Observation of the $J^{PC} = 0^{-+}\pi(1800)$ and $J^{PC} = 2^{-+}\pi_2(1880)$ mesons in the $\eta\eta\pi^-$ decay

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A partial-wave analysis of the reaction $\pi^- p \to \eta\eta\pi^- p$ at 18 GeV/c has been performed on a data sample of 4,400 events obtained by Brookhaven experiment E852. The $J^{PC} = 0^{-+}\pi(1800)$ state with a mass of $1876\pm18\pm16$ MeV/c^2 and a width of $221\pm26\pm38$ MeV/c^2 is observed in the $a_o(980)\eta$ and $f_o(1500)\pi$ decay modes. The $J^{PC} = 2^{-+}\pi_2(1880)$ meson with a mass of $1929\pm24\pm18$ MeV/c^2 and a width of $323\pm87\pm43$ MeV/c^2 is seen decaying through $a_2(1320)\eta$. Both states are potential candidates for non-exotic hybrid mesons.

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This letter presents the results of a partial-wave analysis for the reaction $\pi^- p \to \eta\eta\pi^- p$ at the beam momentum of 18 GeV/c. The data were obtained by the experiment E852 at Brookhaven National Laboratory.

The primary goal of the E852 experiment was to search for non-$q\bar{q}$ mesons which are predicted to exist in QCD. In addition to multiquark states ($q\bar{q}q\bar{q}$, etc.) and quarkless glueballs (ggg), hybrid mesons with excited gluonic degrees of freedom ($q\bar{q}g$) should also exist. Some of the non-$q\bar{q}$ resonances are expected to have "exotic" quantum numbers $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}, ...$ which are forbidden for ordinary mesons. Other non-$q\bar{q}$ states may have non-exotic J^{PC} and, therefore, may mix with normal $q\bar{q}$ mesons. In this case, identification of the hybrid nature of a non-exotic state becomes difficult and requires, at a minimum, to study its branching ratios into various decay channels.

In the framework of the flux-tube model, a $J^{PC} = 0^{-+}$ hybrid meson is expected to have a mass of 1.9-2.0 GeV/c^2[1]. However, the same model also predicts that the second radial excitation of a pion should have approximately the same mass. Moreover, their total widths are expected to be similar and on the order of 230-240 MeV/c^2[1]. Only branching ratios are predicted to be different. While no particular decay mode is expected to dominate the decay of the radial excitation (with $\rho\omega$ partial width being the largest), the hybrid state should predominantly decay through the $f_o(1300)\pi$ channel.

The $\pi(1800)$ state was discovered in the 3π decay by SERPUKHOV-080 group in 1981[2]. Since then, its existence was confirmed by VES and E852 experiments. VES has seen the $\pi(1800)$ in the $\pi^+\pi^-\pi^-$, $K^+K^-\pi^-$, $\eta'\eta\pi^-$, and $\eta\eta\pi^-$ final states[3–5]. E852 experiment has observed this state in the $\pi^+\pi^-\pi^-$ channel[6]. It is in-

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teresting to note that the measurements of the $\pi(1800)$ mass can be separated into two groups: one group with the mass around 1780 MeV/c^2 ($f_o(980)\pi$, $f_o(1300)\pi$, $K_o^*(1430)K$), and another group at 1860 MeV/c^2 ($\sigma\pi$, $\eta'\eta\pi^-$, $\eta\eta\pi^-$). It is possible that two different states were actually observed.

The history of the $\pi_2(1880)$ resonance is much shorter. It was first observed in 2001 in the Crystal Barrel data[7] through its $a_2(1320)\eta$ decay, together with a higher mass $\pi_2(2000)$ state in its $a_0(980)\eta$ decay[8]. These states were soon confirmed by E852 in the $f_1\pi$[9] and $\omega\rho$[10] decay modes. A hint of the $\pi_2(1880)$ presence was seen earlier by VES in their $\eta\eta\pi$ analysis[3], which is the most relevant to our case due to similarities in the production mechanisms.

Data sample

The data sample was collected by experiment E852 at the Multi-Particle Spectrometer facility at Brookhaven National Laboratory (BNL). 18.3 GeV/c^2 π^- beam and a liquid hydrogen target were used. A description of the experimental apparatus can be found in Ref.[11]. More details about the analysis can be found on our website[12].

An online trigger requirement was to detect 3 forward-going charged tracks and 1 charged recoil track. 265 million events of this type were recorded during the 1995 run of the experiment. The following data selection cuts were applied after event reconstruction:

(1) There should be a fully reconstructed beam track, two negative (π^-) and one positive (π^+) downstream tracks and one charged recoil track (p) originating at a common vertex (only the direction of the recoil track was measured). In addition, four photons should be detected.

(2) The vertex should be within the target volume.

(3) The square of the missing mass calculated from the beam and downstream tracks should be within 1 (GeV/c^2)^2 from that of a proton.

(4) The direction of the missing momentum vector is required to be within $\pm 20°$ in azimuth from the direction of the recoil track.

(5) The total energy deposit from large-angle photons should be ≤ 20 MeV to reject events with soft π^o's from decays of recoil baryon isobars.

(6) Fiducial volume cut at the edges of the detector.

During the next stage of the event selection, a SQUAW kinematic fitter[13] was used to do a 3-C fit to select the $\eta\pi^+\pi^-\pi^o\pi^-p$ event sample. One pair of photons should be coming from a π^o decay, another pair of photons should originate from an η decay, and the missing mass should be consistent with a proton. Events with a confidence level of greater than 5% were selected after the fit.

At the same time, events were fitted to other hypotheses. The most important competing hypothesis is $\pi^o\pi^+\pi^-\pi^o\pi^-p$ because the probability of 4 photons coming from a decay of 2 π^o is much greater than in the $\pi^o\eta$ case. Any event which had a competing hypothesis's confidence level better than 10% was rejected. Approximately 180,000 $\eta\pi^+\pi^-\pi^o\pi^-p$ events were selected at this stage.

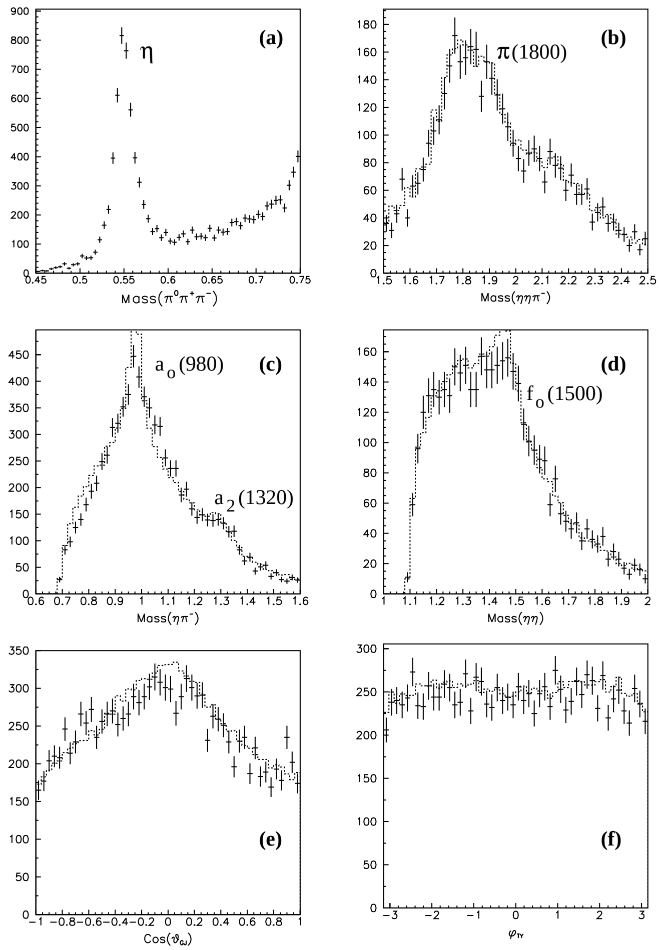

FIG. 1: All plots except of (a) are for the final $\eta\eta\pi^-$ event sample. a) Mass of $\pi^+\pi^-\pi^o$ combination for a fraction of the $\eta\pi^+\pi^-\pi^o\pi^-$ events; b) Mass of $\eta\eta\pi^-$; c) Mass of $\eta\pi^-$; d) Mass of $\eta\eta$; e) cosine of the angle θ in the Gottfried-Jackson frame (π^- as analyzer); f) angle ϕ in the Gottfried-Jackson frame. Dashed lines show quality-of-the-fit comparison based on the final PWA results.

Fig. 1(a) shows the $\pi^+\pi^-\pi^o$ mass distribution for a fraction of this sample. The η meson is clearly seen in the 3π mass distribution, with a background level of less than 10%. Next, all events in which masses of both $\pi^+\pi^-\pi^0$ combinations are above 650 MeV/c^2 were rejected to reduce the background from $\omega \to \pi^+\pi^-\pi^o$ decay. At the last step, the final kinematic fit to the reaction $\pi^-p \to \eta\eta\pi^-p$ was done with a 5% confidence level cut. This resulted in about 4,400 $\eta\eta\pi^-$ events in the final data sample.

Distributions for the final event sample are shown in Fig.1(b-f). The 3-body invariant mass $M(\eta\eta\pi)$ peaks at 1.8 GeV/c^2. Among 2-body masses, $M(\eta\pi)$ shows large contribution of the $a_o(980)\eta$ channel and, to a much smaller extent, the $a_2(1320)\eta$ decay. In turn, $M(\eta\eta)$ has a structure at slightly below 1.5 GeV/c^2. As we found out from PWA, this structure corresponds to the $J^{PC} = 0^{++}$ isoscalar meson $f_o(1500)$. Some preliminary conclusions can be drawn from the angular distributions in the Gottfried-Jackson frames. The symmetric form of the $cos(\theta_{GJ})$ distribution hints to the absence of any strong odd-even spin interference in the data likely caused by the dominance of either even-spin or odd-spin partial waves. The flat ϕ_{TY} distribution indicates that contribution from the projection waves with a non-zero projection M of the total spin J is likely to be small.

Partial Wave analysis

Detailed description of the Partial Wave formalism used in this analysis can be found in Ref.[14]. Analysis was performed in the framework of an isobar model, with a sequential decay of a 3-body wave into an isobar and a final particle followed by a 2-body decay of the isobar into 2 other final particles. Each partial wave is characterized by the total spin, parity and C-parity J^{PC}, by projection M of the total spin and reflectivity ϵ of the system, by the orbital momentum L between the isobar and the bachelor particle, and by the type of isobar. Notation M^ϵ is omitted below because PWA studies indicated that only $M^\epsilon = 0^+$ waves are present in this sample. Positive value of reflectivity indicates that production is dominated by natural parity exchange such as ρ or Pomeron exchanges.

All waves with $J \leq 3$ and $L \leq 3$ had been tried in the fits. Odd-spin waves 1^{++} and 3^{++} were found to be insignificant in contrast to even-spin waves 0^{-+} and 2^{-+}.

Among isobars, the $a_o(980)\eta$, $a_2(1320)\eta$, $f_o(1300)\pi$, $f_2(1270)\pi$, and $f_o(1500)\pi$ combinations had been considered. We didn't find any significant contribution from the $f_o(1300)\pi$ and $f_2(1270)\pi$ modes which may be caused by small branching ratio of these isobars into $\eta\eta$. Simple Breit-Wigner parameterizations with PDG values were used to describe the $a_o(980)$ and $a_2(1320)$ isobars.

Parameters of the $f_o(1500)$ state are not well known. Use of 1507 MeV PDG mass did not result in a good fit which is not surprising considering the position of the peak in Fig.1(d). To determine best parameters for our case we did a systematic scan of the $f_o(1500)$ mass and width in 10 MeV steps. The best overall likelihood was achieved at $M = 1480 \pm 25$ MeV and $\Gamma = 120^{+50}_{-30}$ MeV which is in very good agreement with conclusions from VES[3].

At the end, only 4 partial waves have remained in the final fit: $0^{-+}a_0(980)\eta$ S-wave, $0^{-+}f_0(1500)\pi$ S-wave, $2^{-+}a_2(1320)\eta$ S-wave, and $2^{-+}a_0(980)\eta$ D-wave. In addition, an isotropic non-interfering background wave was introduced in the fit to absorb the non-$\eta\eta\pi$ background. The background wave was at the level from 5% to 15% from the total intensity over the mass range of the fit.

Quality of the fit was judged by comparing data distributions with the ones predicted by applying the fitted spin-density matrix and experimental Monte Carlo acceptance to the Monte Carlo phase space events. Predicted distributions for the final PWA fit are shown as dashed lines in Fig.1. Despite a very small number of partial waves, all data distributions are reasonably well described by the PWA fit as one can see from this figure.

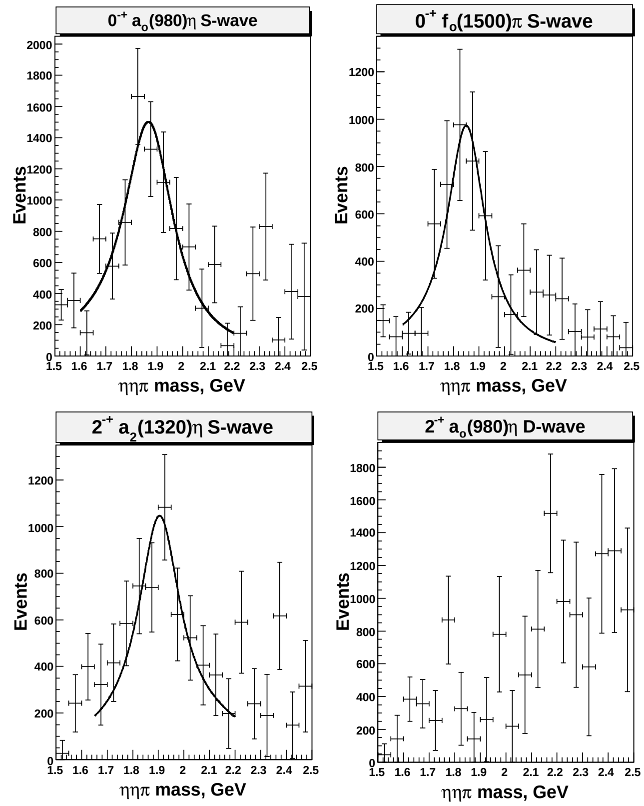

FIG. 2: Intensities for the following partial waves: a) $0^{-+}a_o(980)\eta$ $S-$wave; b) $0^{-+}f_o(1500)\pi$ $S-$wave; c) $2^{-+}a_2(1320)\eta$ $S-$wave; a) $2^{-+}a_o(980)\eta$ $D-$wave. Smooth lines show results of the resonant Breit-Wigner fits.

The final PWA fit was done in the mass range 1.5-2.5 GeV/c^2 in 50 MeV/c^2 steps for all values of the momentum transfer t. Its results are shown in Fig.2 for intensities of the partial waves, and in Fig.3 for some of the phase differences between them. Both 0^{-+} waves (Fig.2(a,b)) peak at 1.8 GeV/c^2 indicating the presence of the $\pi(1800)$ meson in the data. Another peak is seen at 1.9 GeV/c^2 in the $2^{-+}a_2(1320)\eta$ S-wave (Fig.2(c)). It corresponds to the $\pi_2(1880)$ state. Finally, the $2^{-+}a_0(980)\eta$ D-wave (Fig.2(d)) is structureless but it accounts for the majority of events above 2 GeV/c^2.

The phase of the $0^{-+}a_0(980)\eta$ S-wave is rising in relation to the supposedly non-resonant phase of the $2^{-+}a_0(980)\eta$ D-wave (Fig.3(a)). This indicates the resonant behavior of the former confirming the presence of the $\pi(1800)$ state. The phase difference of the same wave relative to the $2^{-+}a_2(1320)\eta$ S-wave is more complex. It raises below 1.8 GeV/c^2 and falls above this mass. Such

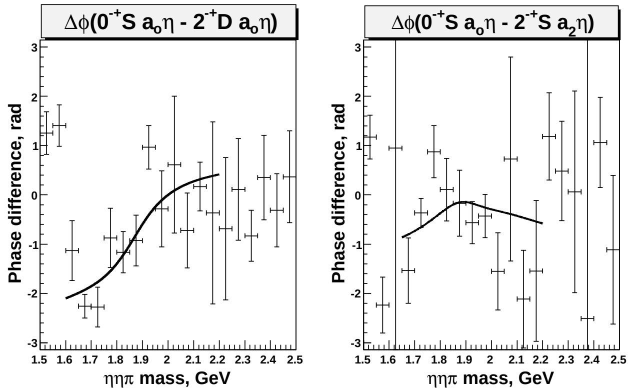

FIG. 3: Phase difference between the following partial waves: a) $0^{-+}a_o(980)\eta$ $S-$wave and $0^{-+}a_o(980)\eta$ $D-$wave. b) $0^{-+}a_o(980)\eta$ $S-$wave. and $2^{-+}a_2(1320)\eta$ $S-$wave. Smooth lines show results of the resonant Breit-Wigner fits.

behavior is expected for 2 single-pole resonant waves with different pole positions. This speaks in favor of the presence of the $\pi_2(1880)$ resonance.

To confirm this conclusion, mass-dependent χ^2 fits were performed. Each of the resonant waves was parameterized with a single-pole relativistic Breit-Wigner form including Blatt-Weiskopf barrier factors. To accomodate for the subthreshold behavior of the $a_2\eta$ and $f_o\pi$ waves at low $\eta\eta\pi$ mass, integration over the available width of decay isobars (a_2, a_o, and f_o) was used in the parameterization.

At first, only the intensities of two 0^{-+} waves were fitted to find the parameters of the $\pi(1800)$ state. When the poles in the $a_o\eta$ and $f_o\pi$ waves were treated independently, the fit resulted in a mass of $M = 1882 \pm 19$ MeV/c^2 and a width of $\Gamma = 236 \pm 42$ MeV/c^2 for $a_o\eta$, and $M = 1865 \pm 25$ MeV/c^2 and $\Gamma = 191 \pm 55$ MeV/c^2 for $f_o\pi$. This fit has $\chi^2/\mathrm{dof} = 0.83$. The results are shown as smooth curves in Figs.2(a,b). As an illustration, the obtained phase of the $0^{-+}a_o\eta$ S-wave is plotted against a presumanbly constant phase of the non-resonant $2^{-+}a_o\eta$ D-wave in Fig.3(a) to confirm the resonant nature of the former.

Unfortunately, the phase of the $0^{-+}f_o(1500)\pi$ wave cannot be measured reliably. Due to a limited phase space for near-threshold decays, the interference region of the $0^{-+}f_o(1500)\pi$ and $2^{-+}a_2(1320)\eta$ waves is outside of $\eta\eta\pi$ Dalitz plot. At the same time, the other important interference term of the $f_o\pi$ wave with the $0^{-+}a_o(980)\eta$ wave is isotropic in all angles, which makes it highly ambiguous with the isotropic background term over limited Dalitz plot. Without reliable and stable phase measurement, our claim about the $f_o(1500)\pi$ decay mode of $\pi(1800)$ is based solely on the Breit-Wigner shape of the wave intensity.

Assuming the same resonance in both 0^{-+} waves, a single-pole fit of their intensities was performed. It has $\chi^2/\mathrm{dof} = 1.2$ with the following parameters for the $\pi(1800)$ state:

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

With these parameters fixed, the intensity of the $2^{-+}a_2\eta$ wave and its phase difference with the $0^{-+}a_o\eta$ wave were fitted. This fit has $\chi^2/\mathrm{dof} = 1.1$ and is shown in Fig.2(c) and Fig.3(b). The $\pi_2(1880)$ state has the following parameters:

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

The $\pi_2(1880)$ parameters from Crystal Barrel are 1880 ± 20 MeV/c^2 and 255 ± 45 MeV/c^2 correspondingly[7].

The fitted Breit-Wigner shapes were integrated to determine the predicted number of events for each state. The following branching ratio was obtained:

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

When the amplitudes of both $\pi(1800)$ waves were mixed together with an unknown branching ratio instead of being treated independently, and a maximum likelihood PWA fit was performed to determine it, a value of 0.40 was obtained. This branching ratio is significantly higher than the value of 0.08 ± 0.03 determined by VES[3] or the value of 0.030 ± 0.014 from Crystal Barrel[7]. Note that all values are given without correction for a $f_o(1500) \to \eta\eta$ branching ratio which is expected to be small.

In summary, we conducted the partial-wave analysis of the reaction $\pi^- p \to \eta\eta\pi^- p$ at 18 GeV/c^2 on a sample of 4,400 events. We observe the $0^{-+}\pi(1800)$ meson decaying through $a_o(980)\eta$ and $f_o(1500)\pi$. We also observe the $2^{-+}\pi_2(1880)$ meson in its $a_2(1320)\eta$ decay.

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