Observation of the $\pi(1800)$ and $\pi_2(1880)$ mesons in the $\eta\eta\pi$ decay

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Overview

- Motivation
- Experimental Setup
- Features of $\pi \rightarrow \pi^-\pi^-\pi^+\pi^0\eta \rho$
- Partial Wave Analysis of $\eta\eta\pi^-$
- Observation of $\pi(1800)$ & $\pi_2(1880)$
- Conclusions & Summary
Radial Excitations of the Pion

$J^{PC} = 0^{-+}$

$\pi$, $\pi(1300)$, $\pi(1800)$

Mass

0 1000 2000 3000 MeV/c$^2$

Width
Radial Excitations of the Pion

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Many† have suggested that the \( \pi(1800) \) is a \( 0^{-+} \) hybrid meson

†See for example T. Barnes, F. E. Close, P. R. Page, & E. S. Swanson Phys. Rev. D55 4157 (1997)
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Radial Excitations of the Pion

\[ J^{PC} = 0^{-+} \]

Rather narrow for 2\textsuperscript{nd} excitation of \( \pi \)

\( \pi \)

\( \pi(1300) \)

\( \pi(1800) \)

Does not decay to \( \rho \pi \) \& \( K^*K \)

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The $\pi_2/\eta_2$ States [J$^\text{PC}$=2$^{-+}$]
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$\pi_2^{-}(1670)$  $\eta_2(1645)$  $\pi_2^0(1670)$  $\pi_2^+(1670)$

*should be mainly $s\bar{s}$*
The $\pi_2/\eta_2$ States [$J^{PC}=2^{-+}$]

$\eta_2(1645)$ should be mainly $s\bar{s}$

$\pi_2^-(1670)$  $\pi_2^0(1670)$  $\pi_2^+(1670)$

$\eta_2(1870)$ has been reported in $\gamma\gamma$ interactions, $p\bar{p}$ interactions, & central production
The $\pi_2^*/\eta_2$ States $[J^{PC}=2^{-+}]$

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However decays are mainly to,

$\eta_2(1870) \rightarrow a_2(1320)\pi$

$\rightarrow f_2(1270)\pi$
The $\pi_2/\eta_2$ States  [$J^{PC}=2^{-+}$]

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Close and Page note that the relative decay rate is compatible with a hybrid interpretation
A new \( \pi_2(1880) \) state has been observed

★ Hybrid partner to \( \eta_2(1870) \)?

\[ \bar{p} p \rightarrow \eta \eta \pi^0 \pi^0 \] (in flight)

\( \pi_2(1880) \) parameters

- \( M = 1880 \pm 20 \text{ MeV}/c^2 \)
- \( \Gamma = 255 \pm 45 \text{ MeV}/c^2 \)

Data strongly requires

\( \pi_2(1900) \rightarrow a_2(1320) \eta \)

Projections of the data and pwa results

BNL-E852 Analysis

**Reaction:**
\[ \pi^- p \rightarrow p \pi^+ \pi^- \pi^- \pi^0 \eta \]
\[ \pi^0 \rightarrow \gamma \gamma \]
\[ \eta \rightarrow \gamma \gamma \]

18 GeV/c pion beam

256 Million triggers of this type acquired

**Brookhaven Experiment 852**

Events reconstructed with:

- 4 photon clusters in LGD
- 3 forward charged particle tracks (total charge of -1) with vertex at the beam
- Consistent recoil track
- Fiducial volume (target & Lead Glass Detector) cuts
- Hadron tagging at the LDG
- CsI barrel rejection
- Kinematic fitting: \( p \pi^+ 2\pi^- \pi^0 \eta \)
Features of the $\pi^- p \rightarrow p\pi^+ \pi^- \pi^- \pi^0 \eta$ System

Kinematic fitting

$\times$ 45600 $\pi^- p \rightarrow \pi^+ \pi^- \pi^- \pi^0 \eta p$

events

$\times$ Rejected $\pi^- p \rightarrow p\pi^+ \pi^- \pi^- \pi^0 \pi^0$

ambiguous events
Selecting $\eta\eta\pi^-$ from $\eta\pi^-\pi^+\pi^0\pi^-$

$\pi(1800)$

First observed by VES
Mass(1770 – 1875) MeV/c²
Also observed by BNL-E852
Intermediate Isobar Decays

\[ X \rightarrow \eta[y] \rightarrow \eta[\eta\pi^-] \]

\[ X \rightarrow [y]\pi^- \rightarrow [\eta\eta]\pi^- \]

- \( a_0(980) \)
- \( a_2(1320) \)
- \( f_o/f_2 \)

Events/20 MeV/c^2

Mass(\eta\pi^-) GeV/c^2

Mass(\eta\eta) GeV/c^2
Partial Wave Analysis

\[ I(\tau) = \sum_{\epsilon \epsilon'} \rho_{\epsilon \epsilon'}(\tau) \sum_{\alpha \alpha'}^{k \epsilon} V_{\alpha}^* A_{\alpha'}^*(\tau) k^{\epsilon} V^{\epsilon} A_{\alpha}(\tau) \]

For pion beam & unpolarized target:

\[ I(\tau) = \frac{1}{2} \sum_{k \epsilon} \left| \sum_{\alpha}^{k \epsilon} V^{\epsilon} A_{\alpha}(\tau) \right|^2 \]

Helicity Decay Amplitudes

\[ A_{\alpha, M}(\tau) = A_{X}^{\lambda_1 \lambda_2; M} A_{\text{iso}}^{\lambda_1 \lambda_2; M} \ldots \]

\[ A_{X}^{\lambda_1 \lambda_2; M} = D_{\lambda M}^{\lambda}(\theta, \phi) \frac{\tilde{L}}{\tilde{J}} (L 0; S \lambda | J \lambda) (S_1 \lambda_1; S_2 - \lambda_2 | S \lambda) K \]

Complex parameters varied in the PWA to fit the data

\[ \epsilon A_{\alpha}(\tau) = a [ A_{\alpha, M}(\tau) \pm b A_{\alpha, -M}(\tau) ] \]

\[ \tilde{J} = \sqrt{J (J + 1)} \]
• Considered all Possible States with:
  ✓ \( J^{PC} = 0^{-+}, 1^{++}, 2^{-+}, 3^{++} \)
  ✓ \( L = S, P, D, \& F \)
  ✓ \(|M| \leq 1 \quad \epsilon = \pm 1\)
  ✓ Isobars
    ✓ \( a_0(980)\eta, f_0(1500)^{+}\pi, a_2(1320)\eta\)
    ✓ \( f_0(1300)\pi, f_2(1270)\pi\)

‡\text{Mass}=1480\pm25 \text{ MeV} \quad \Gamma=120^{+50}_{-30} \text{ MeV}

Maximum-Likelihood Fitting in 50 MeV/c^2 \( \eta\eta\pi^- \) mass bins
Acceptance Correction via MC

• Minimal set of waves
  \( J^{PC}M^{\epsilon}L \) (isobar decay)
  \( 0^{-+}0^{+}S \ a_0(980)\eta \)
  \( 0^{-+}0^{+}S \ f_0(1500)\pi \)
  \( 2^{-+}0^{+}S \ a_2(1320)\eta \)
  \( 2^{-+}0^{+}D \ a_0(980)\eta \)

  background
Quality of the PWA Fit

The quality of the fit was judged by comparing data distributions with PWA spin-density matrix weighted Monte Carlo events.

(c) \( a_0(980) \)

(d) \( f_0(1500) \)

(b) \( \pi(1800) \)

(e) \( \cos \theta_{GJ} \)

(f) \( \phi_{TY} \) (rad)
The $J^{PC} = 0^{-+} \pi(1800) \rightarrow \eta\eta\pi^-$

**Partial Wave Intensities**

$0^+ a_0(980)\eta$ S-wave

$0^+ f_0(1500)\pi$ S-wave

\[ \eta\eta\pi \text{ mass (GeV)} \]

Smooth lines show results of mass-dependent relativistic Breit-Wigner $\chi^2$ fits

**Partial Wave Phase Difference**

$\Delta\phi(0^+ S a_0\eta - 2^+ D a_0\eta)$

\[ \eta\eta\pi \text{ mass (GeV)} \]

**Parameters of the $\pi(1800)$**

$M = 1876 \pm 18 \pm 16$ MeV/c$^2$, $\Gamma = 221 \pm 26 \pm 38$ MeV/c$^2$

$\chi^2$/dof = 23.9/20
Relative Branching Ratio for $\pi(1800)$

The fitted Breit-Wigner shapes were integrated to determine the predicted number of events for each state.

The following branching ratio was obtained

$$\frac{BR[\pi(1800) \to f_0(1500)\pi, f_0 \to \eta\eta]}{BR[\pi(1800) \to a_0(980)\eta, a_0 \to \eta\pi]} = 0.48 \pm 0.17$$

A similar value of $0.40 \pm 0.15$ was obtained in a different maximum-likelihood PWA fit in which the branching ratio itself was one of the fitted parameters.

In both cases our value is higher than the value determined by VES‡ [ Ratio = $0.08 \pm 0.03$ ]

‡Phys. At. Nucl. 59, 976 (1996)
The Mass of the $\pi(1800)$

- BNL-E852($a_0(980)\eta\to\eta\pi$)
- BNL-E852($f_0(1500)\to\eta\pi$)
- BNL-E852($\omega\rho$)
- BNL-E852($\sigma\pi\to3\pi$)
- BNL-E852($f_0(980)\pi\to3\pi$)
- VES$^\dagger(\eta\eta\pi)$
- VES$^\dagger(3\pi)$
- VES$^\dagger(K^*_0(1430)K)$
- VES$^\dagger(\eta\eta'\pi)$

Average $1812\pm14$ MeV/c$^2$

$^\dagger$ PDG 2006
The $J^{PC} = 2^{-+} \pi_2$ Waves

Partial Wave Intensities

Observation of $\pi_2(1880)$

Partial Wave Phase Difference

with $\pi(1800)$ parameters fixed, the intensity of the $2^+a_2\eta$ wave and its phase relative to the $0^+a_0\eta$ wave were fitted

$M = 1929 \pm 24 \pm 18 \text{ MeV}/c^2$, $\Gamma = 323 \pm 87 \pm 43 \text{ MeV}/c^2$

$\chi^2$/dof = 19.9/18
Summary

- A partial-wave analysis of the reaction $\pi^- p \rightarrow \eta \eta \pi^- p$ at 18 GeV/c was performed on a data sample of ~4,000 events.
- The $J^{PC} = 0^{-+} \pi(1800)$ state is observed in the $a_0(980)\eta$ and $f_0(1500)\pi$ decay modes.
  - mass of $1876\pm18\pm16$ MeV/c$^2$ and width of $221\pm26\pm38$ MeV/c$^2$
  - relative branching ratio of $\frac{BR[\pi(1800) \rightarrow f_0(1500)\pi, f_0 \rightarrow \eta \eta]}{BR[\pi(1800) \rightarrow a_0(980)\eta, a_0 \rightarrow \eta \pi]} = 0.48\pm0.17$.
- The $J^{PC} = 2^{-+} \pi_2(1880)$ meson is observed decaying through $a_2(1320)\eta$.
  - mass of $1929\pm24\pm18$ MeV/c$^2$ and width of $323\pm87\pm43$ MeV/c$^2$.
- Both states are potential candidates for non-exotic hybrid mesons.
- These results have been submitted to PLB & are under review.
Is the $\pi(1800)$ a Gluonic Hybrid?

$\pi(1800) \rightarrow f_0(980)\pi \quad \checkmark \quad ?$

$\rightarrow \sigma \pi [ f_0(1370)\pi ] \quad \checkmark \quad ?$

$\rightarrow f_0(1500)\pi \quad \checkmark \quad ?$

$\rightarrow a_0(980)\eta \quad \checkmark \quad ?$

$\rightarrow \omega \rho \quad \times$

$\rightarrow \eta \eta' \pi$

$\rightarrow K_0^*(1430)K \quad \checkmark$

$\rightarrow q\bar{q}(L=1) + q\bar{q}(L=0)$

$\pi(1800)$ is not likely a qq meson, and probably not a hybrid meson either
The $\pi(1800)$ could be a Multiquark or $K^*(892)\bar{K}^*(892)$ Molecule similar to the $a_0(980)/f_0(980)$

$\pi(1800) \rightarrow K^*(892) \bar{K}^*(892)$

$\eta(1760) \rightarrow K^*(892) \bar{K}^*(892)$
Study of resonance production in diffractive reaction $\pi^- A \rightarrow \pi^+ \pi^- \pi^- A$.

By VES Collaboration (D.V. Amelin et al.)

\[ \pi^{(1800)} \rightarrow \pi^+ \pi^- \pi^- \]

\[ M = 1774 \pm 18 \pm 20 \text{ MeV}/c^2 \]

\[ \Gamma = 223 \pm 48 \pm 50 \text{ MeV}/c^2 \]

\[ 0^+ \rightarrow f_0(980) \pi \]

\[ \text{Events/40 MeV} \]

\[ \text{Mass}[\pi^+\pi^+\pi^-] \]

\[ 0^+ \rightarrow \sigma \pi \]

\[ \text{Events/40 MeV} \]

\[ \text{Mass}[\pi^+\pi^-\pi^-] \]

\[ BR[\pi(1800) \rightarrow f_0(980) \pi, f_0 \rightarrow \pi \pi] \]

\[ = 0.44 \pm 0.08 \pm 0.38 \]

\[ \text{BNL-E852} \]

\[ \pi^{(1800)} \rightarrow \rho \pi \]

\[ M = 1863 \pm 9 \pm 10 \text{ MeV}/c^2 \]

\[ \Gamma = 191 \pm 21 \pm 20 \text{ MeV}/c^2 \]
$\pi(1800) \rightarrow \omega\rho$

**BNL-E852**

120k events; 27 waves

Same PWA as $b_1\pi$

$J^{PC} = 0^{-+}$

$M = \sim 1850$ MeV/$c^2$

$\Gamma = \sim 250$ MeV/$c^2$


Events: $0^+ 0^+ P_{\omega/\rho^- 1}$

Events/80 MeV/$c^2$
\( \pi_2(1880) \) observed at BNL

\[ \pi^- p \rightarrow p\pi_2(1900) \rightarrow p\omega\pi\pi \]

Events: \( 2^+ 0^+ P_{\omega/\rho^-} 1 \)

\[ 2^+ \rightarrow \omega \rho^- \]

\[ \pi^- p \rightarrow p\pi_2(1900) \rightarrow p\eta\eta\pi^- \]

\( 2^+ a_2(1320) \eta \) S-wave

\[ 2^+ \rightarrow a_2(1320) \eta \]
\[ \pi_2(1900) \rightarrow \eta \pi^- \pi^- \pi^0 \]

\[ R = \frac{BR[\pi_2(1900) \rightarrow a_2(1320)\eta]}{BR[\pi_2(1900) \rightarrow f_1(1285)\pi]} \approx 38 \]

Flux Tube Model Prediction

R = 23


BNL E852

M \sim 2000 \pm 100 \text{ MeV}/c^2

\Gamma \sim 300 \pm 150 \text{ MeV}/c^2