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:

$$\pi^-Be \rightarrow \pi^+\pi^-\pi^-Be$$

(1)

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

$$\pi^-Be \rightarrow \omega\pi^-\pi^0Be, \quad \omega \rightarrow \pi^+\pi^-\pi^0$$

(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 \( t' < 0.06 \text{GeV}^2 \) (a-c) and \( 0.06 < t' < 0.7 \text{GeV}^2 \) (d-f) were carried out using VES spectrometer exposed by the \( 37 \text{GeV} \) momentum \( \pi^- \) beam. The description of the setup can be found in [5].

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 \( J^PM^\eta \) and are free to interfere with each other. The \( 6 \cdot 10^6 \) events with \( |t'| < 0.06 \text{GeV}^2 \) [4] and \( 2 \cdot 10^6 \) with \( 0.06 < |t'| < 0.7 \text{GeV}^2 \) are analyzed separately.

We present the main features of the most significant waves in the high \( 3\pi \) mass region.

\( J^PM^\eta = 1^{+0^+} \). A peak in the \( 1^{+0^+}D\rho \) wave (Fig.1(b)) and the shoulder

\[^1 t' = t - t_{\min}, \text{ where } t- \text{ momentum transfer from the beam to the final state squared, } t_{\min}-\text{its minimum value.} \]
in the $1^+0^+ S \rho$ wave (Fig.2(a), (d)) are observed at $M \approx 1.7 \text{ GeV}$ 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:

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

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:

$$\frac{Br(a'_1(1700) \rightarrow (\rho\pi)_D)}{Br(a'_1(1700) \rightarrow (\rho\pi)_S)} < 0.35 \quad \frac{Br(a'_1(1700) \rightarrow f_2\pi)}{Br(a'_1(1700) \rightarrow (\rho\pi)_S)} < 0.23 \text{ at 95\% CL}$$

$J^P M^n = 2^{-0}$. 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 $M \approx 1.7 \text{ GeV}$ in the F-wave $\rho \pi$ wave intensity is observed.

$J^P M^n = 3^+0^+$. A resonance-like signal is observed near $M \approx 1.8 \text{ GeV}$ 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
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:

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

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

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

$J^P M^\circ = 4^+1^+$. A bump near $M \approx 2\text{GeV}$ 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:

$$M = 1.95 \pm 0.02 \text{GeV}, \quad \Gamma = 0.34 \pm 0.10 \text{GeV}.$$
Figure 4: The $4^{+}1^{+} D\rho$ (a) and $4^{+}1^{+} Ff_{2}$ (b) wave intensities and the phase difference $\phi (4^{+}\Gamma \rho) - \phi (2^{-}Sf_{2})$ for $0.06 < t' < 0.7 GeV^{2}$.

Figure 5: The $J^{P}M^{\eta} = 1^{-}1^{+} S\rho$ 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:

$$\frac{Br(a_{4}(2040) \to f_{2}(1270)\pi)}{Br(a_{4}(2040) \to \rho\pi)} = 0.5 \pm 0.2.$$  

$J^{P}M^{\eta} = 1^{-}1^{+}$. 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 $M = 1593 \pm 8^{+20}_{-17} MeV$, $\Gamma = 168 \pm 20^{+150}_{-12} MeV$ 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. 3) 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.
Figure 6: Wave intensities of: a) $0^+P\rho_{1}$, b) $2^+P\rho_{2}$ with $-t' < 0.08 GeV^2$, Wave intensities of: c) $3^+S\rho_{3}$, d) $2^+S\rho_{2}$, e) $4^+D\rho_{2}$, f) $1^+S\rho_{1}$.

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.

$J^P\eta = 0^-0^+$. 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 $1^+0^+P\rho_{1}$ 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 $\Gamma = 0.259 \pm 0.019 \pm 0.06 GeV$.

$J^P\eta = 2^-0^+$. 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 $2^-0^+P\rho_{1}$ and $2^-0^+P\rho_{2}$ waves relative to the $1^+0^+P\rho_{1}$ wave is observed. The resonance parameters of the $2^-0^+P\rho_{2}$ peak were estimated in the same way as for $\pi(1740)$: $M = 1.687 \pm$
0.009±0.015 GeV and \( \Gamma = 0.168±0.043±0.053 \) 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 \( \pi_2(1670) \to f_2(1270) \pi \), 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 2\( \sigma \) confidence level:

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

\( J^P M^n = 3^+0^+ \). A peak at \( M_{3\pi} \sim 2 GeV \) and \( \Gamma \sim 0.35 GeV \) is clearly seen in the \( 3^+0^+ S(\rho_3(1690)) \) wave for events with low \( t' \) (Fig. 3(c)). However the resonant phase motion was not found. Such wave behaviour can be attributed to the Deck effect process \( ^{13} \). \( J^P M^n = 2^+1^+ \). The intensive production and decay of the \( a_2(1320) \) is the main process at low masses (Fig. 3(d)). The decay probability was found to be \( Br(a_2(1320) \to \omega \pi^0) = (5 \pm 1)\% \). We define the \( a_2(1320) \) partial width as that of a Breit-Wigner function with the S-wave \( \omega \pi^0 \) 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.

\( J^P M^n = 4^+1^+ \). The signal at \( M \approx 2 GeV \) (Fig. 3(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 \( a_2(1320) \).

\( J^P M^n = 1^-1^+ \). 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. 3(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 \( J^P M^n = 1^-1^+ \) wave analysis

The combined analysis of the \( J^P M^n = 1^-1^+ b_1 \pi \) and the \( J^P M^n = 2^+1^+ \omega \rho \) was carried out in order to understand the nature of the \( b_1 \pi \) wave. The results of the \( \omega \pi^0 \) system PWA were used for this analysis. The diagonal elements and the real
and imaginary parts of the non-diagonal element of the $\rho$-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 $J^P M^q = 1^{-1}+$ 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:

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

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 $\Gamma = 0.29 \pm 0.03 \text{GeV}$ with the mass $M = 1.61 \pm 0.02 \text{GeV}$ and the relative branching ratio: $Br(b_1\pi) : Br(\eta'\pi) : Br(\rho\pi) = 1 : 1.0 \pm 0.3 : 1.6 \pm 0.4$. 

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

The PWA of the reaction $\pi^- Be \rightarrow \pi^+ \pi^- \pi^- Be$ and $\pi^- Be \rightarrow \pi^+ 2\pi^- 2\pi^0 Be$ 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 $3^1 S_0$ $q\bar{q}$ 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 $a_2(1320)^- \rightarrow \omega \pi^- \pi^0$ decay and a wide bump of unknown nature at $M \approx 1.7 \text{GeV}$ 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: $Br(f_2(1270)\pi) : Br(\rho \pi) : Br(\omega \rho) = 0.5 \pm 0.2 : 1.5 \pm 0.4$

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 $M = 1.61 \pm 0.02 \text{GeV}$, the width $\Gamma = 0.29 \pm 0.02 \text{GeV}$ 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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