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Partial-Wave Analysis of the Reaction $\pi^- p \to \pi^+\pi^-\pi^0 n$ at $p_{\pi^-} = 36$ GeV/c. Study of $a_2(1320)$ and $\omega_3(1670)$ mesons.

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Abstract

Amelin D.V. et al. Partial-Wave Analysis of the Reaction $\pi^- p \to \pi^+\pi^-\pi^0 n$ at $p_{\pi^-} = 36$ GeV/c. Study of $a_2(1320)$ and $\omega_3(1670)$ mesons: IHEP Preprint 95-71, OEI UNK. – Protvino, 1995. – p. 9, figs. 5, tables 4, refs.: 14.

Results of the partial-wave analysis of the reaction $\pi^- p \to \pi^+\pi^-\pi^0 n$, studied at $p_{\pi^-} = 36$ GeV/c on $2 \cdot 10^5$ event statistics, are presented. Masses and widths of $a_2(1320)$ and $\omega_3(1670)$ mesons are measured, as well as differential cross-sections $d\sigma/dt$ in the a_2 and ω_3 regions. It is shown that the relative phase between 2^+ and 3^- is consistent with two-resonance description. The estimated limits for the $\pi_0(1300)$, $\pi_2(1670)$, $\omega_1(1420)$ and $\omega_1(1600)$ cross sections are also presented.

Аннотация

Амелин Д.В. и др. Парциально-волновой анализ реакции $\pi^- p \to \pi^+\pi^-\pi^0 n$ при $p_{\pi^-} = 36$ GeV/c. Исследование мезонов $a_2(1320)$ и $\omega_3(1670)$: Препринт ИФВЭ 95-71, OEI UNK. – Протвино, 1995. – 9 с., 5 рис., 4 табл., библиогр.: 14.

Представлены результаты парциально-волнового анализа реакции $\pi^- p \to \pi^+\pi^-\pi^0 n$ при $p_{\pi^-} = 36$ GeV/c, проведенного на статистике $2 \cdot 10^5$ событий. Измерены массы и ширины $a_2(1320)$ и $\omega_3(1670)$, а также дифференциальные сечения $d\sigma/dt$ в области масс a_2 и ω_3. Показано, что разность фаз волн 2^+ и 3^- отвечает вкладу двух резонансов. Представлены также ограничения на сечения рождения $\pi_0(1300)$, $\pi_2(1670)$, $\omega_1(1420)$ и $\omega_1(1600)$ мезонов.

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Introduction

This paper presents the results of the partial-wave analysis for the charge-exchange reaction $\pi^- p \to \pi^+\pi^-\pi^0 n$ on the Beryllium target at $p_{\pi^-} = 36$ GeV/c. The experimental sample, consisting of $\sim 2 \cdot 10^5$ events, was collected by Protvino VES detector [1] and processed by modified version of the Illinois PWA program [2].

The $\pi^+\pi^-\pi^0$ mass spectrum, shown in Fig. 1[a], has a number of prominent structures: well-known $\eta(548)$, $\omega(783)$, $a_2(1320)$ and bump at mass $\approx$ 1670, reffered nowadays as ω_3 in PDG tables [9].

This paper is devoted to the consideration of the most intensive waves in a mass range $0.9 < M_{3\pi} < 2.3$. Other PWA results will be presented elsewhere.

We pay particular attention to the ω_3 signal, which was studied previously in a number of papers [3–6]. First it was identified as $I = 0$ resonance [3], then quantum numbers $J^P = 3^-$ [4, 5] and evidence for its phase motion [5] were reported. Our analysis is based on a significantly higher statistics.

1. Event Selection

The $\pi^+\pi^-\pi^0$ events were selected from the initial $\pi^+\pi^-\gamma\gamma$ sample, consisting of $8 \cdot 10^5$ events, in accordance with the following criteria:

- invariant mass of the $\gamma\gamma$ pair is in π^0 mass range: $115 < m_{\gamma\gamma} < 155\,\mathrm{MeV/c^2}$,
- the π^0 momentum is greater than 2.5 GeV/c,
- total energy of π^+, π^- and π^0 is in the range $33 < E_{\mathrm{tot}} < 38\,\mathrm{GeV}$,
- cuts for the Gottfried-Jackson angles are $\cos\theta_{\pi^+} > -0.95$, $\cos\theta_{\pi^-} < 0.9$, $-0.95 < \cos\theta_{\pi^0} < 0.95$.

Some installation-dependent conditions were also imposed. In particular, only events with tracks, identified as pions by the threshold Čerenkov counter and not identified as electrons by the energy release in gamma detector, were selected. Events with target guard activity, which have probably isobar in the final state, were rejected.

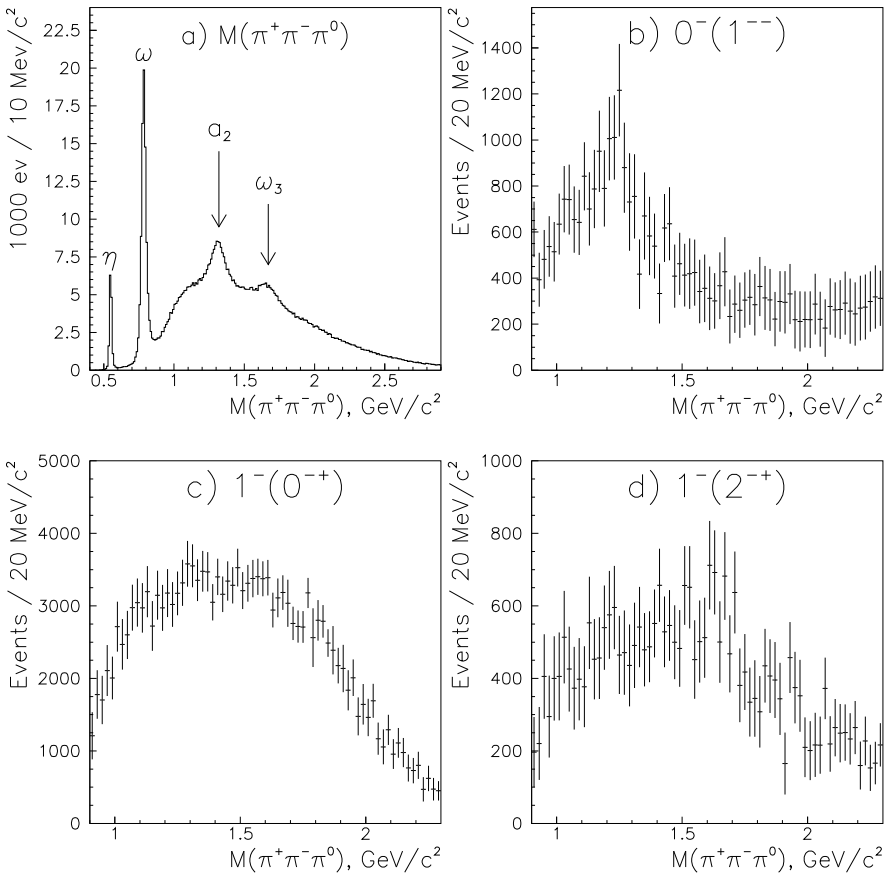

Fig. 1. a) Invariant mass of $\pi^+\pi^-\pi^0$ system, b,c,d) summary in of 1^-, 0^- and 2^- waves.

As a result, $2 \cdot 10^5$ events, matching all the criteria have been selected for the partial-wave analysis.

2. Partial-Wave Analysis

We are dealing with the three-meson PWA technique, based on the isobar model. In accordance to Ref. [2], each wave is denoted as $J^P LM\eta\,(I, d)$, where J is the total angular momentum of 3-meson system, P – space parity, L – orbital momentum of meson-dimeson system, $M = |J_z|$ – projection on the t-channel Gottfried-Jackson system, $\eta = \pm 1$ – symmetry with respect to the reaction plane, which gives the naturality of the exchange particle in the lowest $1/s$ order [10]. In the brackets I denotes the total isospin, and d stands for the meson-isobar decay mode.

Our analysis incorporates isobars with spin $j \leq 2$. For $\rho(770)$-meson the parametrizaton of Ref. [7] is used. The $f_2(1270)$ resonance is parametrized as the relativistic Breit-

Wigner function with standard Blatt-Weisskopf factor [11] for $j=2$ and $R=5.2$ c/GeV.

For the $(\pi^+\pi^-)_S$ wave amplitude we compared a number of parametrizations and conclude that broad $f_0(1300)$ is really significant for the event description, while narrow $f_0(975)$ is not. The so-called M solution of Au, Morgan and Pennington [8] with "subtracted" $f_0(975)$ shows the best likelihood, and it was chosen for physical runs[1].

The general PWA procedure was applied to the mass region $0.9 < M_{3\pi} < 2.3$ GeV/c^2, which was splitted to 70 bins of 20 MeV/c^2 width. Waves, included in fit, are listed in Table 1. For each PWA run the pseudo-wave FLAT was also added in order to control the fit quality.

$I^G(J^{PC})$	List of amplitudes		
$1^-(0^{-+})$	$0^-S0+(1,f_0\pi)$,	$0^-P0+(1,\rho\pi)$	
$0^-(1^{--})$	$1^-P1+(0,\rho\pi)$		
$0^-(1^{+-})$	$1^+S0+(0,\rho\pi)$,	$1^+S1+(0,\rho\pi)$,	$1^+S1-(0,\rho\pi)$
$1^-(1^{++})$	$1^+S0+(1,\rho\pi)$,	$1^+S1+(1,\rho\pi)$,	$1^+S1-(1,\rho\pi)$
$1^-(2^{-+})$	$2^-S0+(1,f_2\pi)$		
$1^-(2^{++})$	$2^+D1+(1,\rho\pi)$,	$2^+D0-(1,\rho\pi)$,	$2^+D1-(1,\rho\pi)$
$0^-(3^{--})$	$3^-F1+(0,\rho\pi)$,	$3^-F0-(0,\rho\pi)$	$3^-F1-(0,\rho\pi)$

Table 1. Partial waves, included into analysis.

The whole $\pi^+\pi^-\pi^0$ statistics was splitted into 4 subsets by the value of the momentum transfer squared: a) $0<t'<0.05$, b) $0.05<t'<0.2$, c) $0.2<t'<0.6$, d) $0.6<t'<1.2$, where $t'=-(t-t_{\rm max})$.

The dominant waves are collected in Figs. 1 and 2. We do not observe any resonant structures in $1^-(0^{-+})$ and $1^-(2^{-+})$ waves (Figs. 1^c, 1^d). In waves with $J^P=1^+$ broad structures are observed, which correspond to the $a_1(1260)$ and $h_1(1170)$ mesons (Fig. 2). Their analysis requires careful study of the non-resonant background and will be presented elsewhere.

The 2^+ and 3^- partial waves were fitted separately in each t' interval by the noncoherent sum of polynomial background and relativistic Breit-Wigner shape, folded with the VES resolution function. The last one was parametrized as the sum of two Gauss functions. The shape of resolution function was obtained with the help of simulation procedure. This method was tested explicitly for the $\omega(783)$ meson, then it was applied for a_2 and ω_3 masses.

The dynamical width is constructed as the sum

$$\Gamma_{\rm tot}(m)=\sum_i \Gamma_i(m)\,, \qquad \Gamma_i(m)=b_i\,\Gamma_0\left(\frac{p_i}{p_{i0}}\right)^{2l+1}\frac{m_0}{m}\cdot\frac{D_l(p_{i0}R)}{D_l(p_iR)}\,, \tag{1}$$

[1]This "subtraction" has been performed with the fit of the M-solution amplitude [8] by the sum of wide and narrow Breit-Wigner functions. The resulting $(\pi^+\pi^-)_S$ amplitude is the difference $F_M - C\cdot BW(m_0,\Gamma_0)$. Fit parameters are $m_0=983$ MeV/c^2, $\Gamma_0=37$ MeV.

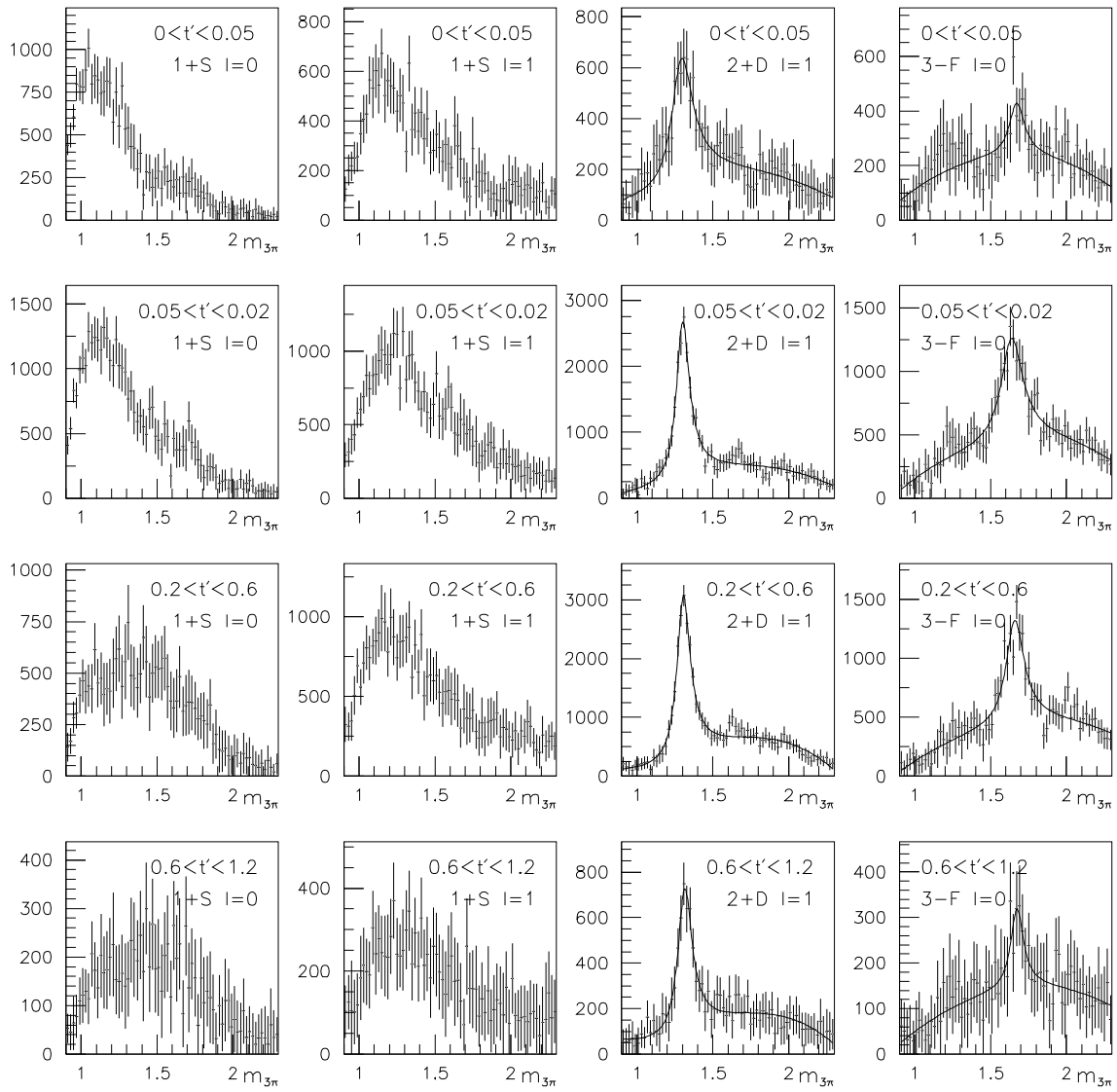

Fig. 2. Summary intensities of the dominant waves in $\rho\pi$ system. Each row corresponds to the particular t' region.

where index "i" denotes a particular decay channel, b_i is its branching ratio, taken from PDG [9], m is the mass of initial state, $p_i = p_i(m)$ is the relative momentum of decay products, $p_{i0} = p_i(m_0)$, function $D_l(x)$ is the Blatt-Weisskopf factor for spin l [11], $R = 5.2$ c/GeV is the hadron size parameter. Channels $\rho\pi$, $\eta\pi$, $K\overline{K}$ and $\omega\pi\pi$ were taken into account for the a_2 fit, and only $\rho\pi$ channel was accounted for ω_3 fit.

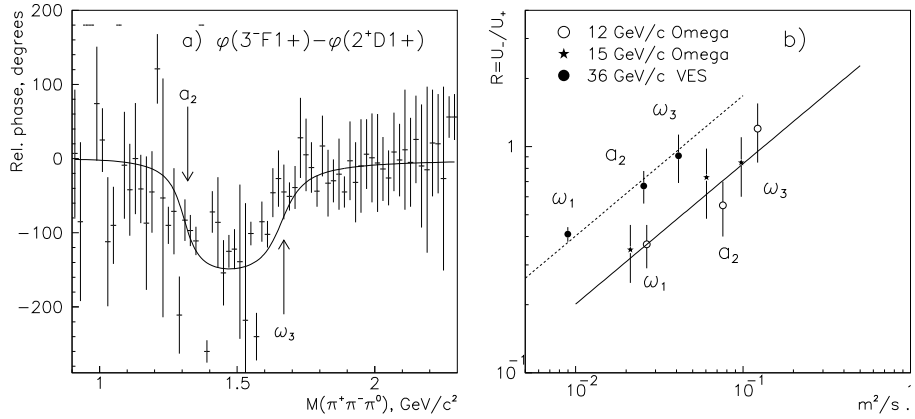

Fig. 3. a) Relative phase of $3^-F1+(0,\rho\pi)$ and $2^+D1+(1,\rho\pi)$ waves, b) The ratio of unnatural to natural exchange contributions $R=U_-/U_+$ as a function of m^2/s.

Results of the fit are

$$\begin{aligned} M(a_2^0) &= 1311.3 \pm 1.6\,(\text{stat}) \pm 3.0\,(\text{syst})\ \text{MeV/c}^2\,, \\ \Gamma_0(a_2^0) &= 103 \pm 6\,(\text{stat}) \pm 3.3\,(\text{syst})\ \text{MeV}\,, \end{aligned}$$

with $N(a_2) = (72.4 \pm 4) \cdot 10^3$ events, and

$$\begin{aligned} M(\omega_3) &= 1665.3 \pm 5.2\,(\text{stat}) \pm 4.5\,(\text{syst})\ \text{MeV/c}^2\,, \\ \Gamma_0(\omega_3) &= 149 \pm 19\,(\text{stat}) \pm 7\,(\text{syst})\ \text{MeV}\,, \end{aligned}$$

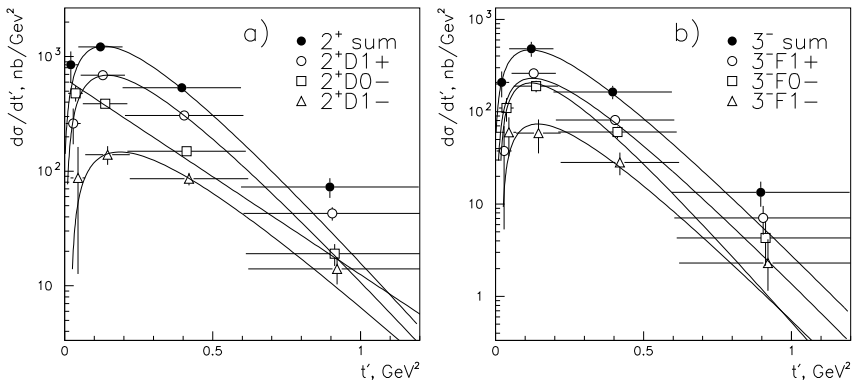

Fig. 4. The t'-dependencies of the separate partial waves of a_2 (a) and ω_3 (b) resonances.

Wave	B, GeV^{-2}	Wave	B, GeV^{-2}
2^+ sum	-	3^- sum	8.6 ± 0.8
2^+D1+	8.4 ± 0.6	3^-F1+	8.1 ± 0.3
2^+D0-	(4.1 ± 0.3)*	3^-F0-	9.0 ± 0.8
2^+D1-	5.6 ± 1.7	3^-F1-	7.8 ± 2.7

Table 2. Slope parameters of t-dependencies for waves of Figs. 4^a and 4^b. All the waves (except 2^+D0-) were fitted by the function $t'e^{-Bt'}$, and 2^+D0- was fitted by $e^{-Bt'}$.

with $N(\omega_3) = (23.4 \pm 2.6) \cdot 10^3$ events. The corresponding cross sections are

$$\begin{aligned} \sigma(a_2) \times \mathrm{Br}(\mathrm{a_2} \to \pi^+\pi^-\pi^0) &= 5.4 \pm 0.6\ \mu\mathrm{b}, \\ \sigma(\omega_3) \times \mathrm{Br}(\omega_3 \to \pi^+\pi^-\pi^0) &= 1.75 \pm 0.26\ \mu\mathrm{b}. \end{aligned}$$

The main source of our systematic errors is the absolute calibration of gamma detector. In our calibration procedure we rescale E_γ, so that the $\omega(783)$ mass was fitted to its PDG value [9].

The resonant character of 3^- signal is confirmed by the behaviour of non-diagonal ρ-matrix elements. In Fig. 3^a the relative phase $3^-F1 + /2^+D1+$ is shown. It has a characteristic drop due to a_2 and increase due to ω_3. The smooth curve corresponds to the phase difference of fitted Breit-Wigner functions.

Wave	Function	Parameter values		
		b_1	b_2	p
1^-P1+	F_1	8.9 ± 0.06	1.8 ± 0.2	0.91 ± 0.003
1^-P1-	F_1	8.7 ± 0.4,	4.3 ± 0.4	0.68 ± 0.08
1^-P0-	F_0	4.02 ± 0.05		

Table 3. Parameters of $\omega(783)$ fits. The t' distributions, presented on Fig. 4, were fitted with the functions $F_0 = e^{-b_1 t'}$, $F_1 = b_1^2 p t' e^{-b_1 t'} + b_2^2(1-p)t' e^{-b_2 t'}$.

3. The t'-dependencies of partial waves

The t-dependencies of a_2 and ω_3 partial waves are presented in Figs. 4^a and 4^b. We observe usual dips at $t \sim 0$ for waves with $J_z \neq 0$ (however, the presence of dip in 2^+D1- is questionable) and typical exponential dependence for 2^+D0- wave. There is an evidence for a dip at $t=0$ for 3^-F0- wave, which may reflect some peculiarity of the ω_3 production mechanism. Parameters of fits are presented in Table 2.

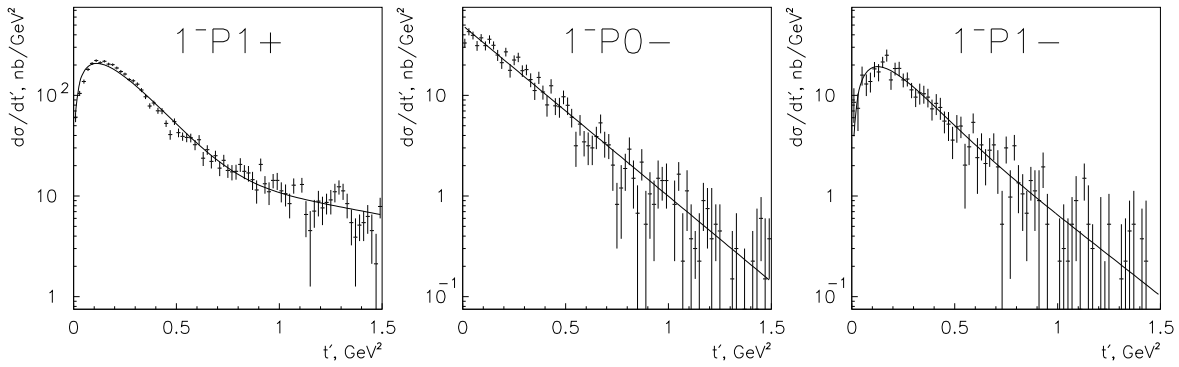

Fig. 5. The t'-dependencies of different partial waves in $\omega(783)$ mass region.

These results can be compared with t'-distributions of the $\omega(783)$ meson, which should be produced via the same ρ and b_1 exchanges, as a_2 and ω_3 [12]. On Fig. 5 the intensities of $\omega(783)$ partial waves, plotted with $0.02\,\mathrm{GeV}^{-2}$ interval, are presented. They exhibit usual dips at $t' \sim 0$ for projectional waves. Fit results are presented in Table 3.

The ratios of unnatural to natural parity exchange contributions are $U_{-/+} = 0.45 \pm 0.03$ for $\omega_1(783)$, $U_{-/+} = 0.77 \pm 0.11$ for the $a_2(1320)$ and $U_{-/+} = 0.93 \pm 0.22$ for $\omega_3(1670)$. In Ref. [13] Hoyer, Roberts and Roy derived the mass and energy dependence for this ratio:

$$R = \frac{U_-}{U_+} = \left(\frac{m^2}{s}\right)^{2(\alpha_N(t)-\alpha_U(t))}, \qquad (2)$$

where m is a mass of decaying resonance, $\alpha_N(t)$ and $\alpha_U(t)$ – natural and unnatural exchange trajectories. In Ref. [14] was found $\alpha_N - \alpha_U = 0.31 \pm 0.08$ at $|t| \approx 0.45$ GeV^{-2}. Comparison of these predictions with our results is presented on Fig. 3^b. The same m^2 dependence as in Ref. [14] is observed, however, the s-dependence of formula (2) is not confirmed. Nevertheless, note that all these results were obtained on the nucleon target.

4. Search for other resonances

Table 4 contains limits for the production cross sections of some other resonances [9], which may be observed in $\pi^+\pi^-\pi^0$ mode. These limits do not contradict to the expected cross sections, provided that ρ-exchange is the main production mechanism.

For $\omega_1(1420)$ and $\omega_1(1600)$ the ρ-exchange diagrams were computed explicitly, and the predicted cross sections are compatible with the experimental limits.

5. Conclusions

The systematic study of $a_2(1320)$ and $\omega_3(1670)$ resonances by the PWA technique has been performed. The cross section of $\pi^- p \to a_2 n$ reaction at $P_{\pi^-} = 36$ GeV/c is found

Name	M, MeV/c^2	Γ, MeV	$\sigma \times$ Br, nb
$\pi_0(1300)$	1300 ± 100	200..600	< 100
$\pi_2(1670)$	1670 ± 20	240 ± 15	< 15
$\omega_1(1420)$	1419 ± 31	174 ± 60	< 3.5
$\omega_1(1600)$	1662 ± 13	280 ± 24	< 8

Table 4. Estimated production rates at $P_{\pi^-} = 36$ GeV/c. The limits correspond to the 1σ confidence level, resonance parameters were taken from PGD [9].

to be $\sigma(a_2) = 7.7 \pm 0.9\mu$b. We present the most accurate measurement of the ω_3 meson parameters: $M(\omega_3) = 1665.3 \pm 5.2\,(\text{stat}) \pm 4.5\,(\text{syst})$ MeV/c^2, $\Gamma_0(\omega_3) = 149 \pm 19\,(\text{stat}) \pm 7\,(\text{syst})$ MeV. Clear evidence for the resonance phase behaviour of 3^-F waves was also obtained.

The measured ratios of unnatural to natural exchange contributions do not confirm the predictions of the naive Regge model [13].

Limits for the production cross sections of $\pi_0(1300)$, $\pi_2(1670)$, $\omega_1(1420)$ and $\omega_1(1600)$ were obtained. In the case of ω_1 mesons these limits are compatible with the expected cross sections.

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