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Study of $\pi^- N \to \eta\pi^- N$ and $\pi^- N \to \eta'\pi^- N$ reactions at 37 GeV/c

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Abstract

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The partial-wave analysis of the $\eta\pi^-$ and $\eta'\pi^-$ systems produced in the reactions $\pi^-N \to \eta(\eta')\pi^-N$ on the beryllium target at the beam momentum of $p_{\pi^-} = 37$ GeV/c is performed. It is shown that: 1) all the waves with negative exchange naturality are negligibly small for both systems; 2) the matrix element squared of the $P+$ wave with $J^{PC} = 1^{-+}$ for the $\eta'\pi^-$ system significantly exceeds that for the $\eta\pi^-$ system, which could testify to the dominance of the systems with valence gluon ($q\bar{q}g$) in the $J^{PC} = 1^{-+}$ wave formation; 3) the ratio $R = \frac{BR(a_2^- \to \eta'\pi^-)}{BR(a_2^- \to \eta\pi^-)} = (4.7 \pm 1.0(stat) \pm 0.4(syst)) \cdot 10^{-2}$ has been obtained.

Аннотация

Бердников Е.Б. и др. Изучение реакций $\pi^-N \to \eta\pi^-N$ и $\pi^-N \to \eta'\pi^-N$ при 37 GeV/c.: Препринт ИФВЭ 93-62. — Протвино, 1993. — 10 с., 6 рис., библиогр.: 13.

Проведен парциально-волновой анализ систем $\eta\pi^-$ и $\eta'\pi^-$, образующихся в реакциях $\pi^-N \to \eta(\eta')\pi^-N$ на бериллиевой мишени при импульсе пучка $p_{\pi^-} = 37$ ГэВ/с. Показано, что: 1). волны с отрицательной натуральностью обмена в обеих системах пренебрежимо малы; 2). квадрат матричного элемента волны P+ с квантовыми числами $J^{PC} = 1^{-+}$ для системы $\eta'\pi^-$ намного больше, чем для системы $\eta\pi^-$, что свидетельствует о доминировании систем с валентным глюоном ($q\bar{q}g$) в образовании волны с $J^{PC} = 1^{-+}$; 3). получено отношение $R = \frac{BR(a_2^- \to \eta'\pi^-)}{BR(a_2^- \to \eta\pi^-)} = (4.7 \pm 1.0(stat) \pm 0.4(syst)) \cdot 10^{-2}$.

1. Introduction

In this paper we continue studying the systems $\eta\pi^-$ and $\eta'\pi^-$ produced in π^-N interactions. The analysis of the $\eta\pi^-$ system was described in [1], the $\eta'\pi^-$ system was studied in [2]; our preliminary results on both systems were presented in [3].

The interest in studying the $\eta\pi$ ($\eta'\pi$) systems is mainly caused by the possibility of searching for the exotic (non-$q\bar{q}$) states with $J^{PC} = 1^{-+}$. In particular, the observation of the $J^{PC} = 1^{-+}$ state $\hat{\rho}^0(1405)$ in the $\eta\pi^0$ system was reported in [4], and one could expect to observe the $\hat{\rho}^-(1405)$ in the $\eta\pi^-$ and $\eta'\pi^-$ systems.

The data from the high-statistics experiment at the VES setup of the IHEP 70-GeV proton synchrotron at the incident beam momentum of $p_{\pi^-} = 37$ GeV/c on the beryllium target have been used for the analysis. The setup is a large aperture magnetic spectrometer which includes a system of proportional and drift chambers and a lead-glass electromagnetic calorimeter. A more detailed description of the VES setup can be found elsewhere [5,6].

2. Event selection

The $\eta\pi^-$ and $\eta'\pi^-$ systems have been studied in the reactions:

$$\pi^-N \to \pi^-\eta N, \quad \eta \to \pi^+\pi^-\pi^0, \quad \pi^0 \to \gamma\gamma \tag{1}$$

and

$$\pi^-N \to \pi^-\eta' N, \quad \eta' \to \pi^+\pi^-\eta, \quad \eta \to \gamma\gamma \tag{2}$$

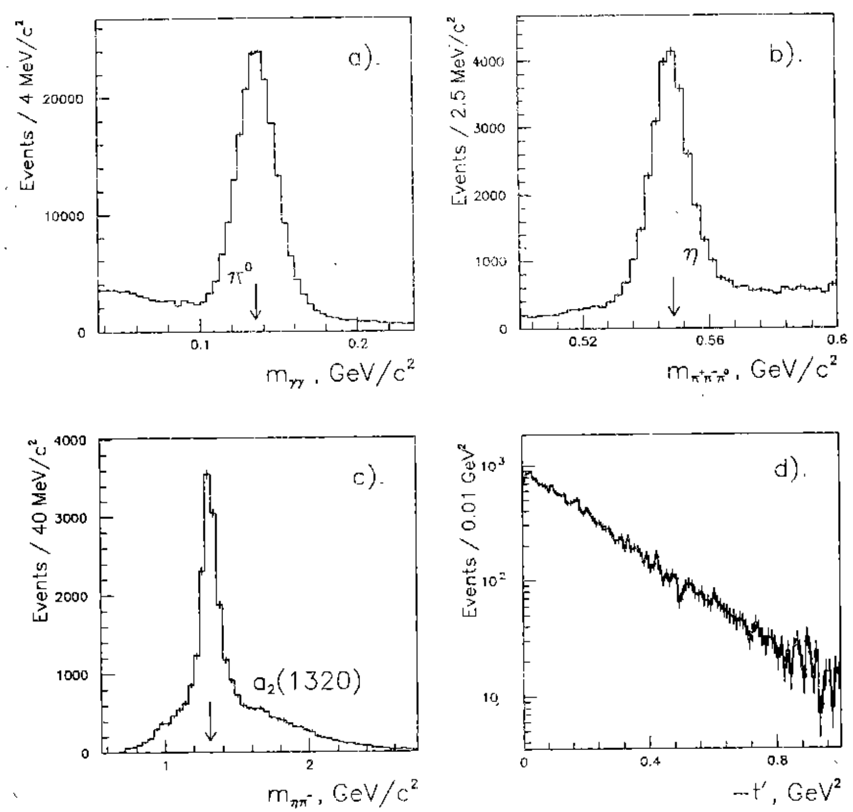

Figure 1. Effective mass distributions of $\gamma\gamma$ (a), $\pi^+\pi^-\pi^0$ (b), $\eta\pi^-$(c); t-distribution for $\eta\pi^-$ events (d).

respectively, which have the same set of particles ($\pi^-\pi^-\pi^+\gamma\gamma$) in the final state. To select the $\eta\pi^-$ events the following criteria have been used:

- the event has three charged tracks (two negative and one positive) and two (or three) gammas in the final state;
- the total energy of the final state lies within the interval of $34 < E_{tot} < 39$ GeV;
- charged particles are not electrons (determined using the energy deposition of the particle in the electromagnetic calorimeter);
- the effective mass of two gammas lies within the interval of the π^0 mass: $105 < m_{\gamma\gamma} < 165$ MeV; one additional gamma is admissible with energy

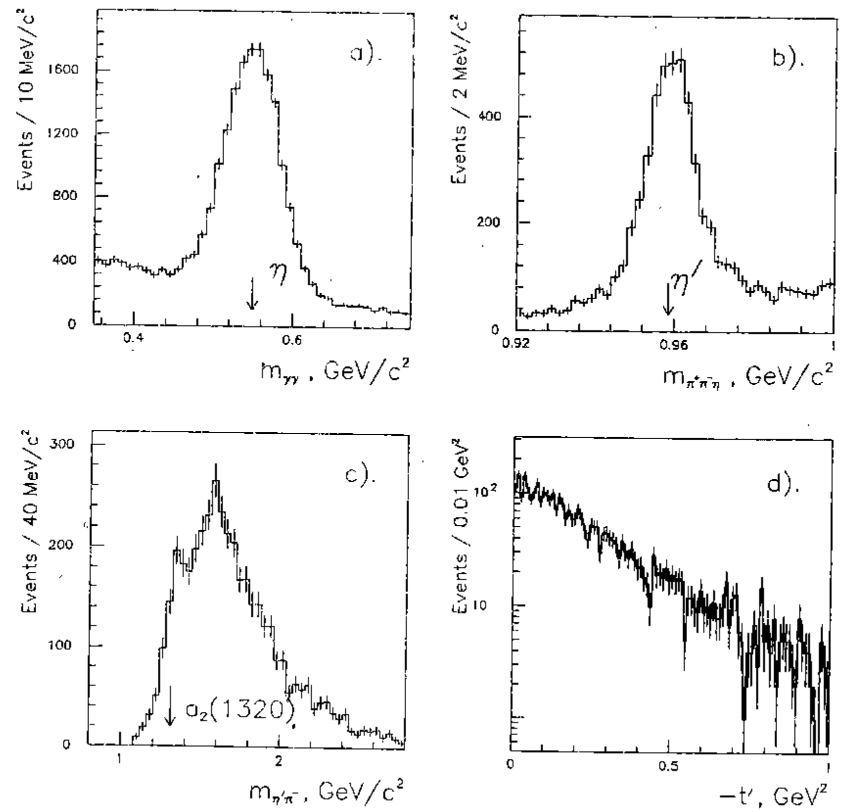

Figure 2. Effective mass distributions of $\gamma\gamma$ (a), $\pi^+\pi^-\eta$ (b), $\eta'\pi^-$(c); t-distribution for $\eta'\pi^-$ events (d).

not exceeding 0.7 GeV. When calculating the π^0-meson momentum the constraint $m_{\gamma\gamma} = m_{\pi^0}$ has been imposed (1C-fit);

- the effective mass of one of $\pi^+\pi^-\pi^0$ subsystems lies in the interval of the η-meson mass: $531 < m_{\pi^+\pi^-\pi^0} < 567$ MeV. The events from control region, i.e. with $503 < m_{\pi^+\pi^-\pi^0} < 521$ MeV or $577 < m_{\pi^+\pi^-\pi^0} < 595$ MeV, have been used to evaluate the background.

After these cuts ~27000 "$\eta\pi^-$" events and ~5500 "background" events have been selected for further analysis. The effective mass spectra of $\gamma\gamma$, $\pi^+\pi^-\pi^0$, $\eta\pi^-$ and t-distribution are shown in Fig.1.

The $\eta'\pi^-$ events have been selected in a similar way. The effective mass of the two gammas had to lie within the η-meson mass region ($480 < m_{\gamma\gamma} < 620$ MeV), while the effective mass of $\pi^+\pi^-\eta$ — in the η'-meson mass region ($940 < m_{\pi^+\pi^-\eta} < 976$ MeV); after these cuts ~ 4200 "$\eta'\pi^-$" events and $\sim$1100 "background" events have been selected. The effective mass spectra of $\gamma\gamma$, $\pi^+\pi^-\eta$, $\eta'\pi^-$ and t-distribution are shown in Fig.2.

3. Partial-wave analysis.

The angular distribution of reactions (1), (2) in the Gottfried-Jackson (GJ) frame can be expressed in terms of amplitudes with positive and negative exchange naturality (see [4,7,8]):

$$I(\Omega) = |H_-(\Omega)|^2 + |H_+(\Omega)|^2, \quad (3)$$

where Ω is the set of coordinates in the GJ frame, H_+ and H_- are linear combinations of wave functions $F^J_{M\eta}$ with definite angular momentum J, its projection M and naturality $\eta = +1$ or -1. The coefficients of these linear combinations are the amplitudes, and their absolute values squared are the intensities of corresponding waves.

The maximum likelihood method has been used for fitting (see [9] for details). To subtract a background the events from control region have been included into the functional with opposite sign:

$$L = -\left[\sum_{i=1}^{N_{ev}} \ln I(\Omega_i) - \sum_{i=1}^{N_{bgr}} \ln I(\Omega_i)\right] + \int I(\Omega)\varepsilon(\Omega)d\Omega. \quad (4)$$

Here N_{ev} is the number of "$\eta\pi^-$" ("$\eta'\pi^-$") events, N_{bgr} is the number of "background" events, $\varepsilon(\Omega)$ is the detection efficiency. The set of waves has been restricted to $J \leq 2$ and $M \leq 1$, i.e. only the waves with $J^{PC}M\eta = 0^{++}0-$, $1^{-+}0-$, $1^{-+}1-$, $2^{++}0-$, $2^{++}1-$, $1^{-+}1+$, $2^{++}1+$, further denoted as $S0$, $P0$, $P-$, $D0$, $D-$, $P+$, $D+$, have been used in the fit.

The partial-wave analysis of the $\eta\pi^-$ system has been performed for the events with $0 < -t' < 1$ GeV^2 in the mass interval of 0.8–2.0 GeV, divided into 30 bins, 40 MeV each. The results are shown in Fig.3. The $D+$ wave with $a_2(1320)$-meson is dominant; the $P+$ wave is small but statistically significant and contains a broad bump. The phase difference between $P+$ and $D+$ waves shows a rapid variation in the a_2-meson mass region. There are no statistically significant signals in the waves with negative exchange naturality, except for the small trace of a_2-meson in the $D-$ wave.

The partial-wave analysis of the $\eta'\pi^-$ system has been performed for the events with $0 < -t' < 1$ GeV^2 in the mass interval of 1.12–2.12 GeV, divided

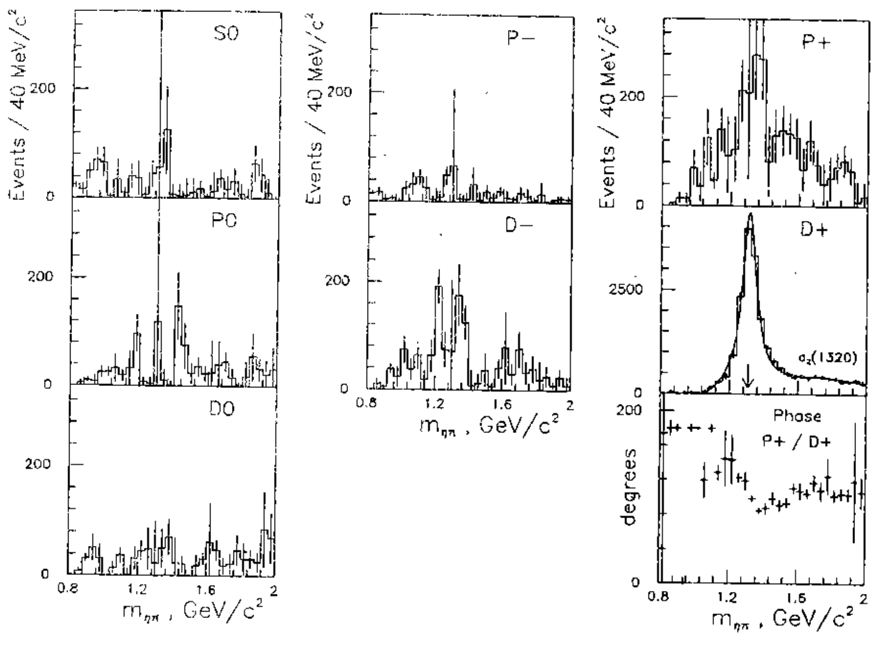

Figure 3. Results of the partial-wave analysis of the $\eta\pi^-$ system.

into 20 bins, 50 MeV each. The results are shown in Fig.4. The $P+$ wave is the largest one in this system. It shows a broad bump peaking at $m_{\eta'\pi^-} \approx 1.6$ GeV. The $D+$ wave is also significant and shows $a_2(1320)$-meson peak with proper phase variation and probably some additional structure(s) at $M_{\eta'\pi^-} > 1.5$ GeV. The waves with negative exchange naturality also do not contain any statistically significant signals.

The discrete ambiguities have been analyzed using the method given in [8]. Eight independent solutions exist for our wave set. For $P+$ and $D+$ waves in both $\eta\pi^-$ and $\eta'\pi^-$ systems all the eight solutions turned out to be equal within the error limits; in case of the waves with negative exchange naturality the difference between solutions in several bins somewhat exceeds the error limits, not changing, however, the conclusion that all these waves are not statistically significant. As an example the intensity variations of the wave $P+$ in the $\eta\pi^-$ and $\eta'\pi^-$ systems are shown in Fig.5; each mass bin is divided here into eight subbins, representing all the eight possible solutions.

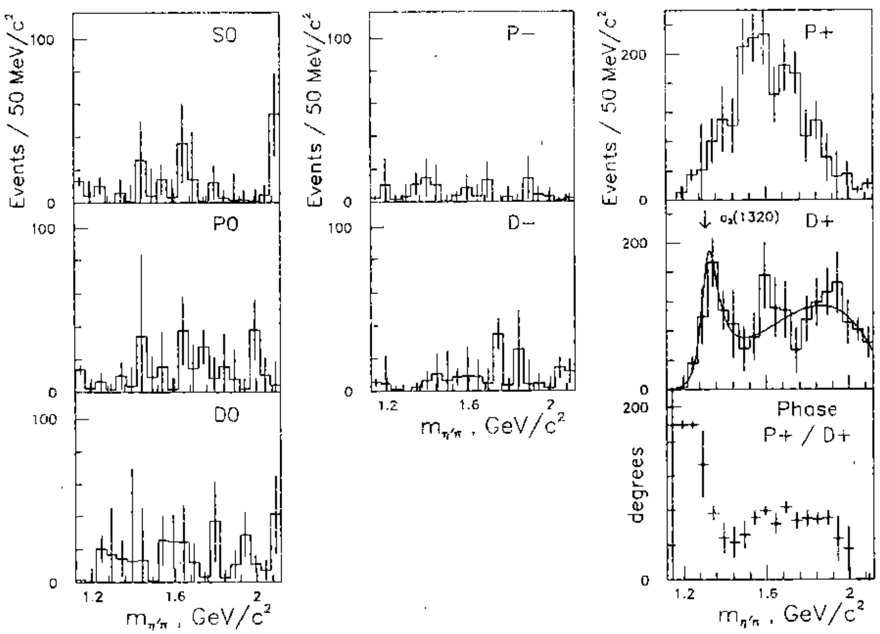

Figure 4. Results of the partial-wave analysis of the $\eta'\pi^-$ system.

4. Discussion.

It is seen in Figs.3 and 4 that there is no statistically significant signals in all the waves with negative exchange naturality in both $\eta\pi^-$ and $\eta'\pi^-$ systems. In particular, the $a_0(1320)$ meson is not seen in the $S0$ wave, the $\hat{\rho}^-(1405)$ meson is not seen in the $P0$ and $P-$ waves; the broad bump without narrow peak of the $\hat{\rho}^-(1405)$ is seen in the $P+$ wave which is statistically significant in both systems.

The peak of $a_2^-(1320)$-meson is dominating in the $D+$ wave spectrum of the $\eta\pi^-$ system. Its Breit-Wigner parameters[1] are: $M = 1317.7 \pm 1.4(stat) \pm 2.0(syst)$ MeV, $\Gamma = 103 \pm 6(stat) \pm 3(syst)$ MeV, in agreement with PDG data [10] for the $\rho\pi$ decay channel. This peak is also seen in the $D+$ wave of the $\eta'\pi^-$ system. Its height is $\sim$3% of that in the $\eta\pi^-$ system.

[1] We used the relativistic Breit-Wigner formula taking into account two main a_2 decay modes $\rho\pi$ and $\eta\pi$.

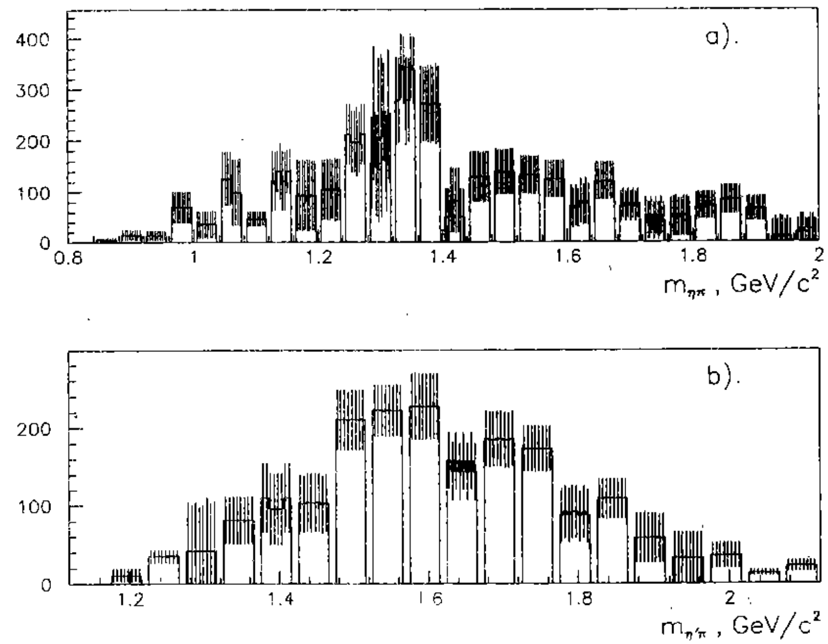

Figure 5. Intensities of the $P+$ wave in the $\eta\pi^-$ (a) and $\eta'\pi^-$ (b) systems for all solutions.

These data allow us to determine the ratio

$$R = \frac{BR(a_2^- \to \pi^-\eta')}{BR(a_2^- \to \pi^-\eta)}, \quad (5)$$

which depends on the pseudoscalar nonet mixing angle [11,12].

However since the $a_2^-(1320)$-meson mass is close to the $\eta'\pi^-$ threshold, the shape of resonance and as a result the obtained value of ratio (5) depend on the expression chosen for the barrier factor, which depends on the c.m.s. decay momentum q. Various expressions for this factor can be found in [11]; we can only mention here that it strongly suppresses the $a_2^- \to \eta'\pi$ decay, because ratio (5) for the standard value of $\eta - \eta'$ mixing angle $\Theta_P = -20^o$ would be of $\sim$0.6 if the barrier factor was omitted. To avoid this problem we use as a value of ratio (5) the ratio of the fitted intensities of the $D+$ wave in $\eta'\pi^-$ and $\eta\pi^-$ systems at the standard a_2-meson mass, because it is almost independent of the expression chosen for the barrier factor. The spectra have been fitted using

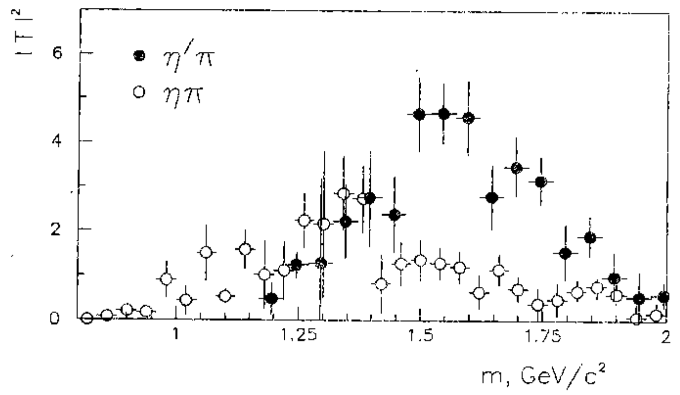

Figure 6. The matrix elements squared of the $P+$ waves in the $\eta'\pi^-$ and $\eta\pi^-$ systems.

the Blatt-Weisskopf formula for spin $J = 2$; ratio (5) has been found to be

$$R = (4.7 \pm 1.0(stat) \pm 0.4(syst)) \cdot 10^{-2}. \quad (6)$$

The value of systematic error is obtained by varying the parametrization of non-a_2 parts of the spectra.

The intensity of the $P+$ wave in the $\eta'\pi^-$ system is remarkably high. In spite of the suppression by the phase space and the barrier factor it is comparable with that in the $\eta\pi^-$ system. To compare the $P+$ wave in the $\eta'\pi^-$ and $\eta\pi^-$ systems it is convenient to use their matrix elements squared, i.e. the intensities divided by the two-body phase space q/m and branching ratios of $\eta(\eta')$ decays [10]. The matrix elements squared of both $P+$ waves are shown in Fig.6. The significant exceeding of the $P+$ wave in the $\eta'\pi^-$ system with respect to the $\eta\pi^-$ system is seen for $M_{\eta'\pi(\eta\pi)} > 1.4$ GeV. The difference between decay constants into $\eta'\pi^-$ and $\eta\pi^-$ is even more significant, because the matrix elements include also the barrier factor, which suppresses the decay into $\eta'\pi^-$ stronger than the decay into $\eta\pi^-$. This relationship between the relative strengths of the decay intensities into the $\eta'\pi$ and $\eta\pi$ modes was predicted in [13] for hybrid systems containing valence gluon ($q\bar{q}g$) with $J^{PC} = 1^{-+}$. This could mean that $q\bar{q}g$ systems are the main component of the $P+$ wave. It is worth mentioning that this property does not depend on whether the hybrid system is resonant or not.

5. Conclusions

The partial-wave analysis of the $\eta\pi^-$ and $\eta'\pi^-$ systems produced in the π^-N interactions at $p_{\pi^-} = 37$ GeV/c is performed. All the waves with natural parity exchange are negligibly small in both of these systems. The dominant wave in the $\eta\pi^-$ system is $D+$ with $a_2^-(1320)$-meson; the $P+$ wave with exotic quantum numbers is small and shows a broad bump without narrow structures. The largest wave in the $\eta'\pi^-$ system is $P+$. The matrix element squared of the $P+$ wave in the $\eta'\pi^-$ system is much larger than that in the $\eta\pi^-$ system. This could mean that systems with valence gluon ($q\bar{q}g$) give the main contribution to the $P+$ wave.

The branching ratio (5) defined as a ratio of fitted intensities of $D+$ waves at the standard a_2 mass is found to be

$$R = \frac{BR(a_2^- \to \pi^-\eta')}{BR(a_2^- \to \pi^-\eta)} = (4.7 \pm 1.0(stat) \pm 0.4(syst)) \cdot 10^{-2}.$$

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