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NEW RESULTS FROM VES.

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ABSTRACT

The results of the partial wave analysis(PWA) of the $\pi^+\pi^-\pi^-$ and $\omega\pi^-\pi^0$ systems are presented. The a_3 and $a_4(2040)$ signals are observed in the $\rho(770)\pi$ and $f_2(1270)\pi$ channels. Indications of the a_1' meson existence was found in the 1^+0^+ $\rho\pi$ S-wave. The decay branching ratio of the $a_2(1320)^-$ to $\omega\pi^-\pi^0$ was measured. The 2^+1^+ wave shows a broad bump at $M \approx 1.7\,GeV$. The decays of the $\pi_2(1670)$, $a_4(2040)$ and $\pi(1740)$ into $\omega\rho^-$ were found. The resonance in the $b_1(1235)\pi$ wave with exotic quantum numbers $J^{PC} = 1^{-+}$ at $M \approx 1.6\,GeV$ is observed and the simultaneous analysis of the 1^{-+} wave in the $b_1(1235)\pi$, $\eta'\pi$ and $\rho\pi$ final states is presented.

1 Introduction

We present the results of the PWA of $\pi^+\pi^-\pi^-$, produced in reaction:

$$\pi^- Be \;\rightarrow\; \pi^+\pi^-\pi^- Be \tag{1}$$

and $\omega\pi^-\pi^0$ system, produced in:

$$\pi^- Be \rightarrow \omega\pi^-\pi^0 Be, \quad \omega \rightarrow \pi^+\pi^-\pi^0 \tag{2}$$

Our previous results of the analysis of reaction (1) were published in [1, 2, 3], and of reaction (2) were partially reported at the conferences [4], [5]. The measurements

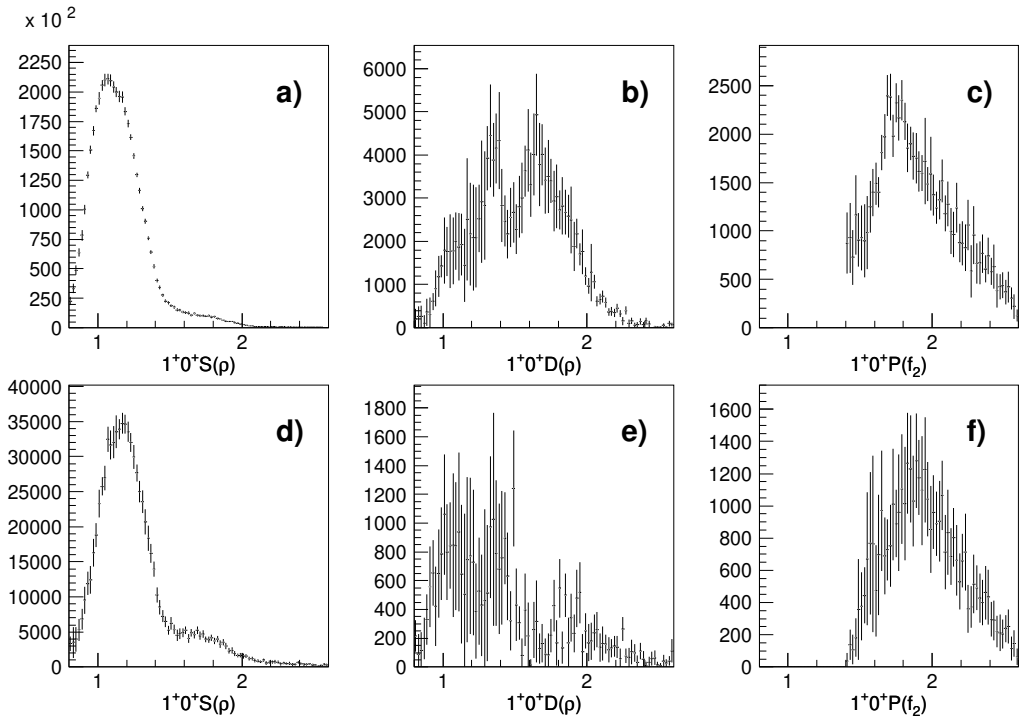

Figure 1: Main $J^{PC} = 1^{++}$ waves for $t' < 0.06\,GeV^2$ (a-c) and $0.06 < t' < 0.7\,GeV^2$ (d-f)

were carried out using VES spectrometer exposed by the $37\,GeV$ momentum π^- beam. The description of the setup can be found in [6].

2 Results of the $\pi^+\pi^-\pi^-$-system PWA.

The selection criteria for reaction (1) and the description of the PWA procedure can be found in [3]. The relativistic covariant helicity formalism [7] is used to construct the amplitudes and the positively definite density matrix of the full rank. The largest waves of the $J^P = 0^-$, 1^+, 2^- channels are decoupled from the other waves with the same $J^P M^\eta$ and are free to interfere with each other. The $6 \cdot 10^6$ events with $|t'| < 0.06\,GeV^2$ [1] and $2 \cdot 10^6$ with $0.06 < |t'| < 0.7\,GeV^2$ are analyzed separately.

We present the main features of the most significant waves in the high 3π mass region.

$J^P M^\eta = 1^+0^+$. A peak in the $1^+0^+ D\rho$ wave (Fig.1(b)) and the shoulder

[1] $t' = t - t_{min}$, where t- momentum transfer from the beam to the final state squared, t_{min}-its minimum value.

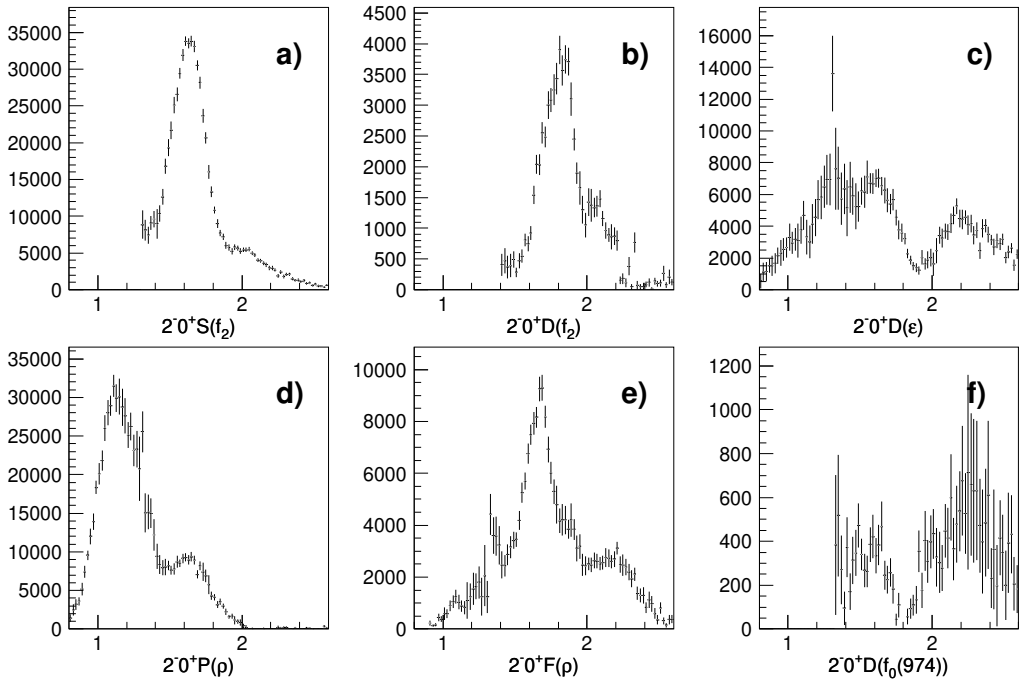

Figure 2: Main $J^{PC} = 2^{-+}$ waves for $t' < 0.06\,GeV^2$

in the $1^+0^+ S\rho$ wave (Fig.1(a), (d)) are observed at $M \approx 1.7\,GeV$ and are considered to be the $a_1'(1700)$ decay into the $\rho\pi$. The peak was fitted with the coherent sum of the Breit-Wigner resonance and the exponential background. The fit results in the following $a_1'(1700)$ parameters:

$$M = 1.80 \pm 0.05\,GeV \quad \Gamma = 0.23^{+0.10}_{-0.03}\,GeV;$$

where the errors are dominated by systematics. The $a_1'(1700)$ branching ratios into the D-wave $\rho\pi$ and P-wave $f_2(1270)\pi$ are found to be:

$$\frac{Br(a_1'(1700) \to (\rho\pi)_D)}{Br(a_1'(1700) \to (\rho\pi)_S)} < 0.35 \quad \frac{Br(a_1'(1700) \to f_2\pi)}{Br(a_1'(1700) \to (\rho\pi)_S)} < 0.23 \text{ at } 95\% \text{ CL}$$

$J^P M^\eta = 2^-0^+$. A complicated wave behaviour for low t' shown in Fig.2 is described by the interplay of the $\pi_2(1670)$ and $\pi_2'(2100)$ states [3, 8]. A peak at $M \approx 1.7\,GeV$ in the F-wave $\rho\pi$ wave intensity is observed.

$J^P M^\eta = 3^+0^+$. A resonance-like signal is observed near $M \approx 1.8\,GeV$ in the $\rho\pi$ and $f_2\pi$ waves, see Fig.3. The phase of the $3^+0^+ D\rho$ as related to the $2^-0^+ S f_2$ is shown in Fig.3(c) and is in accordance with the expectations for a resonance. The

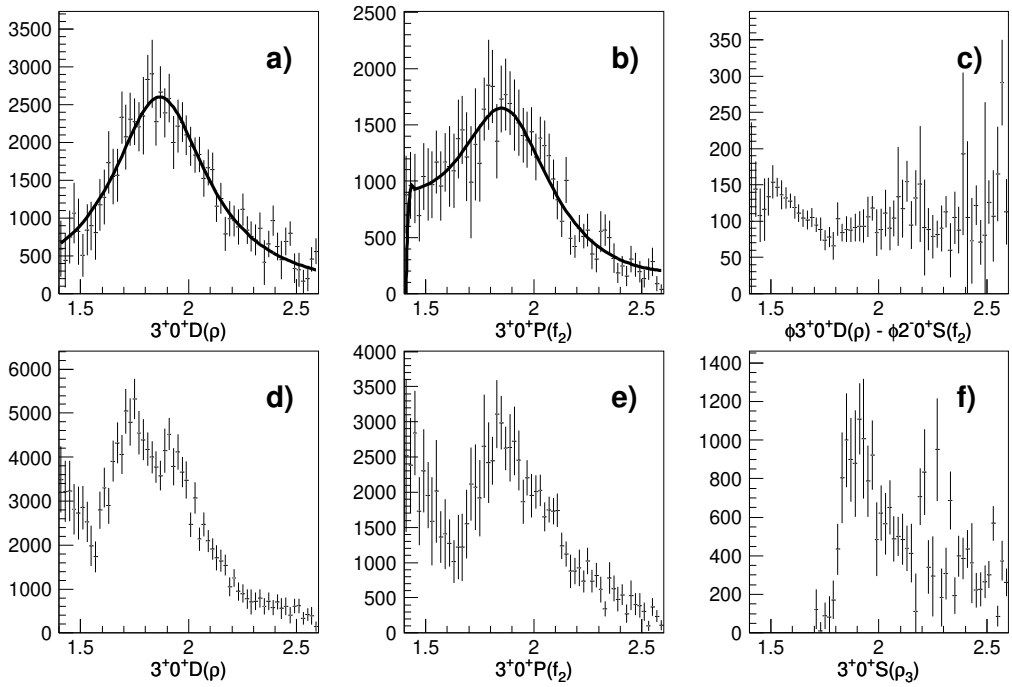

Figure 3: The $3^+0^+D\rho$ (a), $3^+0^+Pf_2$ (b) wave intensities, the phase difference $\phi(3^+D\rho) - \phi(2^-Sf_2)$ (c) for $0.06 < t' < 0.7\,GeV^2$; the $3^+0^+D\rho$ (d), $3^+0^+Pf_2$(e) and $3^+0^+S\rho_3$(f) wave intensities for $t' < 0.06\,GeV^2$

simultaneous fit of the $f_2\pi$ intensity with the relativistic Breit-Wigner function and the $\rho\pi$ intensity with the incoherent sum of the Breit-Wigner and the Chebyshev polynomial background results in the following parameters of the resonance:

$$M = 1.86 \pm 0.02\,GeV, \quad \Gamma = 0.54 \pm 0.03\,GeV.$$

The relative probability of decay into the $f_2(1270)\pi$ and $\rho(770)\pi$ is as follows:

$$\frac{Br(a_3 \to f_2(1270)\pi)}{Br(a_3 \to \rho\pi)} = 0.5 \pm 0.1.$$

$J^PM^\eta = 4^+1^+$. A bump near $M \approx 2\,GeV$ is found in the $4^+1^+G\rho$ and $4^+1^+Ff_2$ waves produced at high t' (Fig.3). The phase of the $4^+1^+G\rho$ relative to the $\pi_2(1670)$ is in accordance with the expectation for the resonance. The simultaneous fit of the $f_2\pi$ intensity with the relativistic Breit-Wigner function and the $\rho\pi$ intensity with the incoherent sum of the Breit-Wigner and the Chebyshev polynomial background results in the following parameters of the resonance:

$$M = 1.95 \pm 0.02\,GeV, \quad \Gamma = 0.34 \pm 0.10\,GeV.$$

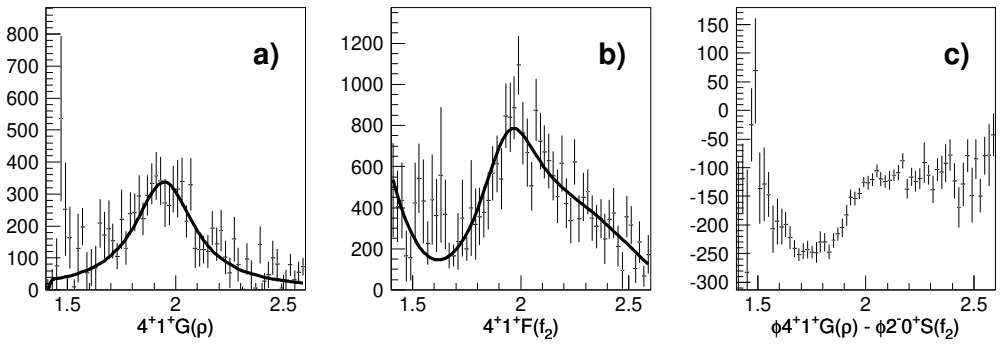

Figure 4: The $4^+1^+D\rho$ (a) and $4^+1^+Ff_2$ (b) wave intensities and the phase difference $\phi(4^+G\rho) - \phi(2^-Sf_2)$ for $0.06 < t' < 0.7\,GeV^2$.

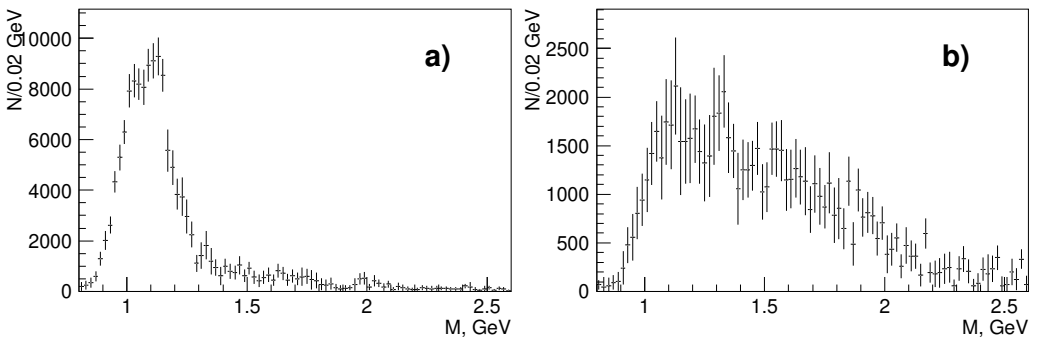

Figure 5: The $J^PM^\eta = 1^-1^+S\rho$ wave intensity for $t' < 0.06\,GeV^2$ (a) and for $0.06 < t' < 0.7\,GeV^2$ (b).

We identify this object with the $a_4(2040)$, having the following branching ratio:

$$\frac{Br(a_4(2040) \to f_2(1270)\pi)}{Br(a_4(2040) \to \rho\pi)} = 0.5 \pm 0.2.$$

$J^PM^\eta = 1^-1^+$. 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 [9]. Later, the observation of the state with $M = 1593 \pm 8^{+20}_{-47}\,MeV$, $\Gamma = 168 \pm 20^{+150}_{-12}\,MeV$ was declared by the E852 [10]. It was shown in [11] the model dependence of the signal behaviour. We do not observe such a narrow signal (Fig. 5) in the fit results with the applied PWA model. However there appears a peak at $M \approx 1.6\,GeV$ with $\Gamma \approx 0.3\,GeV$ in the 1^-1^+ wave intensity, described by the leading term in the expansion of the density matrix in terms of the eigenvalues

(shown in Fig.7).

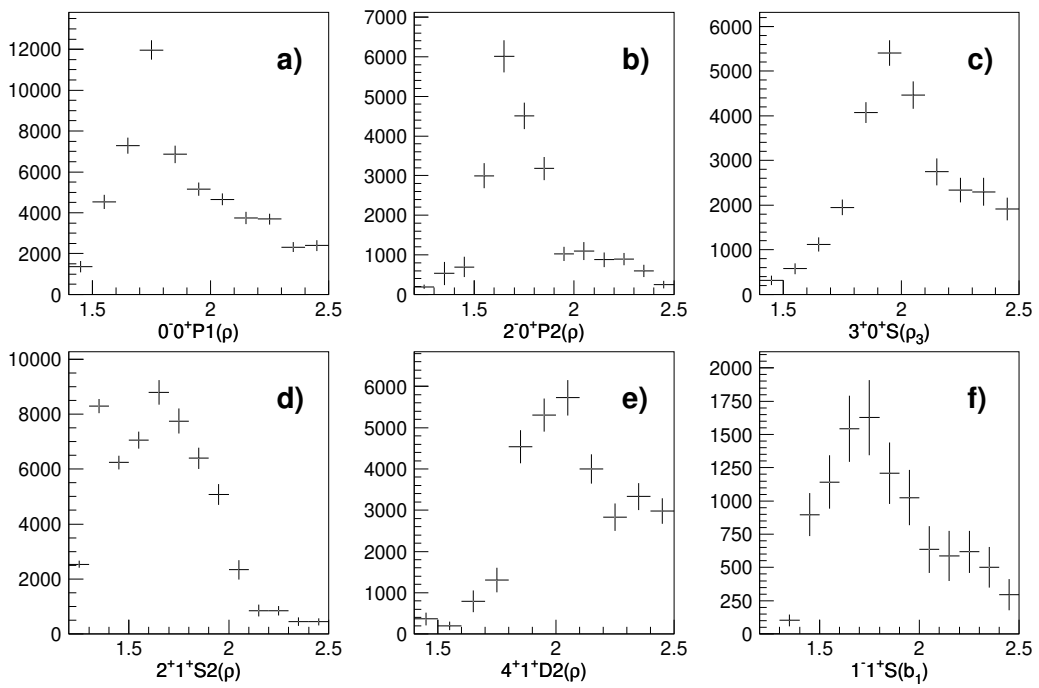

Figure 6: Wave intensities of: a) $0^-0^+P1(\rho)$, b) $2^-0^+P2(\rho)$ with $-t' < 0.08\,GeV^2$., Wave intensities of: c) $3^+0^+S(\rho_3)$, d) $2^+1^+S2(\rho)$, e) $4^+1^+D2(\rho)$, f) $1^-1^+S(b_1)$.

3 The results of the $\omega\pi^-\pi^0$-system PWA

The selection criteria for reaction (2) and the description of the PWA procedure can be found in [12]. The results of the PWA are presented in Fig. 6.

$J^PM^\eta = 0^-0^+$. A peak in the region of $1.74\,GeV$ with the flat background dominates in the wave $0^-0^+P(\rho)$ at low t' (Fig. 6(a)). The phase of this wave relative to the smooth $1^+0^+P(b_1)$ wave has the resonant behaviour. The resonance parameters were determined by the fit of the wave intensity with the incoherent sum of a relativistic Breit-Wigner function and a cubic polynomial and are as follows: the mass $M = 1.737 \pm 0.005 \pm 0.015\,GeV$ and the width $\Gamma = 0.259 \pm 0.019 \pm 0.06\,GeV$.

$J^PM^\eta = 2^-0^+$. A clear peak is observed at $M \sim 1.67\,GeV$ with $\Gamma \sim 0.2\,GeV$ (Fig. 6(b)). The resonant phase behaviour of the $2^-0^+P1(\rho)$ and $2^-0^+P2(\rho)$ waves relative to the $1^+0^+P(b_1)$ wave is observed. The resonance parameters of the $2^-0^+P2(\rho)$ peak were estimated in the same way as for $\pi(1740)$: $M = 1.687 \pm$

$0.009 \pm 0.015\,GeV$ and $\Gamma = 0.168 \pm 0.043 \pm 0.053\,GeV$. We identify this phenomenon with the decay of the $\pi_2(1670)$ into $\omega\rho$. The partial branching ratio was found by normalization to the decay $\pi_2(1670) \to f_2(1270)\pi$ [3], observed in the current experiment decay:

$$Br(\pi_2(1670)^- \to \omega\rho^-) = 0.027 \pm 0.004 \pm 0.01$$

The limits of the $\pi_2(1670)$ decay branching ratios are set at the 2σ confidence level:

$$Br(\pi_2(1670) \to \rho_1(1450)\pi) < 0.0036, \quad Br(\pi_2(1670) \to b_1\pi) < 0.0019.$$

$J^P M^\eta = 3^+0^+$. A peak at $M_{5\pi} \sim 2\,GeV$ and $\Gamma \sim 0.35\,GeV$ is clearly seen in the $3^+0^+S(\rho_3(1690))$ wave for events with low t' (Fig. 6(c)). However the resonant phase motion was not found. Such wave behaviour can be attributed to the Deck effect process [13].

$J^P M^\eta = 2^+1^+$. The intensive production and decay of the $a_2(1320)$ is the main process at low masses (Fig. 6(d)). The decay probability was found to be $Br(a_2(1320) \to \omega\pi^-\pi^0) = (5 \pm 1)\%$. We define the $a_2(1320)$ partial width as that of a Breit-Wigner function with the S-wave $\omega\pi^-\pi^0$ background. The nature of the $1.7\,GeV$ mass structure is unknown. There may be another resonance or the opening of the $\omega\rho$ channel [14]. We can not make preference to a particular hypothesis.

$J^P M^\eta = 4^+1^+$. The signal at $M \approx 2\,GeV$ (Fig. 6(e)) with the resonant phase behaviour can be identified as the $a_4(2040)$. The $a_4(2040)$ parameters are estimated by the fit with the incoherent sum of a D-wave relativistic Breit-Wigner function and a polynomial background to be: $M = 1.944 \pm 0.008 \pm 0.050\,GeV$ and $\Gamma = 0.324 \pm 0.026 \pm 0.075\,GeV$. The t'-dependence of the $a_4(2040)$ is identical to that of the $a_2(1320)$.

$J^P M^\eta = 1^-1^+$. The intensity of the $1^-1^+S(b_1)$ wave for events with high t' shows a wide bump with maximum at $M \sim 1.6 \div 1.7\,GeV$. The highest intensity of this wave does not exceed 15% of the $2^+1^+S2(\rho)$ wave intensity (Fig. 6(f)). The $\omega\rho$ P-waves are included in turn along with the $b_1\pi$ wave. Their intensity distribution differs in form from that of the $b_1\pi$ wave and their inclusion in the fit do not influence on the $b_1\pi$ wave intensity behaviour.

4 The $J^P M^\eta = 1^-1^+$ wave analysis

The combined analysis of the $J^P M^\eta = 1^-1^+$ $b_1\pi$ and the $J^P M^\eta = 2^+1^+$ $\omega\rho$ was carried out in order to understand the nature of the $b_1\pi$ wave. The results of the $\omega\pi^-\pi^0$ system PWA were used for this analysis. The diagonal elements and the real

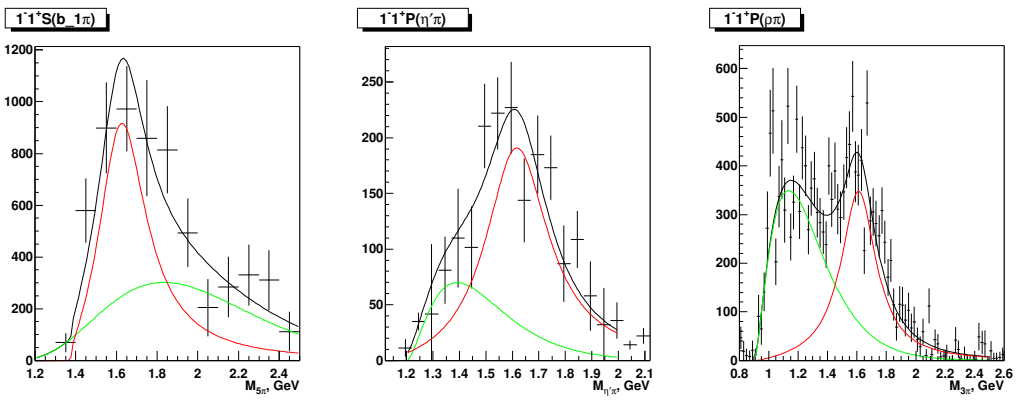

Figure 7: Intensities of the $J^P M^\eta = 1^-1^+$ waves in the channels: $b_1(1235)\pi$, $\eta'\pi$ and $\rho\pi$.

and imaginary parts of the non-diagonal element of the ρ-matrix corresponding to the 1^-1^+ $b_1\pi$ and 2^+1^+ $\omega\rho$ waves with high t' were simultaneously fitted. Fit results were used to predict the coherence parameter for cross checking. The $b_1\pi$ amplitude was saturated by the Breit-Wigner resonance and the coherent background. The $\omega\rho^-$ amplitude was saturated by the $a_2(1320)$-meson, a background and an a_2' state has been also tried. The results of the fits with various ways of the $\omega\rho^-$ wave construction point out to the resonance nature of the $b_1\pi$ signal. The range of the parameters variation is large due to the freedom in the 2^+1^+ state model.

The signal in the $J^P M^\eta = 1^-1^+$ wave of the $\eta'\pi^-$-system with close parameters was observed earlier [15]. The simultaneous fit of the $b_1\pi$ and $\eta'\pi$ intensities with incoherent sum of a Breit-Wigner resonance and a background in each channel was carried out (Fig. 7). The fit results in the following parameters:

$$M = 1.58 \pm 0.03\, GeV, \quad \Gamma = 0.30 \pm 0.03\, GeV.$$

The form of the signal in the 1^-1^+ $\rho\pi$ wave is close to the Breit-Wigner function with these parameters. A fit of all three channels results in the resonance parameters changed within errors. All these facts indicate to the existence of a wide resonance $\Gamma = 0.29 \pm 0.03\, GeV$ with the mass $M = 1.61 \pm 0.02\, GeV$ and the relative branching ratio: $Br(b_1\pi) : Br(\eta'\pi) : Br(\rho\pi) = 1 : 1.0 \pm 0.3 : 1.6 \pm 0.4$.

5 Conclusions

The PWA of the reaction $\pi^- Be \to \pi^+\pi^-\pi^- Be$ and $\pi^- Be \to \pi^+ 2\pi^- 2\pi^0 Be$ was performed.

The mass and the width of the resonance structure in the $J^P M^\eta = 0^- 0^+$ $\omega\rho^-$ wave differs from that for $\pi(1800)$. There may exist two objects of the different nature: a hybrid $\pi(1800)$ and a 3^1S_0 $q\bar{q}$ state decaying into $\omega\rho$.

The indication of the existence of the resonance a_1' mostly decaying to the $\rho\pi$ in the S-wave is found.

The $\pi_2(1670)$ decays into the $\omega\rho$ and $\rho\pi$ in the F-wave are found.

The $a_2(1320)^- \to \omega\pi^-\pi^0$ decay and a wide bump of unknown nature at $M \approx 1.7\,GeV$ are observed in the $J^P M^\eta = 2^+ 1^+$ wave. The a_3 and $a_4(2040)$ decays to the $\rho\pi$ and $f_2\pi$ are observed with the following relative branching ratio of the $a_4(2040)$ decays: $Br(f_2(1270)\pi) : Br(\rho\pi) : Br(\omega\rho) = 0.5 \pm 0.2 : 1 : 1.5 \pm 0.4$

The preliminary results of the 1^{-+} wave analysis point out to the existence of the resonance with exotic quantum numbers, which are forbidden for $q\bar{q}$ states, the mass $M = 1.61 \pm 0.02\,GeV$, the width $\Gamma = 0.29 \pm 0.02\,GeV$ and the following relative branching ratio: $Br(b_1\pi) : Br(\eta'\pi) : Br(\rho\pi) = 1 : 1.0 \pm 0.3 : 1.6 \pm 0.4$.

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