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


Abstract

A partial-wave analysis of the reaction $\pi^- p \rightarrow \eta\eta\pi^- p$ at 18 GeV/c has been performed on a data sample of approximately 4000 events obtained by Brookhaven experiment E852. The $J^{PC} = 0^{-+}$ state is observed in the $a_0(980)\eta$ and $f_0(1500)\pi$ decay modes. It has a mass of $1876 \pm 18 \pm 16$ MeV/$c^2$ and a width of $221 \pm 26 \pm 38$ MeV/$c^2$. The $J^{PC} = 2^{-+}$ meson is observed decaying through $a_2(1320)\eta$. It has a mass of $1929 \pm 24 \pm 18$ MeV/$c^2$ and a width of $323 \pm 87 \pm 43$ MeV/$c^2$. Both states are potential candidates for non-exotic hybrid mesons.

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1. Introduction

This Letter presents the results of a partial-wave analysis of the reaction \( \pi^- p \rightarrow \eta\pi^- p \) at 18 GeV/c pion beam momentum. The data were obtained by experiment E852 at Brookhaven National Laboratory.

The primary goal of E852 was to search for candidates of 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 quark-less glueballs (\( gg \)), 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 \( J^{PC} \neq 0^{-+} \), \( 0^{++}, 1^{-+}, 2^{++}, \ldots \) which are forbidden for ordinary mesons. Other non-\( q\bar{q} \) states may have non-exotic \( J^{PC} \) and those will 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, the study of 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. The primary competing hypothesis is \( J^{PC} = 0^{-+} \) due to similarities in the production mechanisms. The production mechanisms of the reaction \( \pi^- p \rightarrow \eta\pi^- p \) in the \( \eta\pi^- \) mass distribution, with a background level of less than 10%.

2. Data sample

A description of the experimental apparatus can be found in Ref. [11]. More details about the analysis can be found on our website [12].

A Cerenkov tagged \( \pi^- \) beam of momentum 18.3 GeV/c and a 30 cm liquid hydrogen target were used. The target was placed at the center of the dipole magnet with a field of 1 Tesla. The target was surrounded by a four-layer cylindrical drift chamber used to trigger on the charged recoil particle, and a 198-element cylindrical thallium-doped cesium iodide array to reject events with soft photons. The downstream part was equipped with 6 seven-plane drift chamber modules inside the magnet and one large two-plane drift chamber outside of it for charged-particle tracking. Triggering on the multiplicity of forward charged tracks was allowed by three proportional wire chambers. Forward photons were detected by a 3000-element lead glass electromagnetic calorimeter.

The online trigger required three forward-going charged tracks and one charged recoil track. A total of 265 million events of this type were recorded during the second run of the experiment. After event reconstruction, candidate events having one positive pion, two negative pions, and four photons were selected. To reduce background additional cuts were applied on the vertex position, missing mass, and the direction of the missing momentum. Soft pions from recoil baryon decays were also rejected.

A 3-C kinematic fit was made to select the \( \eta\pi^+\pi^-\pi^0\pi^- p \) event sample. One pair of photons was required to come from a \( \pi^0 \) decay and the other pair from an \( \eta \) decay, and the missing mass was required to be consistent with a proton. Events with a confidence level greater than 5% were selected.

Similar fits were made to other hypotheses. The most important competing hypothesis is \( \pi^0\pi^+\pi^-\pi^0\pi^- p \) because the probability of 4 photons coming from the decay of 2 neutral pions is much greater than that for the \( \pi^0\eta \) case. Any event which had a confidence level greater than 10% for a competing hypothesis was rejected. Approximately 180,000 \( \eta\pi^+\pi^-\pi^0\pi^- p \) events were selected at this stage.

Fig. 1(a) shows the \( \pi^+\pi^-\pi^0 \) mass distribution for a fraction of this sample. The \( \eta \) meson is clearly seen in the \( 3\pi \) mass distribution, with a background level of less than 10%.

Only events with at least one \( \pi^+\pi^-\pi^0 \) combination below 650 MeV/c\(^2\) were used in the final kinematic fit to the reaction \( \pi^- p \rightarrow \eta\pi^- p \), with a 5% confidence level cut. This resulted in about 4400 \( \eta\pi^- \) events. The final data sample consisted of about 4000 events in the mass and momentum transfer ranges selected for partial wave analysis (PWA).

Distributions for the final event sample are shown in Fig. 1(b)–(f). The 3-body invariant mass \( M(\eta\pi^-) \) peaks at...
1.8 GeV/$c^2$. Among 2-body masses, $M(\eta\pi^-)$ shows large contribution from the $a_0(980)\eta$ channel and, to a much smaller extent, the $a_2(1320)\eta$ channel. In turn, $M(\eta\eta)$ has a structure at slightly below 1.5 GeV/$c^2$. The PWA analysis described later reveals that this structure corresponds to the $J^{PC} = 0^{++}$ isoscalar meson $f_0(1500)$.

Some preliminary conclusions can be drawn from the angular distributions in the Gottfried–Jackson frames [11]. This is the $\eta\eta\pi$ rest frame with $z$-axis along the beam direction and $y$-axis along the normal to the production plane. The symmetric form of the $\cos(\theta_{qj})$ distribution suggests 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 $\phi_{TY}$ distribution indicates that any contribution from waves with a non-zero projection $M$ of the total spin $J$ is likely to be small.

3. Partial wave analysis

A detailed description of the partial wave formalism used in this analysis can be found in Ref. [13]. The analysis was performed within the framework of an isobar model, with a sequential decay of a 3-body state 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 $J^{PC}$, the projection $M$ of the total spin, the reflectivity $\epsilon$ of the system, the type of isobar, and the orbital angular momentum $L$ between the isobar and the bachelor particle. The notation $M^s$ is omitted below because PWA studies indicated that only $M^s = 0^+$ waves are present in this sample. Positive reflectivity indicates that production is dominated by natural-parity exchange such as $\rho$ or pomeron exchange.

All waves with $J \leq 3$ and $L \leq 3$ were 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 $a_0(980)\eta$, $a_2(1320)\eta$, $f_0(1300)\pi$, $f_2(1270)\pi$, and $f_0(1500)\pi$ combinations were considered. Simple Breit–Wigner parameterizations were used to describe the isobars. There was no significant contribution from the $f_0(1300)\pi$ and $f_2(1270)\pi$ modes.

Resonance parameters from the PDG [14] were used for the $a_0(980)$ and $a_2(1320)$ isobars. To determine the best $f_0(1500)$ parameters from our data, we made a scan of the $f_0(1500)$ mass and width in 10 MeV steps performing a new PWA fit at each step. The best overall likelihood was achieved with $M = 1480 \pm 25$ MeV and $I' = 120^{+50}_{-30}$ MeV, which is in reasonably good agreement with values given in PDG. According to the likelihood ratio test, the presence of the $f_0(1500)\pi$ partial wave is required at the confidence level of more than 99.9% because a logarithm of the likelihood changes by 12–14 points for 4 extra parameters in the mass bins near 1.8 GeV in the PWA fits with and without this partial wave.

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

The 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 the very small number of partial waves, all data distributions are reasonably well described by the PWA fit.

The final PWA fit was done in the mass range from 1.5 to 2.5 GeV/$c^2$ in 50 MeV/$c^2$ steps and for the momentum transfer $-t$ less than 1.2 (GeV/$c^2$)$^2$. Fig. 2 shows the intensities of the partial waves and Fig. 3 shows 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. A peak corresponding to the $\pi_2(1880)$ is observed in the $2^{+-} a_2(1320)\eta$ $S$-wave (Fig. 2(c)). 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 presumably non-resonant phase of the $2^{++} a_0(980)\eta$ $D$-wave (Fig. 3(a)) due to the presence of the $\pi(1800)$ reso-
Weiskopf barrier factors. To accommodate the subthreshold behavior of the $a_2 \eta$ and $f_0 \pi$ waves at low $\eta \eta \pi$ mass, integration over the available width of decay isobars ($a_2$, $a_0$, and $f_0$) was used in the parameterization.

First the intensities of the two $0^+ \pi$ waves were fitted to find the parameters of the $\pi(1800)$ state. When the poles in the $a_0 \pi$ and $f_0 \pi$ 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 $a_0 \pi$, and $M = 1865 \pm 25$ MeV/$c^2$ and $\Gamma = 191 \pm 55$ MeV/$c^2$ for $f_0 \pi$. This fit has $\chi^2$/dof = 14.97/18. The results are shown as solid curves in Fig. 2(a), (b). As an illustration, the phase of the $0^+ a_0 \pi$ S-wave is plotted against the presumably constant phase of the non-resonant $2^+ a_0 \eta$ D-wave in Fig. 3(a) to confirm the resonant nature of the former.

Unfortunately, the phase of the $0^+ f_0(1500) \pi$ wave cannot be measured reliably. The interference region of the $0^+ f_0(1500) \pi$ and $2^+ a_2(1320) \eta$ waves is outside of the $\eta \eta \pi$ Dalitz plot. The other important interference term of the $f_0 \pi$ wave (with the $0^+ a_0(980) \eta$ wave) is isotropic in all angles, which makes it highly ambiguous with the isotropic background term over the limited Dalitz plot. Without a reliable and stable phase measurement, the present identification of the $f_0(1500) \pi$ decay mode for $\pi(1800)$ is based solely on the Breit–Wigner shape of the wave intensity.

Assuming the same resonance in both $0^+ \pi$ waves, a single-pole fit of their intensities was performed. It has $\chi^2$/dof = 23.91/20 with the following parameters for the $\pi(1800)$ state:

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

The systematic errors were found by varying the mass range of the fit and by adding different background parameterizations.

With these parameters fixed, the intensity of the $2^+ a_2 \eta$ wave and its phase difference with the $0^+ a_0 \eta$ wave were fitted. This fit has $\chi^2$/dof = 19.86/18 and is shown in Figs. 2(c) and 3(b). The $\pi_2(1880)$ state has the following parameters:

- $M = 1929 \pm 24 \pm 18$ MeV/$c^2$,
- $\Gamma = 323 \pm 87 \pm 43$ MeV/$c^2$.

Previous measurements [7] yield a $\pi_2(1880)$ mass and width of $1880 \pm 20$ MeV/$c^2$ and $255 \pm 45$ MeV/$c^2$, respectively, which agrees with the present result.

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

$$\frac{BR[\pi^- (1800) \rightarrow f_0(1500) \pi^- , f_0 \rightarrow \eta \eta]}{BR[\pi^- (1800) \rightarrow a_0^*(980) \eta , a_0 \rightarrow \eta \pi^- ]} = 0.48 \pm 0.17.$$  

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 of $0.08 \pm 0.03$ determined by VES [3] or the value of $0.030 \pm 0.014$ from Anisovich [7] but not inconsistent due to large statistical error.
In summary, a partial-wave analysis of the reaction $\pi^- p \rightarrow \eta \eta \pi^- p$ at 18 GeV/c$^2$ was carried out on a sample of 4000 events. We observe the $0^{++}(1800)$ meson decaying through $a_0(980)\eta$ and $f_0(1500)\pi$. We also observe the $2^{++}\pi_2(1880)$ meson in its $a_2(1320)\eta$ decay.

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References