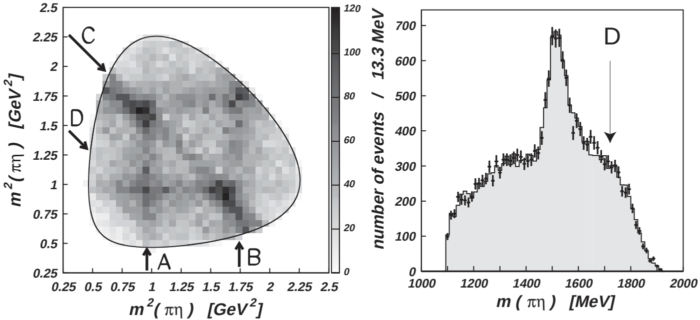
Good description with

- Two isoscalar states: $f_0(1370)$ / $f_0(1500)$
- In addition:
  Both have dominant 4π decay modes.
  ➜ $n\bar{n}$ structure

The $f_0(1710)$ Scalar Meson in Crystal Barrel

First discovered by Crystal-Ball in radiative J/ψ decays into $\eta\eta$

- Spin ($J = 0$ or 2) remained controversial for a long time
- No satisfactory Crystal Barrel signal around 1700 MeV/c^2 for a scalar or a tensor state in $\pi^0\pi^0\pi^0$ or $\pi^0\eta\eta$



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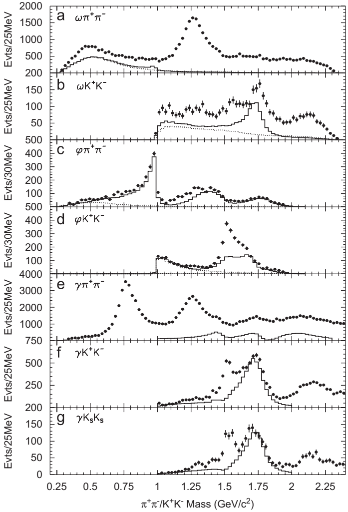
- No satisfactory Crystal Barrel signal around 1700 MeV/c^2 for a scalar or a tensor state in $\pi^0\pi^0\pi^0$ or $\pi^0\eta\eta$
- Consistent with a dominant $s\bar{s}$ assignment
  - ➜ Confirmed by WA102 reporting a much stronger $K\bar{K}$ coupling of $f_0(1710)$ than $\pi\pi$ coupling

BES spoils the Glueball Picture ...

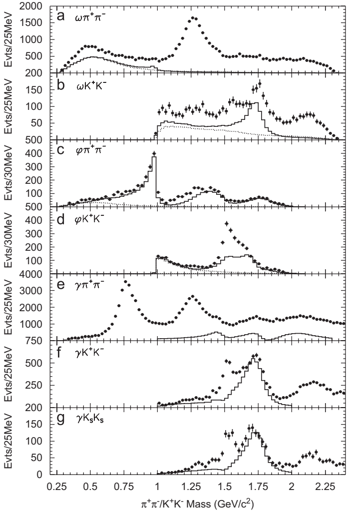


Flavor Tagging

ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

BES spoils the Glueball Picture ...



Flavor Tagging

ωK^+K^- ➜ Peak around 1700 MeV/c^2 (OZI rule: $n\bar{n}$ structure)

$\phi\pi^+\pi^-$ ➜ Enhancement at 1790 MeV/c^2

ϕK^+K^- ➜ No peak around 1700 MeV/c^2

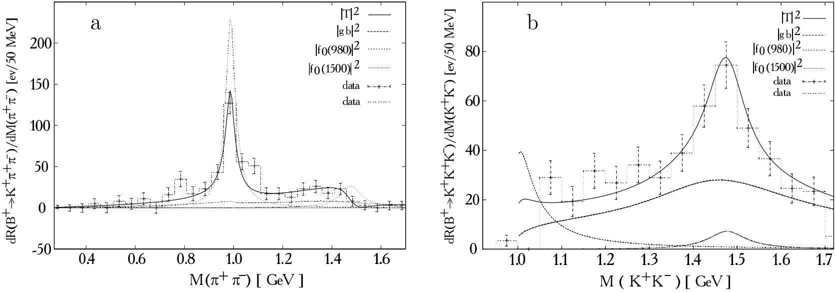
Solution: Two distinct scalar states

- The known $f_0(1710)$ decaying to $K\bar{K}$
- New broad $f_0(1790)$ coupling strongly to $\pi\pi$
  - Not confirmed by other experiments!
  - Mystery why $s\bar{s}$ recoils against ω

Belle makes it even worse ...

Belle measured scalar mesons in $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^+K^-$
(Results essentially confirmed by BaBar)

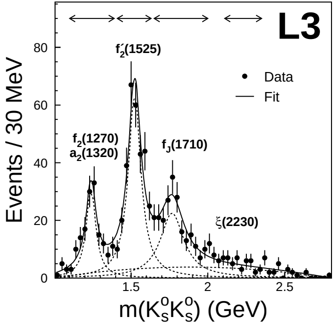
- No peak at 1500 MeV/c^2 for the $f_0(1500)$ (left),
- But a clear peak around 1500 MeV/c^2 decaying to K^+K^-
  ➜ Structure of $f_0(1500)$ remains unclear (or two states)!



Results on Scalar Mesons from $\gamma\gamma$ Fusion

Results were reported by the LEP collaborations at CERN:

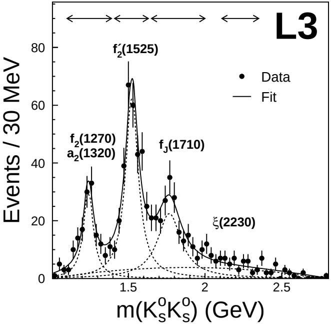
- Three clear peaks in the $K^0_S K^0_S$ mass by L3 (dominated by tensors)
- No peak for the $f_0(1500)$
  ➜ Consistent with known small $s\bar{s}$ component! What about $\pi\pi$ spectrum?

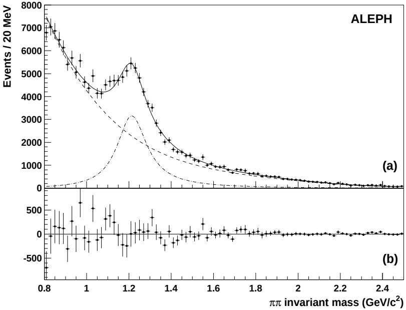


Results on Scalar Mesons from $\gamma\gamma$ Fusion

Results were reported by the LEP collaborations at CERN:

- Three clear peaks in the $K_S^0 K_S^0$ mass by L3 (dominated by tensors)
- No peak for the $f_0(1500)$
  ➜ Consistent with known small $s\bar{s}$ component! What about $\pi\pi$ spectrum?





Scalar Mesons: Key Questions

The following key questions account for the major differences in the models on scalar mesons and need to be addressed in the future:

1. What is the nature of the $f_0(980)$ and $a_0(980)$?

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4. Are the two states, $f_0(1710)$ and $f_0(1790)$ distinct states?

5. ...

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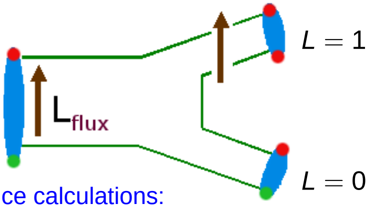
There is convincing evidence for an exotic $J^{PC} = 1^{-+}$ wave.
➜ The interpretation remains controversial.

Exotic waves are (all) observed in diffraction-like reactions.
➜ Observation of $\pi_1(1400) \to \eta\pi$ in $p\bar{p}$ remains exception.

Hybrid-Meson Decays:
(angular momentum in the flux tube stays in one of the daughter mesons)



Lattice calculations:
(lightest) $M_{1^{-+}} \approx (1.9 \pm 0.2)$ GeV/c^2

$$0^{+-} \to b_1\pi \to \pi^+\pi^-\pi^0\pi^0\pi^0$$
$$1^{-+} \to a_1\pi \to \pi^+\pi^-\pi^+\pi^-$$
$$\to f_1\pi \to \eta\pi\pi\pi$$

➜ Multi-particle final states with neutral and charged particles!

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$\pi_1(1400) \to \eta\pi$

Resonant Interpretation {
E852, Phys. Rev. D 60 (1999) 092001.
VES, Phys. Atom. Nuc. D 68 (2005) 3.
Crystal Barrel, Phys. Lett. B 423 (1998) 175.

Non-Resonant Interpretation {
E852 (IU), Phys. Rev. Lett. 91 (2003) 092002.

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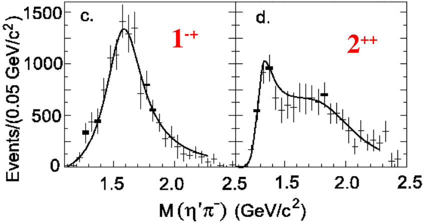

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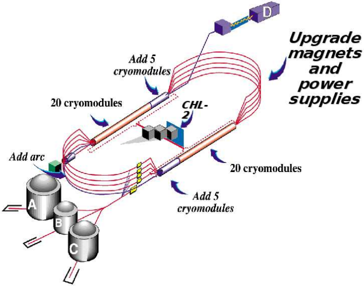
2. $\pi_1(1600)[\to \eta'\pi, \to f_1(1285)\pi] \neq \pi_1'(1600)[\to \rho\pi, \to b_1(1235)\pi]$
   - $\to \eta'\pi^-$: dominant 1^{-+} partial wave (E852, 2001; VES, 2005)
   - $\to \rho^0\pi^-$: small relative structure with leakage from other waves (Evidence: E852, '02; COMPASS, '09; Negative: VES, '04; IU, '06; CLAS, '09)
   - $\to b_1(1235)\pi/f_1(1285)\pi$: structure in 1^{-+} partial wave (E852, '05, '04; VES, '99, '05)

Outline

The GlueX Experiment at Jefferson Laboratory



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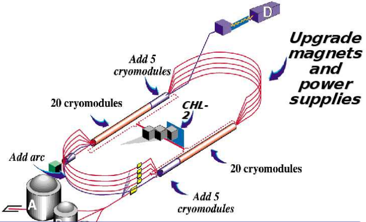

The 12 GeV upgrade is under construction.

- Construction of Hall-D broke ground in April 2009.
- Construction of the GlueX detector has started.
- Current plans call for the first beam in HallD/GlueX in late 2014.

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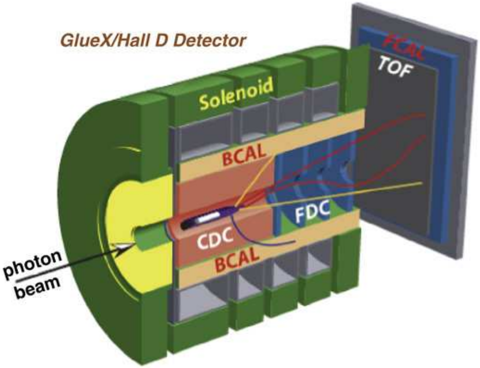
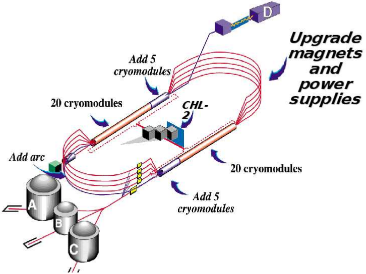
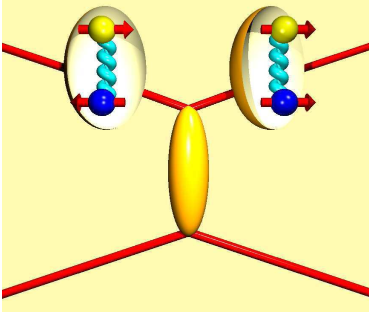
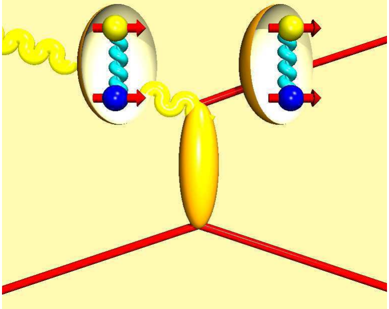




The Advantage of a Photon Beam





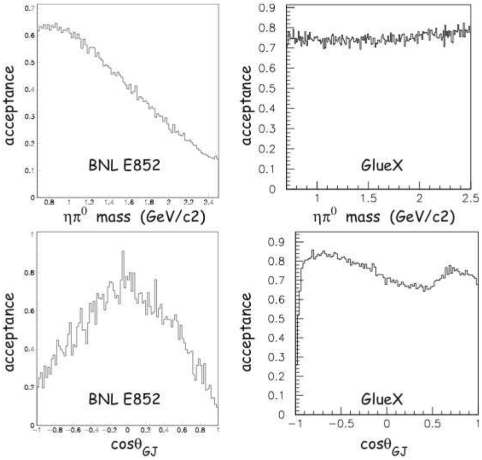
Pion Beam

- π with $S = 0$, $L = 0$ and $m = 1$
  ➜ $J^{PC} = 1^{++}, 1^{--}$
- Spin flip required for exotic quantum numbers

Photon Beam

- γ with $S = 1$, $L = 0$ and $m = 1$
  ➜ $J^{PC} = 0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, \ldots$
- No spin flip needed for exotic QN's

Case Study: GlueX versus E852 Acceptance



- High, and reasonably uniform acceptance up to 2.5 GeV/c^2.
- Sensitive to charged particles and photons.
- Some particle ID in the initial phases, plans to upgrade this.
- Able to fully reconstruct the 4-12 particle final states.

➜ $\pi^0\eta$ Photoproduction

Outline

Summary and Outlook

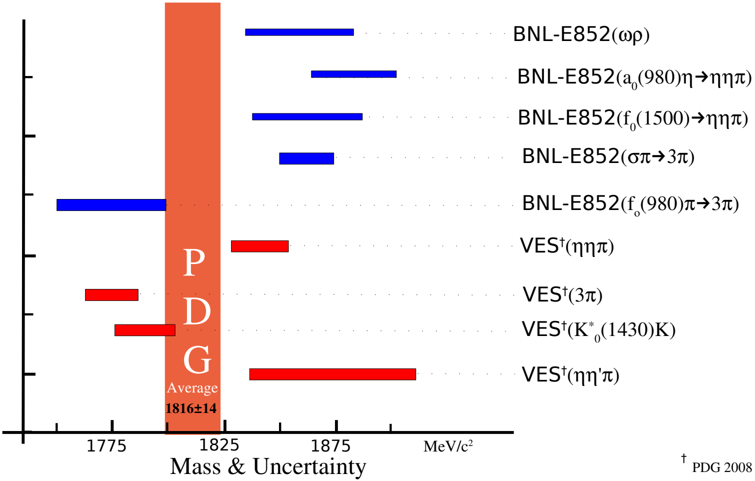
QCD predicts glueballs and nonets of mesons with exotic quantum numbers.

- There is fair evidence for a scalar glueball.
- There are hints for some states with exotic quantum numbers; two states are consistent with a π_1 state. What about the other states?

  ➜ We have just started to see results from COMPASS.
- The first searches in photoproduction have come up negative, but the acceptance has been poor, and the lower energy regime may not have been optimal.
- The GlueX experiment at Jefferson Lab is now under construction with first beam in the hall expected in 2014.
- GlueX has high acceptance for multi-particle final states, sensitivity to photons, and a linearly-polarized photon beam.

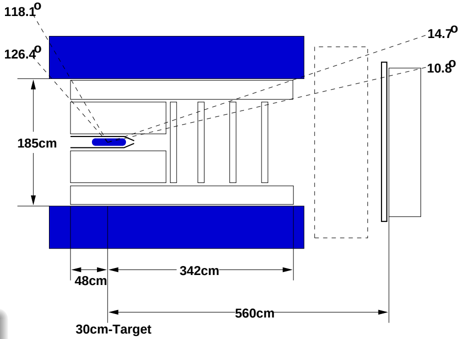
Backup Slides

The Mass of the $\pi(1800)$



† PDG 2008

The GlueX Detector



Magnet and Target

- 2 T Solenoid, Superconducting
- LH_2 Target

The GlueX Detector

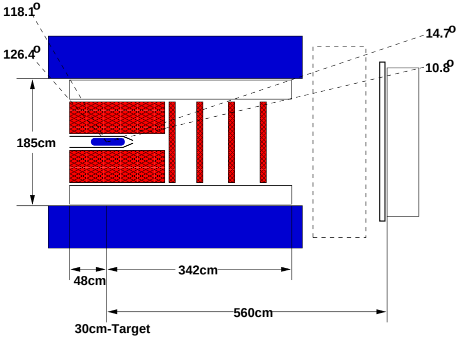
Tracking Chambers

Central Drift Chamber (CDC)

- Straw-Tube Chamber ($N = 3522$)
  ➜ $d = 1.6$ cm, $l = 150$ cm
  ($\sigma_\phi = 150\ \mu$m, $\sigma_z = 1.5$ mm)
- dE/dx for PID

Forward Drift Chamber(s) (FDC)

- 2304 wires, 10368 cathode strips
- $\sigma_{x,y} \sim 200\ \mu$m



The GlueX Detector

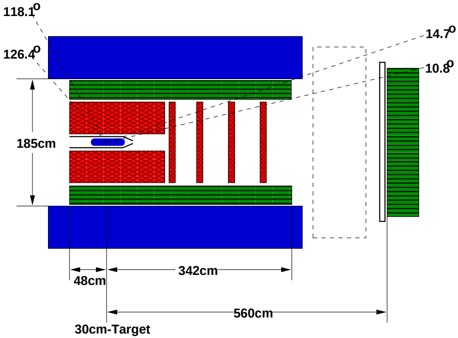
Calorimetry

Barrel Calorimeter

- 15.5 radiation lengths
- $\frac{\sigma_E}{E} = \frac{5.5\,\%}{\sqrt{E}} \oplus 1.6\,\%$
- $\frac{\sigma_{\Delta T}}{E} = \frac{74\ \text{ps}}{\sqrt{E}} \oplus 33$ ps

Forward Calorimeter

- F8-00 lead glass, 2800 blocks
- 14.5 radiation lengths
- $\frac{\sigma_E}{E} = \frac{5.7\,\%}{\sqrt{E}} + 2\,\%$
- $\sigma_r \approx 5 - 6$ mm



The GlueX Detector

Timing

Start Counter

- Event start time
  ➜ Designed to operate at $10^8\ \gamma\,/\,s$
- 40 detectors, 500 mm in length
- $\sigma_t \approx$ 0.26 ns to 0.16 ns

Forward Time-of-Flight

- Two planes of scintillator paddles
- 250 cm x 6 cm x 2.5 cm
- $\sigma_{\Delta t} \approx$ 80 ps