Study of exotic resonances in diffractive reactions

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The results of a partial wave analysis of 3π system produced in the reaction $\pi^- A \rightarrow \pi^+\pi^-\pi^- A$ at the momentum of 36.6 GeV/c on beryllium target are presented. Resonant signals from $a_1'(1750), a_3(1860), a_4(2050)$ are observed in different channels. Small bump at $M \approx 1.6$GeV in the exotic wave $J^{PC}M^\eta = 1^{-+}1^+$ is seen. The combined analysis of VES data on this wave in $\eta'\pi, b_1(1235)\pi$ and $\rho\pi$ channels points to the existence of a hybrid meson with $M \approx 1.6$ GeV.

1. THE PWA OF THE REACTION $\pi^- A \rightarrow \pi^+\pi^-\pi^- A$.

In this report we present the results of a partial wave analysis of $\pi^+\pi^-\pi^-$ system and a combined analysis of the exotic $J^{PC} = 1^{-+}$ wave seen in various final states. The experimental data were obtained at VES facility - a large aperture magnetic spectrometer running with the negatively charged particles beam with the momentum of 36.6 GeV/c. The results on the reaction $\pi^- Be \rightarrow \pi^+\pi^-\pi^- Be$ are based upon the statistics of about $6.0 \cdot 10^6$ events for low t' region ($-t' < 0.03\mathrm{GeV}^2$) and $3.0 \cdot 10^6$ for high t' ($0.03 < -t' < 1.0\mathrm{GeV}^2$). Our previous results were published in [1]. The PWA of the $\pi^+\pi^-\pi^-$ system has been performed in the 0.8–2.6 GeV mass region in 20 MeV bins. The modified version of the Illinois PWA program [2] has been used for the analysis. This version of PWA program uses isobar model and relativistic covariant helicity formalism [3] to construct amplitudes and positively definite density matrix of sufficiently high rank ρ_{ij} to describe the 3π state. The set of partial waves is given below:

FLAT							
$\mathbf{0^-}$	$0^-\mathrm{S}0^+\,\epsilon$	$0^-\mathrm{S}0^+\,f_0$	$0^-\mathrm{P}0^+\,\rho$	$0^-\mathrm{D}0^+\,f_2$			
$\mathbf{1^+}$	$1^+\mathrm{S}0^+\,\rho$	$1^+\mathrm{P}0^+\,\epsilon$	$1^+\mathrm{D}0^+\,\rho$	$1^+\mathrm{P}0^+\,f_2$	$1^+\mathrm{P}0^+\,f_0$		
	$1^+\mathrm{S}1^+\,\rho$	$1^+\mathrm{P}1^+\,\epsilon$	$1^+\mathrm{D}1^+\,\rho$	$1^+\mathrm{P}1^+\,f_2$	$1^+\mathrm{S}1^-\,\rho$		
$\mathbf{1^-}$	$1^-\mathrm{P}1^+\,\rho$	$1^-\mathrm{P}0^-\,\rho$	$1^-\mathrm{P}1^-\,\rho$				
$\mathbf{2^-}$	$2^-\mathrm{S}0^+\,f_2$	$2^-\mathrm{D}0^+\,\epsilon$	$2^-\mathrm{D}0^+\,f_2$	$2^-\mathrm{P}0^+\,\rho$	$2^-\mathrm{F}0^+\,\rho$	$2^-\mathrm{D}0^+\,f_0$	
	$2^-\mathrm{S}1^+\,f_2$	$2^-\mathrm{D}1^+\,\epsilon$	$2^-\mathrm{D}1^+\,f_2$	$2^-\mathrm{P}1^+\,\rho$	$2^-\mathrm{F}1^+\,\rho$	$2^-\mathrm{S}1^-\,f_2$	$2^-\mathrm{P}1^-\,\rho$
$\mathbf{2^+}$	$2^+\mathrm{D}1^+\,\rho$	$2^+\mathrm{D}0^-\,\rho$	$2^+\mathrm{D}1^-\,\rho$	$2^+\mathrm{P}1^+\,f_2$			
$\mathbf{3^+}$	$3^+\mathrm{S}0^+\,\rho_3$	$3^+\mathrm{P}0^+\,f_2$	$3^+\mathrm{D}0^+\,\rho$	$3^+\mathrm{S}1^+\,\rho_3$			
$\mathbf{4^-}$	$4^-\mathrm{P}0^+\,\rho_3$	$4^-\mathrm{D}0^+\,f_2$	$4^-\mathrm{F}0^+\,\rho$				
$\mathbf{4^+}$	$4^+\mathrm{F}1^+\,f_2$	$4^+\mathrm{G}1^+\,\rho$					

The notations of the waves are given here in the form of $\mathrm{J^P LM^\eta}$ isobar [2]. The FLAT wave is constant over all variables and non-interfering with other waves. The isobars

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$\rho(770)$, $f_2(1270)$, $\rho_3(1690)$ have been described by relativistic Breit-Wigner functions with standard parameters. The S-wave in the channel $\pi^+\pi^-$ has been parameterized by two different states, namely a "narrow" resonance with the $f_0(980)$ parameters and ϵ [2], a "broad" wave which is the AMP M-solution [4] with $f_0(980)$ pole removed. The parameterization by two states allows us to describe the experimental behaviour of the S-wave. The PWA with parameterization of $\pi\pi$ S-wave by three or four resonances ($f_0(800), f_0(980), f_0(1300), f_0(1500)$) gives essentially the same results. In addition to the waves listed in the table other waves with higher spin or with negative exchange naturality were included in the PWA and then omitted as not significant.

To make the resonant picture more clear the following method has been used. Hermitian density matrix of an arbitrary rank d can be represented as a sum of terms (products of eigenvectors) corresponding to its eigenvalues:

$$\rho^{ij} = \sum_{k=1}^{d} V_k^i * V_k^{*j} * e_k = \rho_L^{ij} + \rho_S^{ij}, \quad \rho_L^{ij} = V_1^i * V_1^{*j} * e_1, \quad \rho_S^{ij} = \sum_{k=2}^{d} V_k^i * V_k^{*j} * e_k$$

Here we singled out a term corresponding to the largest eigenvalue into ρ_L, and collected all other terms into ρ_S. This decomposition has the following advantages:

- the matrix ρ_L has rank one so arguments of its nondiagonal elements are indeed phase differences for the corresponding pairs of waves;
- in this approach ρ_S doesn't only describe a small noncoherence which is expected in the physical process (e.g. due to the different production mechanisms) but can also work as "garbage collector" which absorbs incoherent parts of the initially almost coherent density matrix, arising because of various imperfections of the PWA model.

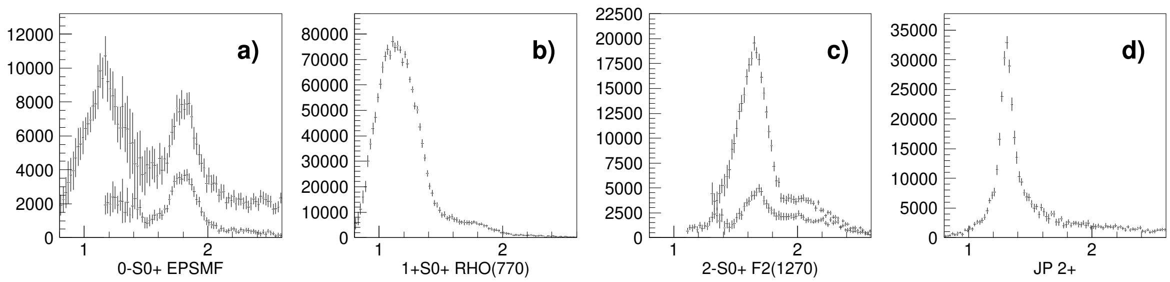

Figure 1. Intensities of dominant waves $J^{PC} = 0^{-+}, 1^{++}, 2^{-+}$ and 2^{++} for $0.03 < -t' < 1.0\, GeV^2$. a) 0^{-+} $-$ $\epsilon\pi$ and $f_0\pi$ waves, b) 1^{++} $-$ $\rho\pi$S-wave, c) 2^{-+} $-$ $f_2\pi$S-wave and $\rho\pi$F-wave, d) 2^{++} $-$ sum of $\rho\pi$ and $f_2\pi$ waves.

2. RESULTS OF PWA.

We present below the main features of the most significant waves at high t'

$\mathbf{J^{PC} = 0^{-+}}$. Two resonances are clearly seen (Fig. 1 a)):

[2]We have named it ϵ instead of f_0 because it includes broad part of $\pi\pi$ amplitude and does not coincide with any specific f_0 resonance.

- $\pi(1300)$ in the channels $\rho\pi$ and $\epsilon\pi$; - $\pi(1800)$ in the channels $\epsilon\pi$ and $f_0\pi$.

$\mathbf{J^{PC} = 1^{++}}$. The intensity of the largest wave $1^+\mathtt{S}0^+\rho$ is presented in Fig.1 b). In this wave the a_1 signal is seen at $M \approx 1.2$ GeV together with some shoulder at $M \approx 1.7$ GeV. This shoulder looks like a clear resonant peak in the coherent ρ_L part of the ρ-matrix. Fitted parameters of this $a_1'(1700)$ object are: $M = 1.75 \pm 0.02$ GeV, $\Gamma = 0.30 \pm 0.07$ GeV.

$\mathbf{J^{PC} = 2^{-+}}$. A large set of waves with these quantum numbers forms rather complicated structure. A clear signal from the $\pi_2(1670)$ resonance is seen in the dominant $2^-\mathtt{S}0^+f_2$ wave , $2^-\mathtt{D}0^+\epsilon$, $2^-\mathtt{P}0^+\rho$ and included for the first time $2^-\mathtt{F}0^+\rho$ wave (Fig. 1 c)). Apart of it a bump at $M \approx 2.1$ GeV is seen in $2^-\mathtt{S}0^+f_2$ wave, which was preferably identified as $\pi_2'(2100)$ resonance in [5,1]. In the $2^-\mathtt{D}0^+\epsilon$, $2^-\mathtt{D}0^+f_0(980)$ waves there are two maxima at $M \approx 1.7$ GeV and $M \approx 2.1$ GeV, which were identified as the $\pi_2(1670)$ and $\pi_2'(2100)$ resonances.

$\mathbf{J^{PC} = 2^{++}}$. The wave $2^+D1^+\rho$ is the largest one with nonzero total spin projection $M = 1$. This wave is dominated by the $a_2(1320)$ meson. No trace of a second 2^{++} resonance is seen in the sum of the $2^+D1^+\rho$ and $2^+P1^+f_2$ waves (Fig. 1 d)).

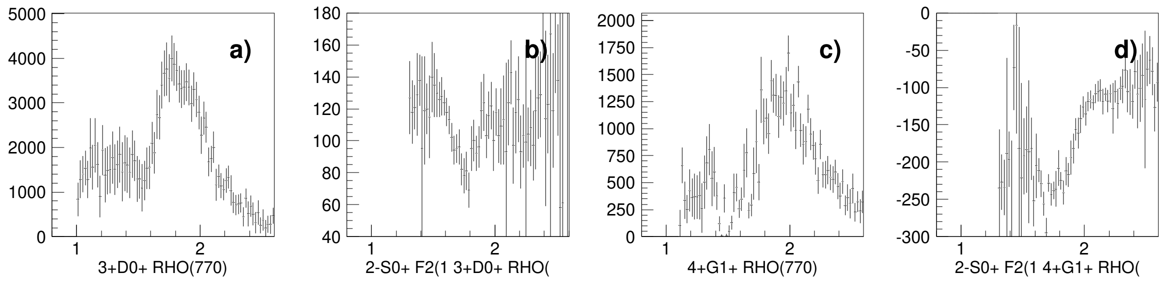

Figure 2. The $3^+0^+D\rho$ (a) wave intensity, the phase difference $\phi(3^+\mathtt{D}\rho) - \phi(2^-\mathtt{S}f_2)$ (b). The $4^+1^+\mathtt{G}\rho$ wave intensity (c), the phase difference $\phi(4^+\mathtt{G}\rho) - \phi(2^-\mathtt{S}f_2)$ (d).

$\mathbf{J^{PC} = 3^{++}}$. A resonance-like signal is seen in $3^+\mathtt{D}0^+\rho$ wave at $M \approx 1.8$ GeV. A phase of the $3^+\mathtt{D}0^+\rho$ wave with respect to $\pi_2(1670)$ is shown on Fig.2 b) and is in accordance with expectations for BW resonance. We interpret this object as the a_3-resonance with the following parameters: $M = 1.86 \pm 0.02$ GeV $\quad \Gamma = 0.48 \pm 0.06$ GeV. This resonance is also seen in the $f_2\pi$ channel. In the $\rho_3\pi$ channel it is distorted by the kinematical threshold and in addition the phase variation is rather small. The branching ratios are: $\frac{\Gamma(a_3(1860)\to f_2(\pi^+\pi^-)\pi^-)}{\Gamma(a_3(1860)\to \rho^0(\pi^+\pi^-)\pi^-)} = 0.5 \pm 0.2$, $\frac{\Gamma(a_3(1860)\to \rho_3(\pi^+\pi^-)\pi^-)}{\Gamma(a_3(1860)\to \rho^0(\pi^+\pi^-)\pi^-)} < 0.5$.

$\mathbf{J^{PC} = 4^{++}}$. For this J^{PC} two waves $4^+\mathtt{G}1^+\rho$ and $4^+\mathtt{F}1^+f_2$ are the most significant and were included in the final analysis. Clear resonance-like signal is seen at $M \approx 2$ GeV. The phase of the $4^+\mathtt{G}1^+\rho$ wave with respect to the $2^-\mathtt{S}0^+f_2$ wave is in accordance with that expected for BW resonance (Fig.2 c, d). We interpret this object as $a_4(2050)$ with the following parameters: $M = 1.99 \pm 0.02$ GeV, $\quad \Gamma = 0.33 \pm 0.08$ GeV.

$\mathbf{J^{PC} = 1^{-+}}$. The most intensive 1^{-+} wave has a nonzero angular momentum projection on Gottfrid-Jakson z-axis and therefore is better seen at high t' (Fig. 3 c). The intesity of this wave is very small and does not exceed 2% of total intensity at any $M_{3\pi}$. At $M \approx 1.2$ GeV the bump is seen in all three waves $1^{-+}1^{+}, 1^{-+}1^{-}$ and $1^{-+}0^{-}$. These structures are produced mainly by the leak from the very intensive 1^{++} channel due to imperfections of PWA model. Three facts point to this interpretation - strong dependence of these signals on the parameters of PWA model, incoherence of the $1^{-+}1^{+}$ signal with others, anomalously narrow t'-dependence.

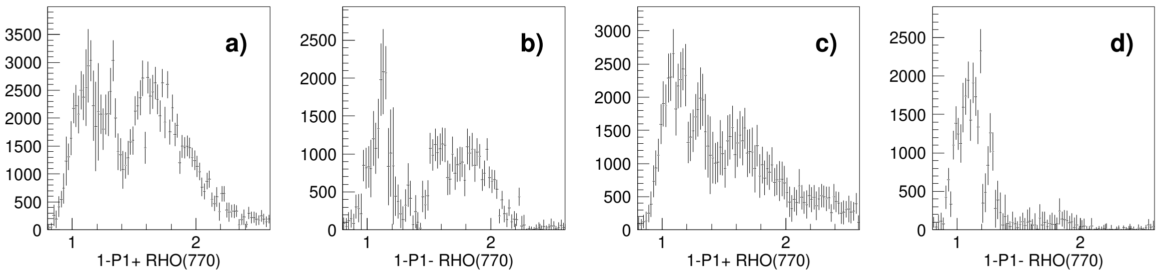

Figure 3. The intensities of the $J^P M^\eta = 1^{-}1^{+}$ (a) and the $1^{-}1^{-}$ (b) waves in the $\rho\pi$ system at high t' for the "tight" density matrix parameterization (see text). Two intensities for the "loose" parameterization are shown respectively on (c) and (d).

At $M \approx 1.6$ GeV a broad shoulder is seen. Its intensity at $M \approx 1.6$ GeV is only 3% of the intensity of the $a_2(1320)$ signal at its maximum. The observation of a signal in the $1^{-}1^{+}P(\rho)$ wave with $M = 1.62 \pm 0.02$ GeV, $\Gamma = 0.24 \pm 0.05$ GeV was previously reported as preliminary by the VES [6]. Later, the observation of the relatively narrow resonance at $M \approx 1.6$ GeV was reported by the E852 [7]. It was shown in [8] that the intensity and the shape of this wave are very dependent on the details of the PWA model. With our PWA model we do not see the narrow signal at $M \approx 1.6$ GeV in the wave $1^{-+}1^{+}$. Moreover the intensity of the signal at $M \approx 1.6$ GeV in the unnatural parity exchange sector is compatible with zero (Fig.3 d)) as one could expect, contrary to the results reported in [7]. The result of [7] can be reproduced partially by the use of oversimplified PWA model with fully coherent waves in $2^{-+}, 1^{++}$ and 0^{-+} sectors (Fig.3 a,b). It indicates that the appearance of a relatively strong signal with comparable intensity in both positive and negative naturalities [7] is an artifact of too tight PWA model. Instead the signal in the wave $1^{-+}1^{+}$ is very broad and less intensive than the signal reported in [7].

It can be seen on the Fig. 4 where the fraction of $1^{-+}1^{+}$ wave corresponding to the highest eigenvalue of density matrix is shown. On Fig. 4 b) the absolute phase of this wave is plotted as well. To get the reference phase we used the results of mass-dependent fit of the most intensive $0^{-+}, 2^{++}, 2^{-+}$ and 4^{++} waves by known BW resonances and phase space-like backgrounds. The shape of the 1^{-+} signal and its phase rising at $M \approx 1.6$ GeV do not exclude the presence of the resonance in this region. Due to its smallness and broadness this signal taken alone can not be interpreted without ambiguity. At the same time clear bumps are seen at $M \approx 1.6$ GeV in two other channels $\eta'\pi$ [9] and $b_1(1235)\pi$ [10] (Fig. 6). These observations taken altogether point to the possible existence of exotic resonance at $M \approx 1.6$ GeV.

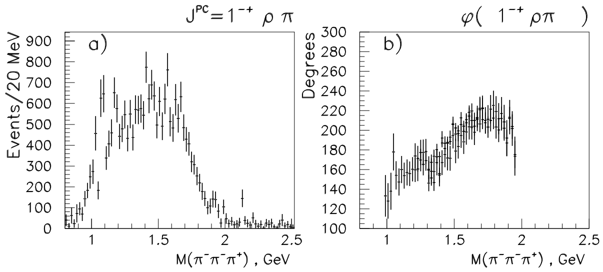

Figure 4. The $J^PM^\eta = 1^-1^+\mathtt{S}\rho$ wave intensity (a) and its absolute phase estimation (b).

3. THE COMBINED ANALYSIS OF $J^{PC} = 1^{-+}$ WAVES

To estimate the parameters of this resonance the analysis of the wave $J^{PC} = 1^{-+}$ in the channels $\eta'\pi, b_1\pi$ and $\rho\pi$ was performed.

The wave $J^{PC} = 1^{-+}$ in the $\eta'\pi$ channel
The wave $1^{-+}1^+$ is the dominant one [9] in diffractive production of $\eta'\pi-$ system at $P_\pi = 36.6$ GeV/c. It has the maximum at $M \approx 1.6$ GeV (Fig. 6 b)). Due to the smallness of other waves and poor knowledge of their parameters the phase motion of $1^{-+}1^+$ wave is not known and the resonance nature of the signal could not be established from the data on this channel. Assuming that this signal is Breit-Wigner resonance the parameters were found [8]: $M = 1.57 \pm 0.02 \pm 0.02$ GeV, $\Gamma = 0.55 \pm 0.06 \pm 0.04$ GeV. The most striking feature of this wave is that its intensity in $\eta'\pi$ channel is higher than that in $\eta\pi$ channel.

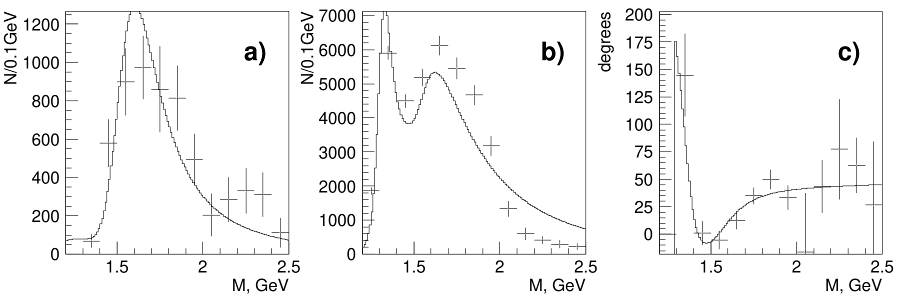

Figure 5. The system $\omega\pi^-\pi^0$: a) the $J^PM^\eta = 1^-1^+\mathtt{S}b_1\pi$ wave intensity, b) the $J^PM^\eta = 2^+1^+\mathtt{S}\omega\rho$ wave intensity, c) $\phi(1^-1^+\mathtt{S}b_1\pi) - \phi(2^+1^+\mathtt{S}\omega\rho)$.

The wave $J^{PC} = 1^{-+}$ in the $b_1\pi$ channel of $\omega\pi^-\pi^0$ system
The mass-dependent fit of the ρ-matrix elements corresponding to the waves $J^{PC}M^\eta = 1^-1^+$ $b_1\pi$ and $J^{PC}M^\eta = 2^+1^+$ $\omega\rho$ was carried out. The outcome of the $\omega\pi^-\pi^0$ system mass-independent PWA at high t' region was used for it [10]. The $b_1\pi$ amplitude was saturated by a Breit-Wigner resonance and a coherent background. The $\omega\rho^-$ amplitude was described by the $a_2(1320)$-meson. In this model broad signal in this wave at higher masses is nothing else but a tail of the a_2 meson due to the opening of $\omega\rho$ channel. The

results of the fit point out to the resonance nature of the $b_1\pi$ signal (Fig. 5). The range of the parameters variation is large due to the freedom in the 2^+1^+ wave model.

Parameters of the exotic resonance

The fit to the $\eta'\pi$, $b_1\pi$ and $\rho\pi$ intensities with incoherent sum of a single Breit-Wigner resonance and backgrounds in each channel was performed (Fig. 6). The fit results in the following parameters: $M = 1.56 \pm 0.06$ GeV, $\Gamma = 0.34 \pm 0.05$ GeV
and the branching ratio: $Br(b_1\pi) : Br(\eta'\pi) : Br(\rho\pi) = 1 : 1.0 \pm 0.3 : 1.5 \pm 0.5$.

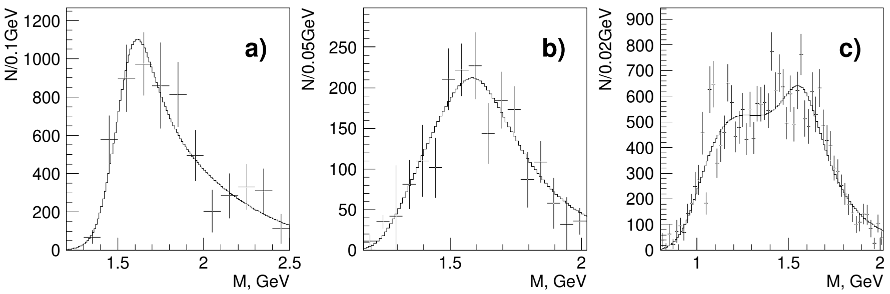

Figure 6. Intensities of the $J^P M^\eta = 1^-1^+$ waves in the channels: $b_1(1235)\pi$, $\eta'\pi$ and $\rho\pi$.

A resonance with these quantum numbers can not be constructed from $q\bar{q}$ pair and could be either some kind of a multiquark state or a hybrid meson. Despite large uncertainty in the estimations of branching fractions for 1^{-+} state the enhanced decay to $\eta'\pi$ looks as very peculiar for hybrid mesons [11]. On the basis of this feature we consider the hybrid interpretation of the observed state as preferable.

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