Evidence for Two Pseudoscalar Resonances of the $\eta\pi^+\pi^-$ System in the $D(1285)$ and E/ι Regions

A. Ando,[(1),(a)] K. Imai,[(2)] S. Inaba,[(1)] T. Inagaki,[(1)] Y. Inagaki,[(2)] A. Itano,[(3)] S. Kobayashi,[(4)] K. Maruyama,[(5)] A. Murakami,[(4)] T. Nakamura,[(2)] K. Ohmi,[(6)] H. Okuno,[(5)] A. Sasaki,[(7)] T. Sato,[(1)] J. Shirai,[(1)] K. Takamatsu,[(1)] R. Takashima,[(8)] N. Tamura,[(2)] T. Tsuru,[(1)] and Y. Yasu[(1)]

[(1)] *National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan*
[(2)] *Kyoto University, Sakyo, Kyoto 606, Japan*
[(3)] *National Institute of Radiological Sciences, Chiba 260, Japan*
[(4)] *Saga University, Saga 840, Japan*
[(5)] *Institute for Nuclear Study, Tokyo University, Tanashi, Tokyo 188, Japan*
[(6)] *University of Tsukuba, Niihari, Ibaraki 305, Japan*
[(7)] *Akita University, Akita 010, Japan*
[(8)] *Kyoto University of Education, Fushimi, Kyoto 612, Japan*

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High-statistics data on the reaction $\pi^- p \rightarrow \eta\pi^+\pi^- n$ at 8.06 GeV/c were obtained. An isobar-model partial-wave analysis was performed for the $\eta\pi\pi$ system. The $\eta(1275)$ meson was confirmed as a narrow $IJ^{PC}=00^{-+}$ resonance. It decays through both $\delta\pi$ and $\epsilon\eta$. A narrow state with $IJ^{PC}=00^{-+}$ was found in an $\eta\pi\pi$ decay channel at 1.42 GeV. It has a prominent peak in a $\delta\pi$ decay mode. No significant $E(1420)$ signal with $IJ^{PC}=01^{++}$ was found near the mass region of 1.42 GeV.

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The discovery of $\iota(1440)$ [1,2] in the radiative decay of J/ψ raised great interest in the low-mass meson spectroscopy. The $\iota(1440)$ has been considered to be a glueball candidate, because it was produced prominently in a gluon channel. It has $J^{PC}=0^{-+}$ and decays into $K\bar{K}\pi$ mainly through $\delta\pi$.[2-4] However, no clear signal has been seen in the $\eta\pi\pi$ decay channel.[3,5] In hadronic reactions, on the other hand, the pseudoscalar state $E(1420)$ was observed in the $K\bar{K}\pi$ channel of the reaction $\bar{p}p$ at rest[6] and the $\pi^- p$ reaction,[7,8] while an assignment of 1^{++} for $E(1420)$ was reported in other experiments.[9,10] In the $\eta\pi\pi$ channel, a pseudoscalar resonance was found at 1.275 GeV and an indication of another 0^{-+} wave was seen near 1.4 GeV.[11] More extensive studies, especially in the $\eta\pi\pi$ channel in the low-mass region, are therefore desirable.

The reaction $\pi^- p \rightarrow \eta\pi^+\pi^- n$ with $\eta \rightarrow 2\gamma$ was measured at 8.06 GeV/c with the charged and gamma spectrometer using the KEK 12-GeV proton synchrotron. The layout of the spectrometer is shown in Fig. 1. The momenta of both charged pions and gamma rays of the $\eta\pi^+\pi^-$ final state were measured. Two charged pions were tracked with a large-aperture superconducting magnet and 24 planes of multiwire proportional chambers (MWPC's) and drift chambers (W1–W4). The energies of gamma rays were measured with a converter of lead glass (AC) (2.5 radiation lengths) and an array of total-absorption lead-glass counters (MR) (11.8 radiation lengths). The conversion points of two gamma rays were measured with an MWPC (W5) which was set just behind the converter. The detectors were assembled as close as possible to get a large acceptance. The lead-glass counters were placed at a distance of 3.93 m from the hydrogen target. Two scintillation-hodoscope counters (H1 and H2) were used for the trigger. Lead-scintillator sandwich counters (AV1, AV2, and TV), which were sensitive to both charged particles and gamma rays, covered the off-acceptance region of the spectrometer to reject unwanted events. The target-veto counters (TV) assured that there was no other particle except a

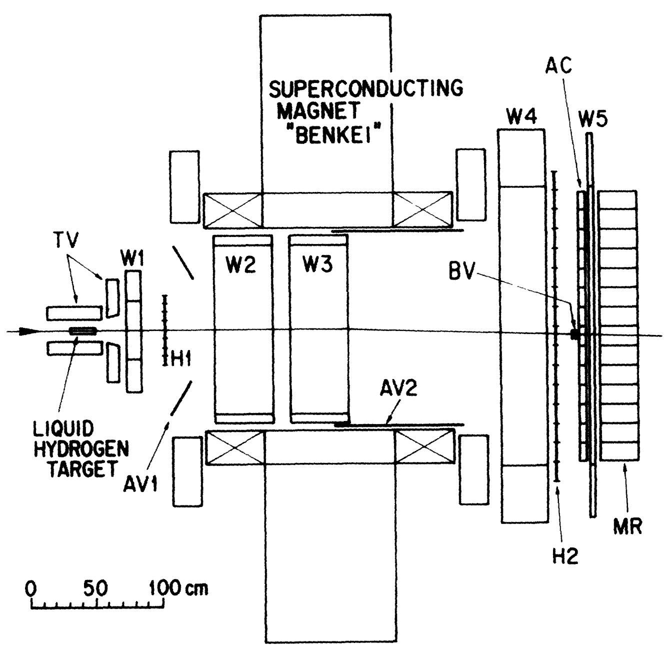

FIG. 1. Layout of the charged and gamma spectrometer.

neutron. Noninteracting pions in the incident beam were vetoed by a double of scintillation counters (BV) set downstream of the H2. The trigger logic was $[\text{Beam} \times \overline{\text{BV}} \times \text{H1}(\geq 2) \times \text{H2}(2 \text{ or } 3) \times (N_\gamma \geq 2) \times \overline{\text{AV1}} \times \overline{\text{AV2}} \times \overline{\text{TV}}]$, where N_γ was the number of MR blocks in each of which the energy more than 300 MeV was deposited. As a fast selective trigger at the second stage of the trigger logic, a multiplicity of two or three was required in one MWPC plane of the chamber set W3. Details of the spectrometer system were described elsewhere.[12]

A spectrum of the squared missing mass recoiling against the $\eta\pi\pi$ system is shown in Fig. 2(a). The spectrum of the digamma mass for events with an $\eta\pi\pi$ effective mass above 1.21 GeV is shown in Fig. 2(b). Clear peaks at the neutron and η masses are seen in these figures. The following event selection criteria were applied to get the $\eta\pi\pi$ sample: (1) The squared missing mass lies between 0.30 and 1.21 GeV^2; and (2) the digamma effective mass lies between 0.51 and 0.59 GeV. The regions of the above selections are indicated by arrows in Figs. 2(a) and 2(b).

The $\eta\pi\pi$ mass spectrum shown in Fig. 3(a) was obtained by a two-constraint fit requiring that η's and neutrons should have their nominal masses. From the width of the η' peak we estimate a mass resolution of 14 MeV (FWHM). A clear peak around 1.28 GeV is also seen. This peak is enhanced by introduction of a so-called δ cut which required that the $\eta\pi$ effective mass should lie between 0.95 and 1.01 GeV as shown in Fig. 3(b).

A partial-wave analysis for the $\eta\pi\pi$ system was performed in the mass region between 1.21 and 1.51 GeV, with use of the data in the t' region between 0.05 and 0.5 (GeV/c)^2. The analysis program[13] was a modified version of the Stanford Linear Accelerator Center–Berkeley isobar-model program.[14] We used the intermediate isobars "ϵ" and ρ for $\pi\pi$ and δ for $\eta\pi$, respectively. The "ϵ" in the analysis program was given by the S-wave $\pi\pi$ phase shift which was the result of the coupled-channels fit. The Breit-Wigner parameters were used for δ, values of the mass and the width of which were 0.98 and 0.055 GeV, respectively. The analysis was done in 10-MeV $\eta\pi\pi$ mass bins. The maximum-likelihood method was adopted as a fitting procedure. We started the analysis with all possible waves under the condition that both total spin and isospin of $\eta\pi\pi$ were less than 2. The waves which gave no significant increase of likelihood were discarded. Finally we got a solution which consisted of seven waves[15] $00-\delta\pi S$, $00-\epsilon\eta S$, $01+\delta\pi P$, $01+\epsilon\eta P$, $11+\delta\pi P$, $11+\rho\eta S$, and $11-\rho\eta P0-$.

Figures 4 and 5 show the acceptance-corrected intensities and the phase variations of various waves, respectively. The $01+\epsilon\eta P$ and $11+\delta\pi P$ waves are not illustrated because their contributions are small and do not have a significant structure. The phases were defined relatively with respect to the $11+\rho\eta S$ wave.

The $01+\delta\pi P$ wave [Fig. 4(a)] has a narrow structure around 1.28 GeV in the intensity distribution. The phase shows a rapid forward motion of about 180° across 1.28 GeV as shown in Fig. 5(a). This structure is considered to arise from the isoscalar meson $D(1285)$ with $J^{PC}=1^{++}$. We see no significant structure around 1.42 GeV in the $01+\delta\pi P$ intensity, where

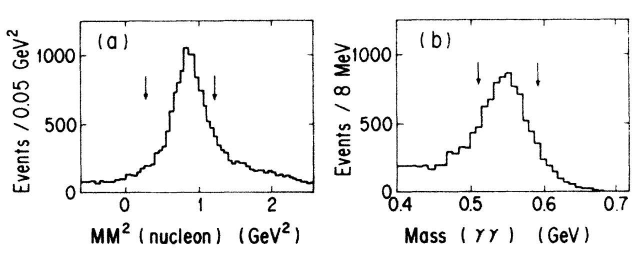

FIG. 2. (a) Missing-mass-squared distribution. (b) Digamma mass distribution for the $\eta\pi\pi$ mass above 1.21 GeV. The arrows indicate the cuts applied to select good events.

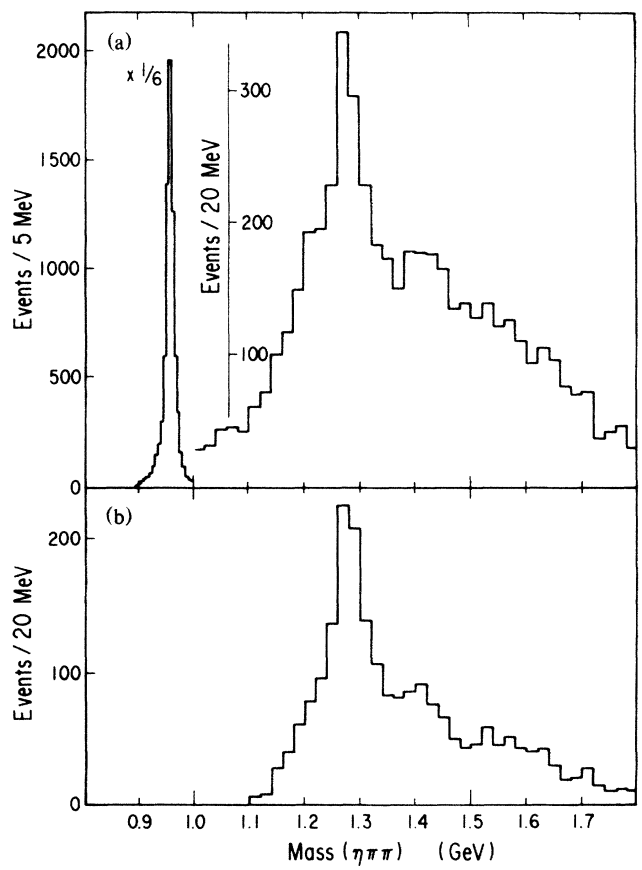

FIG. 3. (a) Raw mass spectrum for the $\eta\pi\pi$ system. (b) Mass spectrum for the $\eta\pi\pi$ above 1.1 GeV with a δ cut [0.95 GeV $< M(\eta\pi) <$ 1.01 GeV].

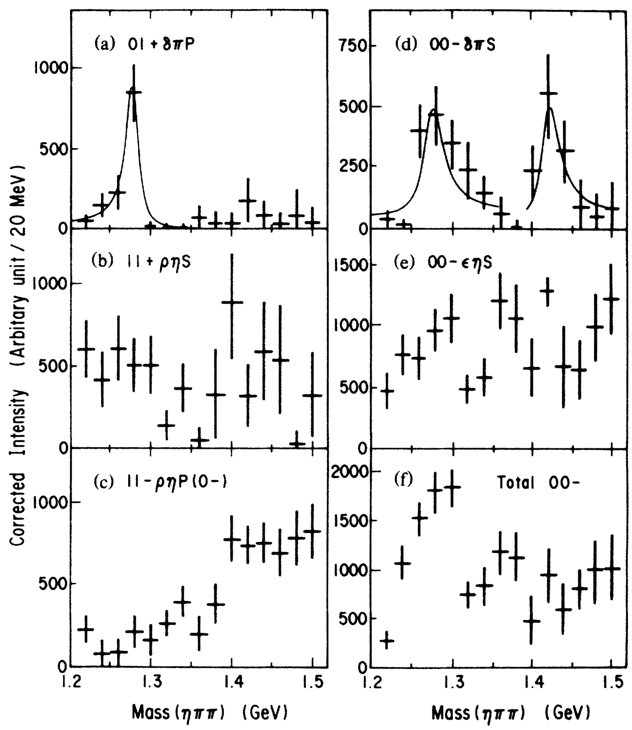

FIG. 4. Intensity distributions of the labeled partial waves. Intensities are plotted by summing up in every 20-MeV bin. The solid lines are the Breit-Wigner fit.

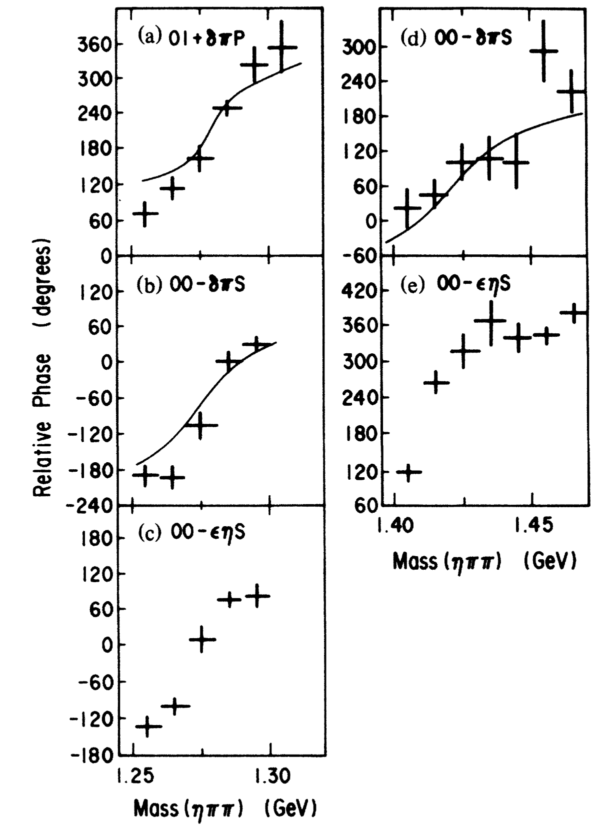

FIG. 5. Phase variation of the labeled partial waves. (a)–(c) Effective-mass region around 1.28 GeV. (d),(e) Effective-mass region around 1.42 GeV. The solid lines are the Breit-Wigner fit.

another isoscalar meson $E(1420)$ with $J^{PC}=1^{++}$ is expected to exist.

The $00-\delta\pi S$ wave [Fig. 4(d)] has two narrow structures around 1.28 and 1.42 GeV. The phases show forward motions across 1.28 and 1.42 GeV as shown in Figs. 5(b) and 5(d), respectively. The structure around 1.28 GeV is considered to come from $\eta(1275)$, which was previously reported[11] to be a candidate for a radially excited state of $\eta(548)$. We observed another structure around 1.42 GeV in the $\eta\pi\pi$ channel.

The $00-\epsilon\eta S$ wave [Fig. 4(e)] has the largest intensity in the solution. A structure is seen around 1.28 GeV on considerable background. The structure has almost the same intensity and width as those of the $00-\delta\pi S$ wave. The phase variation shows a remarkable forward motion around 1.28 GeV [Fig. 5(c)]. This means that the $\eta(1275)$ decays not only into $\delta\pi$ but also into $\epsilon\eta$. The relative phase between the $00-\epsilon\eta S$ and $00-\delta\pi S$ waves is about 80°.

The $11+\rho\eta S$ wave has a considerable amount of intensity in the relevant region as shown in Fig. 4(b). Therefore we chose this wave as the reference of the phase motion. The $11-\rho\eta P0-$ wave [Fig. 4(c)], which is an unnatural-parity–exchange wave, shows a monotonic increase with mass. Other unnatural-parity–exchange waves made little contribution to the solution.

The stability of the solution obtained was checked as follows. The major features of the solution were not changed by our providing additional partial waves. The contribution from higher partial waves ($J\geqslant 2$) was found to be negligible in the mass region of the analysis. We added other isobars, A_2 and $f(1270)$, but their contributions were small and had little effect on the solution. We tried to use other parameter combinations, Hyams's $0^+\pi\pi$ phase shift[16] for "ε" and Breit-Wigner parameters[17] for δ in which the $K\bar{K}$ threshold effect was included. The structures around 1.28 and 1.42 GeV were, however, almost unchanged.

Non-η background which exists below the η peak in the digamma mass spectrum [Fig. 2(b)] is about 10% in the $\eta\pi\pi$ mass region between 1.21 and 1.51 GeV. To estimate the contribution of non-η background to the solution, we applied a partial-wave analysis to the events of digamma mass between 0.40 and 0.48 GeV. It was found that these background events fell into the $00-\epsilon\eta S$ wave with little admixture of other waves.

The observed peaks in $01+\delta\pi P$ and $00-\delta\pi S$ intensities were fitted with the Breit-Wigner form and a constant background against both intensity distributions and phase variations. The results are shown with solid lines in Figs. 4 and 5. Masses and widths obtained are as follows: 1.280 ± 0.004 GeV, and 19 ± 5 MeV[18] for $D(1285)$ $(01+\delta\pi P)$; 1.279 ± 0.005 GeV and 32 ± 10 MeV for $\eta(1275)$ $(00-\delta\pi S)$; and 1.420 ± 0.005 GeV and 31 ± 7 MeV for the pseudoscalar $(00-\delta\pi S)$, respectively. The widths were not corrected with the mass resolution of the spectrometer. The mass resolution of the spectrometer for $\eta\pi\pi$ was estimated to be about 20 and 25 MeV (FWHM) at 1.28 and 1.42 GeV, respectively, from a Monte Carlo simulation which reproduced well the η' mass resolution.

The peak at 1.28 GeV in the raw mass distribution [Fig. 3(a)] was found to be a superposition of $\eta(1275)$ and $D(1285)$. This result is consistent with that of the experiment by Stanton *et al.*[11] We did not obtain evidence for the axial-vector meson $E(1420)$ which was observed in the $K\bar{K}\pi$ system produced in the $\pi^- p$ reaction by Dionisi *et al.*[9] and in the $\pi^+(p)p$ reaction by Armstrong *et al.*[10] They reported that the $E(1420)$ meson decays mainly through $\bar{K}^*K/\bar{K}K^*$ and not through $\delta\pi$, which means the axial vector meson $E(1420)$ may be an $s\bar{s}$ dominant state.

The intensity of the $00-\epsilon\eta S$ wave shows no clear peak around 1.42 GeV. The phase variation shows, on the other hand, a forward motion as seen in Fig. 5(e). The total $00-$ intensity in Fig. 4(f) has no clear structure around 1.42 GeV. It may be said that the two $00-$ waves exhibit a destructive interference[19] in this region.

The peak of the $00-\delta\pi S$ wave at 1.42 GeV is similar to the one at 1.28 GeV in intensity. Recently Chung *et al.*[7] have reported the result of the experiment on the reaction $\pi^- p \rightarrow K\bar{K}\pi n$ at 8.0 GeV/c using the multiparticle spectrometer at Brookhaven National Laboratory. They showed peaks around 1.28 and 1.42 GeV in the raw mass distribution. The Dalitz-plot analysis gave two narrow peaks, at 1.28 GeV with $J^{PG}=1^{++}$ and at 1.42 GeV with $J^{PG}=0^{-+}$. The latter one has substantially a $\delta\pi$ decay mode. The partial-wave analysis[8] performed on the same data has confirmed the results, which are consistent with ours. However, they did not see a significant peak around 1.28 GeV in the $J^{PG}=0^{-+}$ wave. If $\eta(1275)$ decays through $\delta\pi$, it should be seen in $K\bar{K}\pi$ as well as in $\eta\pi\pi$.

The pseudoscalar(1420) we observed in the $\eta\pi\pi$ channel has the same quantum numbers as ι and decays mainly through $\delta\pi$. It may well be said that the pseudoscalar(1420) is the same state as ι. It seems, on the other hand, to be natural that the pseudoscalar(1420) is assigned to a radially excited state of $\eta'(958)$, because it has comparable intensity with $\eta(1275)$ as shown in Fig. 4(d).

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(a)Present address: Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567, Japan.

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[15]Our notation of $IJPxyLM\xi$ is the following: I = isospin, J = total spin, P = parity, xy = intermediate state, L = orbital angular momentum between x and y, M = z component of J, and ξ = exchange naturality. When $M\xi$ is unwritten, its value is taken as $0+$. Each wave includes both the nucleon spin-flip and -nonflip contributions, because the spin state at the nucleon vertex was not observed.

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[17]We tried the following parameters: The mass of δ was 0.98 GeV and its width (constant) was 0.1 and 0.25 GeV below and above the $K\bar{K}$ threshold, respectively.

[18]If we take an upper limit of two standard deviations into account on the fitted value, the true width of the $D(1285)$ is estimated to be 21 MeV, which is close to the value 26.2 ± 3.1 MeV of C. G. Wohl *et al.* (Particle Data Group), Rev. Mod. Phys. **56**, S158 (1984).

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