Hadron Spectroscopy

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Indiana University

- Hadrons, QCD and the new states of matter

- Recent results: experiment, theory and phenomenology and connection between them  
  Too many results: focus on “-onia”

- Challenges: Amplitude analysis
\( \rho : A.R.\text{Erwin (1961) J. A. Anderson (1960)} \)

\( \phi : P.L.\text{Connolly, Pevsner (1962)} \)

\( \omega : L.\text{Alvarez (1961)} \)
\[ J = \alpha' M^2 + \alpha(0) \]

\[ \text{bootstrap} = \text{Mandelstam representation + linear Regge trajectories enjoyed some success} \]
\[ \alpha' = \alpha(0) \]

\[ \rho : \text{A.R. Erwin (1961)} \]

\[ \omega : \text{L. Alvarez (1961)} \]

\[ \phi : \text{P.L. Connolly, Pevsner (1962)} \]

"The bootstrap manifesto"

**bootstrap = Mandelstam representation + linear Regge trajectories enjoyed some success**

\[ j = \frac{m^2}{2\pi\sigma} \]

\[ A(s, t) = \frac{\Gamma(-\alpha(s))\Gamma(-\alpha(t))}{\Gamma(-\alpha(t) - \alpha(s))} \]

**Strong interactions as a string theory**
S-Matrix Theory of Strong Interactions
without Elementary Particles

Geoffrey F. Chew
Department of Physics and Lawrence Radiation Laboratory, University of California, Berkeley, California

“The bootstrap manifesto”

Relativistic rotor:

\[ J = \frac{m^2}{2\pi} \theta \]

Bootstrap =
Mandelstam representation +
linear Regge trajectories enjoyed some success

Polyakov, Wilson: loop theory

AdS/CFT

\[ A(s, t) = \frac{\Gamma(-\alpha(s))\Gamma(-\alpha(t))}{\Gamma(-\alpha(t) - \alpha(s))} \]

Tuesday, August 9, 2011
\[ A(s, t) = \frac{\Gamma(-\alpha(s))\Gamma(-\alpha(t))}{\Gamma(-\alpha(t) - \alpha(s))} \]

In this paper, I present an indecently optimistic view of strong interaction theory. My belief is that a major breakthrough has occurred and that within a relatively short period we are going to achieve a depth of understanding of strong interactions that a few years ago, I, at least, did not expect to see within my lifetime. I know that few of you will be convinced by the arguments given here, but I would be masking my feelings if I were to employ a conventionally cautious attitude in this talk. I am bursting with excitement, as are a number of other theorists in this game.

I present my view of the current situation entirely in terms of the analytically continued \( S \) matrix, because there is no other framework that I understand for strong interactions. My oldest and dearest friends...
QED (at the atomic scale)

weakly interacting photons +
non-relativistic charges

Vacuum fields : Coulomb potential
+ (de-coupled) harmonic oscillators

Conventional bound states (atoms):
radiation coupled

|H> = |e+ p>|γ>
QED (at the atomic scale)

- weakly interacting photons + non-relativistic charges

Conventional bound states (atoms):
radiation coupled

\[ |H> = |e_p >|\gamma> \]

Vacuum fields: Coulomb potential + (de-coupled) harmonic oscillators

QCD (at the nuclear scale)

- self-interacting gluons with strong coupling + relativistic (light) or non-relativistic (c,b) quarks

Vacuum fields: Confined Coulomb potential + (coupled) magnetic charges (monopoles, vortices)

New states of matter (hadrons):
radiation strongly coupled

\[ |H> = \sum |q_i g_i > \]

Conventional bound states (atoms):
radiation coupled

\[ |H> = |e^+ p >|\gamma> \]

Heavy quarkonia:
Confined Coulomb + excited glue (quark model template)
Features of the Hadron Spectrum: Charmonium

- quark model template
  - ground state flux tube dominates

- hybrid candidate X(4260)
  - sign of excited glue

- molecular (DD*) candidate X(3872)
  - residual hadronic forces

- possible extra states M=3900 - 4200
  - ?

- charged charmonia M=4000 - 4500 (aka tetraquarks)
  - ???

Christopher Hearty (BaBar)
(Hadron Spectroscopy, Friday)
leading Regge trajectory

$O(\alpha^4 m_q)$

daughters

leading Regge trajectory

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leading Regge trajectory

daughters

O(\alpha^4 m_q)
$X(3872)$ discovered by Belle in $J/\psi \pi^+\pi^-$ (2003) confirmed by CDF other modes from Bell, BaBar

mass between $D^*D$ and $DD\pi$ thresholds $O$(MeV) width ($1$ MeV)

- if $J^{PC}=1^{++}$ then $S$-wave $D^*D$ molecule (several fm)?
- $2^+$ (BaBar, 2010) QM?
**X(3872)** discovered by Belle in J/ψ π⁺π⁻ (2003) confirmed by CDF other modes from Bell,BaBar

mass between D*D and DDπ thresholds O(MeV) width (1MeV)

* if J^PC=1^{++} then S-wave D*D molecule (several fm)?
* 2^+ (BaBar, 2010) QM ?

* need radiative decays of X, 2P and 1D

\[ B^+ \rightarrow X(3872)(\rightarrow J/\psi \gamma)K^+ \]
\[ B^0 \rightarrow X(3872)(\rightarrow J/\psi \gamma)K_S^0 \]

\[ \mathcal{B} (B^+ \rightarrow K^+ X(3872) \mathcal{B} (X(3872) \rightarrow R\gamma), 10^{-6} \]

\[ J/\psi \quad 1.78^{+0.48}_{-0.44} \pm 0.12 \quad 2.8 \pm 0.8 \pm 0.1 \]
\[ \psi' \quad < 3.45 \quad 9.5 \pm 2.7 \pm 0.6 \]

small cc component ?
The jury is still out

* if molecule then maybe closely related to the f_0(980) in KK
precision strong phases from weak D-decays

\[ \sqrt{4\pi} \langle Y_0^0 \rangle = \left| \frac{S}{2} \right|^2 + \left| P \right|^2 \]
\[ \sqrt{4\pi} \langle Y_2^0 \rangle = \frac{\sqrt{5}}{2} \left| P \right|^2 \]
\[ \sqrt{4\pi} \langle Y_1^0 \rangle = 2 |S| |P| \cos \phi_{SP} \]

\[ D^+_s \to K^+ K^- \pi^+ \] (Babar 2011)

slightly “tilted” P-wave distribution due to S-wave interference

model independent determination of S-wave phase
\[ \mathcal{B}(B^+ \to X(3915)K^-) \times \mathcal{B}(X(3915) \to J/\psi \omega) = (7.1 \pm 1.3 \pm 3.1) \times 10^{-5}. \]

Belle (2005)

**PDG X(3915)**

Belle (2007)

**M(J/\psi\omega)**

**X(3940)**

\[ \mathcal{B}(B^+ \to X(3915)K^-) \times \mathcal{B}(X(3915) \to J/\psi \omega) = (3.0 \pm 0.7 \pm 0.6 \pm 0.5 \pm 0.3) \times 10^{-5}, \]

\[ \mathcal{B}(B^0 \to X(3915)K^0) \times \mathcal{B}(X(3915) \to J/\psi \omega) = (2.1 \pm 0.9 \pm 0.3) \times 10^{-5}. \]

X(3872)

X(3915)

**M = 4274.4^{+8.4}_{-6.7} \pm 1.9**

\[ \Gamma = 32.3^{+21.9}_{-15.3} \pm 7.6 \]

**CDF 2011**

**second peak @ 3.1 \sigma**

\[ \mathcal{B}(B^+ \to Y(4140)K^+) \times \mathcal{B}(Y(4140) \to J/\psi \phi K^+) = (0.149 \pm 0.039 \pm 0.024) \times 10^{-5}. \]

\[ \mathcal{B}(B^+ \to Y(4140)K^+) \times \mathcal{B}(Y(4140) \to J/\psi \phi K^+) = (0.149 \pm 0.039 \pm 0.024) \times 10^{-5}. \]

M = 3900 - 4200 range

**Y(4140)**

not seen in Belle (and possible Y(4275))

\[ M = 4143.4^{+2.9}_{-3.0} \pm 0.6 \]

\[ \Gamma = 15.3^{+10.4}_{-6.1} \pm 2.5 \]
X^± (4430) Belle (2009) $\overline{B}^0 \rightarrow K^- (\psi' \pi^+), B^+ \rightarrow K^0_s (\psi' \pi^+)$
not seen in BaBar (also in $J/\psi \pi^-$)
\( X^{\pm} (4430) \) Belle (2009) \( \bar{B}^0 \rightarrow K^- (\psi' \pi^+), B^+ \rightarrow K^0_s (\psi' \pi^+) \)
not seen in BaBar (also in \( J/\psi \pi^+ \))

\( X^{\pm} (4430) \)

\( K^*(890) \)

\( \sum \text{ of } K^* \text{'s BW's} + \text{background} \)

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\( X^\pm (4430) \) Belle (2009) \( \bar{B}^0 \rightarrow K^- (\psi'\pi^+), B^+ \rightarrow K^0_s (\psi'\pi^+) \), not seen in BaBar (also in J/\psi \pi^-)

\( X^+ (4430) \)

\( K^* (890) \)

\( M(\pi^+\psi') \)

\( M(\pi^+\psi') \) with \( X^+ \)

\( M(\pi^+\psi') \) without \( X^+ \)

sum of \( K^* \)'s BW's + background
\[ \pm (4430) \text{ Belle (2009)} \quad \overline{B}^0 \rightarrow K^-(\psi'\pi^+), B^+ \rightarrow K^0_s (\psi'\pi^+) \]

not seen in BaBar (also in J/ψ π̄⁻)

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

\[ M(K^*) \]

\[ \text{sum of K*′s BW's + background} \]
$X^+ (4050,4250)$ Belle (2009) $\bar{B}^0 \to K^- (\chi_c^1 \pi^+)$
\[ \bar{B}^0 \rightarrow K^-(\chi_c^1 \pi^+) \]

- **X^+ (4050,4250) Belle (2009)**
- **K*(890)**

**sum of K*'s BW's + background**

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\( X^+ (4050, 4250) \) Belle (2009) \( \bar{B}^0 \rightarrow K^- (\chi_{c1} \pi^+) \)

with \( X^+_1, X^+_2 \)

\[ M(\pi^+ X_{c1}) \]

sum of \( K^* \)'s BW's + background
$X^+ (4050, 4250)$ Belle (2009) $\bar{B}^0 \rightarrow K^- (\chi_{c1} \pi^+)$

$M(\pi^+ \chi_{c1})$

$\chi_{c1} \pi^+$

$K^*(890)$

sum of $K^*$'s BW's + background
$\bar{B}^0 \rightarrow K^- (\chi_c 1 \pi^+)$

- $X^+ (4050, 4250)$ Belle (2009)
- $M(\pi^+ \chi_c 1)$

- No $X^+ 1, X^+ 2$
- But with a $K_2^*$

- Sum of $K^*$'s BW's + background
Charged resonances in Dalitz plot analysis of $\Upsilon(5S)$ decays to ($\Upsilon(1S), \Upsilon(2S), \Upsilon(3S), h_b, h'_b$) $\pi^+\pi^-$. 

\[
A(s_1, s_2) = |BW_{Z}(s_1) + BW_{Z}(s_2) + A_{NR} + A_{f_0}(980) + A_{f_2}(1275)|^2
\]
Physical (coherent) backgrounds are important
Role of hadronic backgrounds

BES II proposed a new $J=I=1$, ($\rho$-like) broad resonance strongly coupled to $KK$

$J/\psi \rightarrow K^+K^-\pi^0$

$X(1580)\text{ reflection}$

$K^*(890)$

$[M(K^+\pi^0)^2]$ (GeV/c²)²

$Events/(40\text{MeV}/c²)$

$M(K^+\pi^0)$ (GeV/c²)

$BES (2006)(b)$
Role of hadronic backgrounds

BES II proposed a new $J=I=1$, ($\rho$-like) broad resonance strongly coupled to $KK$

$J/\psi \rightarrow K^+K^-\pi^0$

- No isovector KK amplitudes
- All $K^*$s
- Missing strength at "X" location

K*(890) reflection
Role of hadronic backgrounds

BESII proposed a new \( J=I=1, (\rho\text{-like}) \) broad resonance strongly coupled to KK

\[ J/\psi \rightarrow K^+ K^- \pi^0 \]

no isovector KK amplitudes

missing strength at "X" location

\( \pi\pi \) isovector amplitude is known to be inelastic at 1.6GeV

unitarity demands other channel most likely \( \pi\pi \rightarrow K\bar{K} \)
Role of hadronic backgrounds

BESII proposed a new $J=I=1$, $(\rho$-like) broad resonance strongly coupled to $KK$

$$J/\psi \rightarrow K^+K^0\pi^0$$

- **no isovector KK amplitudes**
- **missing strength at “X” location**
- **$\pi\pi$ isovector amplitude is known to be inelastic at 1.6GeV**

**Unitarity demands other channel most likely**

$$\pi\pi \rightarrow KK$$

*PGuo et al. (IU 2011)*

With $KK \rightarrow \pi\pi$ the virtual $\pi\pi$ channel in $J/\psi \rightarrow (\pi\pi)\pi \rightarrow KK\pi$

may explain the “X”
\[ \pi^- p \rightarrow \pi^+ \pi^- \pi^- p \]

Resonance production:
Compact source

Deck background:
extended source

Difference in phase motion
seen in mass dependence

M.G. Bowler et al (1975)

Deck + resonance

ACCMOR (40 GeV)

Deck (background) only

Mass \(3\pi\)
$\pi^- p \to \pi^+ \pi^- \pi^- p$

Resonance production: Compact source

Deck background: extended source

Difference in phase motion seen in mass dependence

M.G. Bowler et al (1975)

Deck + resonance

ACCMOR (40GeV)

Deck (background) only

Mass $3\pi$

COMPASS (190GeV)

Intensity comparable to background

Exotic Meson Signal

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PDG: 2 entries for $\pi_2(1670)$

<table>
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<tr>
<th>Value (MeV)</th>
<th>EVTS</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>CHG</th>
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<td>1749 ± 11</td>
<td>145k</td>
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<td>$18 \pi^{-} p \rightarrow \omega \pi^{-} \pi^{0} p$</td>
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<td>1676 ± 3</td>
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<td>1 CHUNG 02 E852</td>
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<td>1665 ± 10</td>
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<td>$450 p p \rightarrow p_{f} 3 \pi^{0} p_{s}$</td>
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<td>1670 ± 4</td>
<td>3</td>
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<td>13 ANTREASYAN 90 CBAL</td>
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<td>1</td>
<td>$63,94 \pi^{-} p$</td>
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<tr>
<td>1000 ± 10</td>
<td>0</td>
<td>18 ASCOLI 73 HBC</td>
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<td>1</td>
<td>$5-25 \pi^{-} p \rightarrow p \pi_{2}$</td>
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</table>

We do not use the following data for averages, fits, limits, etc. • • • • •

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evolution in statistics \[ \pi^- p \rightarrow \pi^- \pi^+ \pi^- p \]

- CERN ca. 1970: \( O(10^2/10\text{MeV}) \)
- BNL (E852) ca. 1995: \( a_1 \) and \( a_2 \)
- E852 2003 Full sample: \( O(10^3/10\text{MeV}) \)
- COMPASS 2010: \( O(10^5/10\text{MeV}) \)
- 96M events: \( O(10^6/10\text{MeV}) \)
evolution in statistics \( \pi^- p \rightarrow \pi^- \pi^+ \pi^- p \)

- Almost infinite floating-point power
- Fast communication with CPU
- Short latency

96M events

\( O(10^6 /10\text{MeV} ) \)

COMPASS 2010

\( a_2(1320) \)

\( a_1(1260) \)

\( a_1(1260) \)

\( \rho_2(1670) \)
Amplitude Analysis: Major challenge

1. Amplitude extraction is model dependent

2. Analytical continuation to complex energy plane is needed to extract resonance parameters

3. Finally, connection between S-matrix poles and QCD: lattice, models needs to be made

\[ \pi^-(190\text{GeV})p \rightarrow \pi^+\pi^-\pi^-p \]

- bump = resonance or else?
- dynamically generated \( \sigma \) ?
- glueball ?
- quark model (nn, ss) ?
1. Precision data

2. Dispersion relation + chiral constraints give precise determination of the $\sigma$ resonance

3. "Microscopic" study: $N_C$ dependence
Hunting for the hybrid meson
\( Y(4260) \) discovered by BaBar in \( J/\psi \pi^+\pi^- \) (2005) confirmed by CLEO, Belle other modes from BaBar \( J^{PC}=1^{--} \) (from \( e^+e^- \)) width \( \mathcal{O}(100\,\text{MeV}) \)

Possible \( Y(4050) \) not confirmed in BaBar

\[
M = 4252 \pm 6^{+2}_{-3} \, \text{MeV}
\]

\[
\Gamma = 105 \pm 18^{+4}_{-6} \, \text{MeV}
\]

Theory favor: Hybrid
new multiplets from lattice

isovector meson spectrum with $m_\pi \sim 700$ MeV

J.Dudek et al. JLab
new multiplets from lattice

quark model states

isovector meson spectrum with $m_{\pi} \sim 700$ MeV

J.Dudek et al. JLab
new multiplets from lattice

J.Dudek et al. JLab

quark model states

large overlap with gluonic operators includes 1-+ exotic

isovector meson spectrum with $m_\pi \sim 700$ MeV

same pattern in ss, cc

hybrid interpretation of the $Y(4260)$

J.Dudek et al. JLab

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lowest quasi-gluon eigenstate in presence of static source has $J^{PC} = 1^{++}$ quantum numbers

$P_g = 1^+$ (one unit of orbital angular momentum)

C.Morningstar et al, G.Ball.
lowest quasi-gluon eigenstate in presence of static source has $J^{PC}=1^+$ quantum numbers

hybrid “=”

$J^{PC}$ glue

$J^{PC} Qar{Q}$

$1^{--} \times 0^{++} = 1^{--}$

$1^{++} \times 1^{--} S_{QQ} = 1^{--}$

$0^{-+}, 1^{--}, 2^{++}$

From (variational) QCD in the Coulomb gauge

P.Guo, et al.

also from other models

J.Dudek, et al.

C.Morningstar et al, G.Ball.
lowest quasi-gluon eigenstate in presence of static source has $J^{PC}=1^+$ quantum numbers

hybrid “=”

$J^{PC}_{\text{glue}}$  
$J^{PC}_{\overline{Q}Q} 1^--

1^{++} \times 0^{--}_{S_{QQQ}} = 1^{--}$

$1^{++} \times 1^{--}_{S_{QQQ}} = 0^{--}, 1^{++}, 2^{++}$

ss analogue? $Y(2175)$

David Muller (BaBar)  
(Hadron Spectroscopy, Friday)

From (variational) QCD in the Coulomb gauge  
P. Guo, et al.

also from other models  
J. Dudek, et al.

C. Morningstar et al, G. Ball.

(One unit of orbital angular momentum)

$P_g=1^+$

$Y(4260)$
\[
\pi^- p \rightarrow \eta \pi^- p
\]

\[
\pi^- p \rightarrow \eta \pi^0 n
\]

\[M = 1370 \pm 16^{+50}_{-30} \text{ MeV } / c^2\]
\[\Gamma = 385 \pm 40^{+65}_{-105} \text{ MeV } / c^2\]

No consistent B-W interpretation possible but a weak \(\eta \pi\) interaction exists and can reproduce the exotic wave.

search for \(n\bar{n}\) hybrid \(\pi_1(1600)\)
\( \pi^- p \rightarrow \eta \pi^- p \)

\[ M = 1370 \pm 16^{+50}_{-30} \text{ MeV} / c^2 \]
\[ \Gamma = 385 \pm 40^{+65}_{-105} \text{ MeV} / c^2 \]

search for \( n\bar{n} \) hybrid \( \pi_1(1600) \)

\( \pi^- p \rightarrow \eta \pi^0 n \)

No consistent B-W interpretation possible but a weak \( \eta \pi \) interaction exists and can reproduce the exotic wave

\( \pi^- p \rightarrow \eta'^- p \)

\[ M = 1597 \pm 10^{+45}_{-10} \text{ MeV} / c^2 \]
\[ \Gamma = 340 \pm 40^{+50}_{-50} \text{ MeV} / c^2 \]
\[ \pi^- p \rightarrow \eta \pi^- p \]
\[ M = 1370 \pm 16^{+50}_{-30} \text{ MeV} / c^2 \]
\[ \Gamma = 385 \pm 40^{+65}_{-105} \text{ MeV} / c^2 \]

\[ \pi^- p \rightarrow \eta \pi^0 n \]

No consistent B-W interpretation possible but a weak \( \eta \pi \) interaction exists and can reproduce the exotic wave

\[ \pi^- p \rightarrow \eta' \pi^- p \]
\[ M = 1597 \pm 10^{+45}_{-10} \text{ MeV} / c^2 \]
\[ \Gamma = 340 \pm 40^{+50}_{-50} \text{ MeV} / c^2 \]

Tuesday, August 9, 2011
$\pi^- p \rightarrow \eta \pi^- p$

$M = 1370 \pm 16^{+50}_{-30} \text{ MeV} / c^2$

$\Gamma = 385 \pm 40^{+65}_{-105} \text{ MeV} / c^2$

No consistent B-W interpretation possible but a weak $\eta \pi$ interaction exists and can reproduce the exotic wave

$\pi^- p \rightarrow \eta \pi^0 n$

$M = 1597 \pm 10^{+45}_{-10} \text{ MeV} / c^2$

$\Gamma = 340 \pm 40^{+50}_{-50} \text{ MeV} / c^2$

$\pi^- p \rightarrow \rho^0 \pi^- p$

$M = 1593 \pm 8^{+29}_{-47} \text{ MeV} / c^2$

$\Gamma = 168 \pm 20^{+150}_{-12} \text{ MeV} / c^2$

BNL (E852) yes/no

COMPASS yes

E852 result

$\pi^- p \rightarrow \pi^- (1600)p$

$\pi^- p \rightarrow \rho^0 \pi^- p$

Figure 25: (a) The $1^{++} 1^{++}$ P-wave $\rho \pi$ partial wave in the charged mode $(\pi^- \pi^- \pi^-)$ for the high-wave set PWA and the low-wave set PWA and (b) the phase difference $\Delta \Phi$ between the $2^{++}$ and $1^{--}$ for the two wave sets.
\[ \pi^- p \rightarrow \eta \pi^- p \]

\[ M = 1370 \pm 16 \pm 30 \text{ MeV} / c^2 \]

\[ \Gamma = 385 \pm 40 \pm 105 \text{ MeV} / c^2 \]

No consistent B-W interpretation possible but a weak \( \eta \pi \) interaction exists and can reproduce the exotic wave

\[ \pi^- p \rightarrow \eta \pi^0 n \]

\[ M = 1593 \pm 10 \pm 47 \text{ MeV} / c^2 \]

\[ \Gamma = 168 \pm 20 \pm 12 \text{ MeV} / c^2 \]

\[ \pi^- p \rightarrow \rho^0 \pi^- p \]

\[ M = 1597 \pm 10 \pm 45 \text{ MeV} / c^2 \]

\[ \Gamma = 340 \pm 40 \pm 50 \text{ MeV} / c^2 \]

BNL (E852) yes/no

COMPASS yes

\[ \pi^- p \rightarrow \eta' \pi^- p \]

\[ \pi^- p \rightarrow \pi^- (1600)p \]

\[ \pi^- p \rightarrow \pi^- (1600)p \]

FIG. 25: (a) The 1^+ 1^+ P-wave \( \rho \pi \) partial wave analysis in the charged mode (\( \pi^- \pi^- \pi^+ \)) for the high-wave set PWA and low-wave set PWA and (b) the phase difference \( \Delta \Phi \) between the 2^++ and 1^- for the two wave sets.

\[ \Delta \Phi(2^+ \rightarrow 1^-) \]

\[ M = (1660 \pm 10 \text{ MeV}/c^2) \]

\[ \Gamma = (269 \pm 21 \text{ MeV}/c^2) \]

\[ \text{Leakage negligible: } \leq 5\% \]
\[ \pi^- p \rightarrow \eta \pi^- p \]

\[ M = 1370 \pm 16^{+50}_{-30} \text{ MeV} / c^2 \]
\[ \Gamma = 385 \pm 40^{+65}_{-105} \text{ MeV} / c^2 \]

No consistent B-W interpretation possible but a weak \( \eta \pi \) interaction exists and can reproduce the exotic wave

\[ \pi^- p \rightarrow \eta^0 n \]

\[ M = 1597 \pm 10^{+45}_{-10} \text{ MeV} / c^2 \]
\[ \Gamma = 340 \pm 40^{+50}_{-50} \text{ MeV} / c^2 \]

\[ \pi^- p \rightarrow \rho^0 \pi^- p \]

\[ M = 1593 \pm 8^{+29}_{-47} \text{ MeV} / c^2 \]
\[ \Gamma = 168 \pm 20^{+150}_{-12} \text{ MeV} / c^2 \]

BNL (E852) yes/no
COMPASS yes

E852 result

\[ \pi^- p \rightarrow \pi^- (1600)p \]
\[ \pi^0 (1600) \rightarrow \rho^0 \pi^- \]

**Dennis Weygand**
(JLab)
(Hadron Spectroscopy, Friday)

\[ \pi^- p \rightarrow \pi^- (1600)p \]
\[ \pi^0 (1600) \rightarrow \rho^0 \pi^- \]

FIG. 25: (b) The \( 1+1^+ \) partial wave \( \rho \pi \) partial wave analysis for high-(\( 3\pi^0 \)) and low-(\( 2\pi^0 \)) wave set PWA and (b) the phase difference \( \Delta \Phi = 2\pi^+ - 1^+ \) for the two wave sets.

- BW parameters for \( \pi_5 (1600) \)
  \[ M = (1660 \pm 10^{+9}_{-62}) \text{ MeV} / c^2 \]
  \[ \Gamma = (269 \pm 21^{+82}_{-64}) \text{ MeV} / c^2 \]

- Leakage negligible: <5%
From Hadrons to QCD constituents

Major challenges

1. Amplitude extraction is model dependent

2. Analytical continuation to complex energy plane is needed to extract resonance parameters

3. Finally connection between S-matrix poles and QCD: lattice, models needs to be made

bump = resonance or else?

f_0(400-1200)  f_0(980)  f_0(1510)  f_0(1720)  f_0(1370)

|T|^2

inelasticity ?

dynamically generated σ ?

quark model (nn, ss) ?

Tuesday, August 9, 2011
New initiatives for development of hadron spectroscopy efforts

Les NABIS

Extracting CP phases from Dalitz plot & CP studies (US/Germany)

Workshops/summer schools on hadronic physics and amplitude analysis INT, ECT*, JLab

Tuesday, August 9, 2011