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ON THE SUBTLETIES OF THE SPECTRUM OF LIGHT MESON RESONANCES
II. DATA ANALYSIS

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1. Introduction

Here we present the results of our renewed analysis of the processes

$$e^+e^- \to \omega\pi^0 , \qquad (1)$$

$$e^+e^- \to \pi^+\pi^-\pi^0 \qquad (2)$$

with taking into account new data [1,2] as well as the previous ones [3] concerning the decay

$$\tau^- \to \nu_\tau \omega\pi^- . \qquad (3)$$

We consider these processes in the framework of the vector-dominance-model (VDM) in the same manner as it has been done in the previous paper [4]. However, now we rather veryfy absence of any contradictions between resonances predicted by our model (see, Part I of this work) and experimental data than determine phenomenological resonances from the data.

In Section 2 we consider the experimental manifestation of the predicted ρ/ω-resonances in the indicated processes and obtain their parameters.

In Section 3 we try to estimate leptonic widths of these resonances in order to compare their experimental properties with their theoretical interpretation.

In Conclusion we discuss an intended deviation of experimental data from the theoretically predicted lowest excitations of ρ-, ω-, and K^*-vector mesons.

2. The experimental manifestation of the predicted ρ/ω-resonances

New experimental data [1,2] concerning to processes (1) and (2) differ very much from the previous ones and new analysis of these processes seems to be essential.

The processes (1) and (3) are defined in the framework

of VDM-model by the contributions of ρ-resonances. The spectral function measured in the τ-decay (3) can be connected directly with the cross section of the process (1)[3], what we shall do. The process (2) is defined by ω-resonances but we take into account the contribution of ϕ-meson and its interference with other resonances too *).

A contribution of each resonance "*i-prime*" to the cross section of these processes is determined by three parameters: its mass $m(V^i)$, its total width $\Gamma(V^i)$, and the ratio of its strong and electromagnetic coupling constants $B(V^i) = g(V^i V\pi)/g(V^i)$ ($V = \rho$-, ω-meson depending on whether V^i is ω^i- or ρ^i-excitation). The connection of the latter constants with the corresponding decay widths are presented in paper [4]. For ρ-, ω-, and ϕ-mesons their parameters are shown in Table 1.

There is some difference between these parameters of ρ-, ω-, and ϕ-mesons and their parameters presented in paper [4] in consequence of changes and more precision of experimental data [5].

Remark, the constant $g_{\rho\omega\pi}$ can be defined in two ways: firstly, from the value of the decay width $\Gamma(\omega \to \rho\pi \to \pi^+\pi^-\pi^0) = 7.49\pm0.10$ MeV [5] we have $g_{\rho\omega\pi} = 15.53\pm0.10$ GeV^{-1}, and secondly, from the $SU(6)_W$-relation $g_{\rho\omega\pi} = 2g_{\rho\pi\pi}/m_\rho$, and from $\Gamma(\rho\to\pi^+\pi^-) \approx \Gamma_\rho^{tot}$ we have $g_{\rho\pi\pi}=6.00\pm0.06$ and $g_{\rho\omega\pi}=15.60\pm0.16$ GeV^{-1}. We see, both ways give the same value of $g_{\rho\omega\pi}$.

In our calculations, as values of the parameters of ρ-, ω-, and ϕ-mesons we take magnitudes presented in Table 1 except for the parameter B_ρ. We obtain the best fitting of the experimental data with a little bigger value of this parameter than presented in Table 1. This point can be connected with our approximation of neglecting the dependence of the resonance width on energy far from the resonance position.

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*) In this connection I am compeled to indicate that the contribution of ϕ-meson in this process was included in the previous paper [4] as opposed to affirmation in the second reference of [6].

Table 1

Parameters of ρ-, ω-, and φ-vector mesons

Meson V	m_V MeV	Γ_V^{total} MeV	$\Gamma(V\Rightarrow e^+e^-)$ keV	$g_{VV'\pi}$ GeV^{-1}	g_V	B_V GeV^{-1}
ρ(770)	768.3 ±0.5	149.1 ±2.9	6.77 ±0.32	15.5 ±0.1	5.03 ±0.12	3.09 ±0.08
ω(782)	782.0 ±0.1	8.43 ±0.10	0.60 ±0.02	15.5 ±0.1	17.05 ±0.28	0.91 ±0.02
Φ(1020)	1019.41 ±0.01	4.41 ±0.07	1.37 ±0.05	0.79 ±0.02	-12.88 ±0.24	-0.060 ±0.002

Bisides radial excitations of ρ- and ω-mesons we include in our fitting their $^3D_1$-wave orbital excitations too. But we do not calculate these states within our model, and thus we can only estimate positions of these states by analogy with the position of $^1D_1$-states indicated in Table 2 of Part I of this work also taking into account the results of calculations /7/ of $^3D_1$-states. We propose these 1^3D_1-states lain inside the mass interval 1600-1700 MeV and their first radial excitations 2^3D_1 lain inside the mass interval 2000-2150 MeV.

The set of all states and the corresponding resonances involved into our fitting are indicated in the first and second columns of Table 2 respectively. We have not fixed masses of resonances at our fitting but we permitted them deviate by ±100 MeV around their position predicted by our model.

The best fitting of the cross sections of processes (1) (with taking into account data on the process (3)) and (2) was obtained under values of resonance parameters indicated in three consecutive columns.

In the sixth column of Table 2 we show values of the strong coupling constants $g^0(V^IV\pi)$ evaluated from the total resonance width under an assumption that this channel is the only. Real constants are defined by

$$g(V^IV\pi) = g^0(V^IV\pi)\times BR^{1/2}(V^I\Rightarrow V\pi). \quad (4)$$

Table 2

The parameters of resonances under the best fitting of the cross sections of processes (1) and (2)

State $n^{2S+1}L_J$	Resonance V^I	$m(V^I)$ MeV	$\Gamma(V^I)$ MeV	$B(V^I)$ GeV^{-1}	$g^0(V^IV\pi)$ GeV^{-1}	$\frac{BR(\rho^I\Rightarrow\omega\pi)}{BR(\omega^I\Rightarrow\rho\pi)}$
1^3S_1	ρ	768.3 ±0.5	149.1 ±2.9	3.30 ±0.10	15.5 ±0.1	–
	ω	782.0 ±0.1	8.43 ±0.10	0.911 ±0.020	15.5 ±0.1	–
	φ	1019.4	4.41 ±0.07	-0.061 ±0.002	0.79 ±0.02	–
2^3S_1	ρ'	1450 ±3	283 ±5	-0.148 ±0.001	8.81 ±0.35	0.40±0.06
	ω'	1387 ±11	305 ±33	-0.028 ±0.001	5.59 ±0.33	
1^3D_1	ρ'	1590 ±57	260 ±31	-0.093 ±0.001	6.86 ±1.10	0.14±0.04
	ω'	1660 ±3	159 ±3	-0.018 ±0.001	2.53 ±0.02	
3^3S_1	ρ''	1856 ±64	60 ±7	-0.015 ±0.001	2.12 ±0.02	0.80±0.16
	ω''	1950 ±10	184 ±36	-0.005 ±0.001	1.90 ±0.19	
2^3D_1	ρ'^V	2000 ±60	50 ±1	0.011 ±0.001	1.97 ±0.03	0.52±0.02
	ω'^V	2175 ±5	165 ±4	-0.009 ±0.001	1.43 ±0.02	
4^3S_1	ρ^V	2400 ±13	245 ±8	0.009 ±0.001	2.46 ±0.76	0.32±0.20
	ω^V	2250 ±7	178 ±17	0.011 ±0.001	1.39 ±0.07	

Remark: for the best fitting $\chi^2(e^+e^-\Rightarrow\omega\pi)$=46.9, χ^2/n_D=1.3 (n_D= 50-15); $\chi^2(e^+e^-\Rightarrow\pi^+\pi^-\pi^0)$=14.9, χ^2/n_D=1.0 (n_D=29-15). Errors correspond to χ^2-change of 1. Underlined values are the input ones.

Unfortunately, branching ratios $BR(V^I\Rightarrow V\pi)$ are unknown and they enter into our calculations as unknown parameters. However, we can propose the equality of the corresponding constants of ρ'- and ω'-resonances

$$g(\rho'\omega\pi) = g(\omega'\rho\pi). \qquad (5)$$

Then, we can estimate the quotient of the branching ratios

$$BR(\rho' \Rightarrow \omega\pi)/BR(\omega' \Rightarrow \rho\pi) = [g^0(\omega'\rho\pi)/g^0(\rho'\omega\pi)]^2 \qquad (6)$$

which is given in the last column of Table 2. It is interesting that this quotient is less than unity for all resonances. So this is an evidence that ρ'-resonances have more open decay channels than the corresponding ω'-resonances (For example, there is no decay of ω' which is analogous to $\rho'^0 \Rightarrow \rho^+\rho^-$).

Experimental points for processes (1) and (2) are indicated in Fig. 1. The behaviour of the cross sections of these processes predicted by the VDM-model with the resonance parameters from Table 2 is shown on the same figure. Entirely, there are no any contradictions between our predictions and experimental data.

However, only first two resonances $\rho'/\omega'(1400)$ and $\rho''/\omega''(1600)$ could be considered as well established confirming the previous hypothesis of their existence /4,6,7/ (see, also, review /5/). But even for these resonances the values of the parameters $B(V')$ are essentially changed as compaired to their values indicated in paper /4/. These parameters $B(\rho')$ and $B(\rho'')$ (and $B(\omega')$ and $B(\omega'')$ respectively) noticeably decrease in their absolute values and have a common sign (opposite to the sign of $B_\rho(B_\omega)$). Thus, their interference becomes constructive and leads to that the dip in the cross section of the process $e^+e^- \Rightarrow \pi^+\pi^-\pi^0$ at ~1.5 GeV becomes more smooth while an analogous dip in the cross section of the process $e^+e^- \Rightarrow \omega\pi^0$ does not appear at all in contrast with the prediction /4/.

Concerning higher $\rho'''(\omega''')$-, $\rho'^V(\omega'^V)$-, $\rho^V(\omega^V)$-resonances we can only conclude that their existence is not in contradiction with the available data. However, the latter are not sufficient for the firm evidence of the existence of

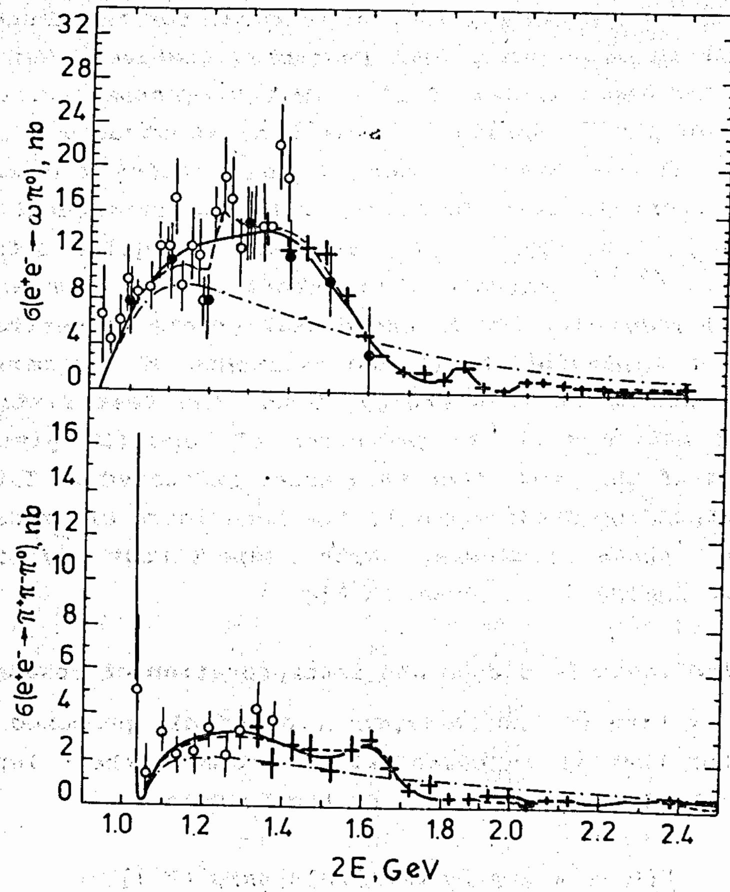

Fig. 1. The total cross section of the processes: $e^+e^- \Rightarrow \omega\pi^0$ (up) and $e^+e^- \Rightarrow \pi^+\pi^-\pi^0$ (down). Experimental data: ○ /1/, + /2/, ● /3/. Theoretical predictions: point-dotted curves show the contribution $\rho(770)$ (up) and $\omega(782)+\phi(1020)$ (down) only; solid curves accomodate all resonances excluding $\tilde{\rho}/\tilde{\omega}(1200)$; dotted curves include $\tilde{\rho}/\tilde{\omega}(1200)$ too.

these higher resonances and, what is more, for the determination of their parameters. Most probably, the lack of data is a reason for small widths of ρ'''- and ρ'^{V}-resonances.

Now we pay attention to some fine substructure in the behaviour of the cross section of the process $e^+e^-\Rightarrow\omega\pi^0$ at 1.2 GeV. There is some sharp dip with the subsequent rapid rising at this energy. It is essential that quite different experiments /1,3/ indicate this behaviour. Of course, this could be a manifestation of accidental errors. Nevertheless, we consider a possibility of the existence of a superfluous narrow resonance at this energy. Then, the best fitting of the cross sections of the processes (1) and (2) gives the parameters of this and other resonances indicated in Table 3. The corresponding predictions of the behaviours of cross sections of these processes with superfluous $\tilde{\rho}/\tilde{\omega}(1200)$-resonances included are shown in Fig. 1.

3. The leptonic widths and interpretation of resonances

Now we turn to the interpretation of all proposed resonances. For that it is essential to estimate their leptonic widths defined within $q\bar{q}$-model by the formula

$$\Gamma(V^i\Rightarrow e^+e^-) = [\alpha^2 m(V^i)/3]\times[4\pi/g^2(V^i)], \qquad (7)$$

where $\alpha\approx 1/137$. Leptonic constant $g(V^i)$ can be estimated from the values of $B(V^i)$ and strong decay parameters

$$g(V^i) = g^0(V^i\Rightarrow V\pi)\times \mathrm{BR}^{1/2}(V^i\Rightarrow V\pi)/B(V^i), \qquad (8)$$

and for the leptonic width we can write

$$\Gamma(V^i\Rightarrow e^+e^-) = \Gamma^0(V^i\Rightarrow e^+e^-)/\mathrm{BR}(V^i\Rightarrow V\pi). \qquad (9)$$

Remark, the relation of the leptonic widths as well as the leptonic constants of ρ^i and ω^i does not depend on unknown branching ratios of strong decay; thus

$$\Gamma(\rho^i\Rightarrow e^+e^-)/\Gamma(\omega^i\Rightarrow e^+e^-) = [m(\rho^i)/m(\omega^i)]\times[g(\omega^i)/g(\rho^i)]^2 = \\ = [m(\rho^i)/m(\omega^i)]\times[B(\rho^i)/B(\omega^i)]^2. \qquad (10)$$

Table 3

The parameters of resonances within the scheme with the superfluous $\tilde{\rho}/\tilde{\omega}(1200)$-resonance

State $n^{2S+1}L_J$	Resonance V^i	$m(V^i)$ MeV	$\Gamma(V^i)$ MeV	$B(V^i)$ GeV^{-1}	$g^0(V^iV\pi)$ GeV^{-1}	$\mathrm{BR}(\rho^i\Rightarrow\omega\pi)/\mathrm{BR}(\omega^i\Rightarrow\rho\pi)$
Parameters of ρ-, ω-, and ϕ-resonances are the same as in Table 2						
Superfluous resonance	$\tilde{\rho}$	1208 ±2	40 ±10	0.018 ±0.012	6.46 ±0.81	1.98±0.65
	$\tilde{\omega}$	1189 ±1	296 ±63	0.003 ±0.014	9.09 ±0.96	
2^3S_1	ρ'	1496 ±4	333 ±24	−0.186 ±0.003	9.13 ±0.33	0.67±0.07
	ω'	1400 ±5	572 ±40	−0.047 ±0.001	7.46 ±0.26	
1^3D_1	ρ''	1575 ±4	289 ±31	−0.049 ±0.004	7.41 ±0.41	0.11±0.02
	ω''	1662 ±10	147 ±16	−0.015 ±0.002	2.43 ±0.13	
3^3S_1	ρ'''	1859 ±4	50 ±29	−0.010 ±0.001	2.08 ±0.60	1.21±0.75
	ω'''	1900 ±8	240 ±50	−0.003 ±0.001	2.29 ±0.23	
2^3D_1	ρ'^{V}	1992 ±6	45 ±12	0.008 ±0.001	1.70 ±0.22	5.1 ±4.0
	ω'^{V}	1964 ±39	773 ±570	0.002 ±0.001	3.85 ±1.42	
4^3S_1	ρ^{V}	2029 ±318	509 ±77	−0.010 ±0.004	5.52 ±1.38	0.02±0.02
	ω^{V}	2397 ±49	83 ±72	−0.002 ±0.001	0.86 ±0.37	

Remark: for the best fitting $\chi^2(e^+e^-\Rightarrow\omega\pi)=39.1$, $\chi^2/n_D=1.2$ (n_D= 50−18); $\chi^2(e^+e^-\Rightarrow\pi^+\pi^-\pi^0)=19.0$, $\chi^2/n_D=1.7$ (n_D=29−18). Errors correspond to χ^2-change of 1.

As we obtain from values of the resonance parameters presented in Tables 2 and 3, ratios $g(\rho^i)/g(\omega^i)$ are close to the expected quark ratio ~3. Thus, below we make our estimations only for ρ^i-resonances.

We take acount of unknown ratios of strong decay modes in the following way. We rewrite these ratios in the form of identity

$$\mathrm{BR}(\rho^i \Rightarrow \omega\pi) = [\mathrm{BR}(\rho^i \Rightarrow \omega\pi)/\mathrm{BR}(\omega^i \Rightarrow \rho\pi)]\times \mathrm{BR}(\omega^i \Rightarrow \rho\pi). \qquad (11)$$

Then, we substitute values from Tables 2 and 3 in place of the first factor (If a certain value of this factor from Table 3 is more than unity, then we take it equal to unity). For the second factor we choose, more or less arbitrarily, it to be equal to 1/2, which corresponds to roughly equal probabilities of 3π- and 5π-decay modes of the ω^i-resonances. Estimations of leptonic widths of ρ^i-resonances obtained in such manner for both schemes with and without the superfluous $\tilde{\rho}(1200)$-resonance are presented in Table 4.

Now, interpreting resonances on the basis of the $q\bar{q}$-model we can estimate values of the wave functions of relative quark-antiquark motion "at zero" by means of the formula*)

$$|\psi(\rho^i)(0)| = m^{3/2}(\rho^i)/[\sqrt{6}g(\rho^i)]. \qquad (12)$$

Estimations for these values are presented in Table 4 too. The value of $\psi_\rho(0)$ is calculated from the data presented in Table 1. It is necessary to emphasize that a value of the wave function "at zero" for ρ-meson thus calculated is equal to only one-half of the theoretical prediction evaluated in the framework of our nonrelativistic potential model. So this indicates the limiting usage of our theoretical predictions of *absolute* values of the resonance parameters.

*) Remark, the colour factor $1/\sqrt{3}$ was omitted in the corresponding formula (16) in paper /4/. Of course, it does not influence the ratios of the wave functions and hence the final results.

Table 4

Estimation of leptonic widths of ρ-resonances

Resonance	Estimation of leptonic width			Wave function "at zero"	$\chi_i =$ $\lvert\psi_i(0)/\psi_\rho(0)\rvert$	
	$g^0_{\rho^i}$	$\mathrm{BR}(\rho^i \Rightarrow \omega\pi)$ keV	$\Gamma(\rho^i \Rightarrow e^+e^-)$ keV	$\lvert\psi_i(0)\rvert$ $\mathrm{GeV}^{3/2}$	Exp.	Theor.a)
$\rho(770)$	5.03 ±0.12	~ 1	6.77 ±0.32	0.0547 ±0.0016	1	1
The scheme without "superfluous" resonance						
ρ' (1450)	−67 ±9	0.20 ±0.03	0.36 ±0.08	0.024 ±0.003	0.43 ±0.06	0.79 ±0.02
ρ'' (1600)	−74 ±13	0.07 ±0.02	0.94 ±0.31	0.042 ±0.013	0.76 ±0.24	~0.40?
ρ'''(1862)	−163 ±13	0.40 ±0.01	0.040 ±0.005	0.010 ±0.001	0.19 ±0.02	0.72 ∓0.01
ρ^{iv} (1990)	197 ±20	0.26 ±0.01	0.042 ±0.008	0.011 ±0.001	0.21 ±0.02	~0.30?
ρ^{v} (2400)	270 ±150	0.16 ±0.10	0.044 ±0.046	0.014 ±0.010	0.26 ±0.18	0.70 ∓0.03
The scheme with "superfluous" resonance						
$\tilde{\rho}$ (1208)	360 ±240	1.00 ±0.32	0.002 ±0.002	0.002 ±0.001	0.03 ±0.02	?
ρ' (1496)	−49 ±2	0.33 ±0.04	0.42 ±0.06	0.027 ±0.002	0.48 ±0.04	0.79 ±0.02
ρ'' (1575)	−150 ±15	0.06 ±0.01	0.25 ±0.07	0.022 ±0.003	0.40 ±0.06	~0.40?
ρ'''(1859)	−210 ±65	0.60 ±0.40	0.17 ±0.02	0.007 ±0.003	0.12 ±0.06	0.72 ∓0.01
ρ^{iv} (1992)	212 ±38	~1	0.010 ±0.003	0.005 ±0.001	0.10 ±0.02	~0.30?
ρ^{v} (2029)	−550 ±260	0.01 ±0.01	0.20 ±0.22	0.021 ±0.015	0.38 ±0.27	0.70 ∓0.03

a) Up and down signs of deviations correspond to "weak" and "strong" spin-spin coupling scheme respectively.

In Table 4 ratios

$$\chi(\rho^i) \equiv |\psi(\rho^i)(0)/\psi(\rho)(0)| \qquad (13)$$

are exponded too. In the last column of Table 4 we present ratios (13) calculated within our potential model. According to a nonrelativistic approximation values of the wave functions of orbital excitations "at zero" vanish. However, they become different from zero owing to the relativistic smearing and amount to nearly one-half of the values for neighbouring radial excitations [7,8]. These theoretical estimations are indicated in Table 4 by the question-mark.

Taking into account considerable uncertainties of our determination of values of the resonance parameters, particularly, leptonic widths, we can state a satisfactory agreement between "experimental" estimations and theoretical predictions for the behaviour of the wave functions indicated in Table 4 resonance states "at zero". There is a marked difference for the higher $\rho'''(1859)$-resonance interpreted as second radial excitation of ρ-meson. However, as we have mentioned above, the estimation of the parameters of higher resonances is more difficult and unreliable. It is necessary to remark also that we neglect the mixture of states with the same quantum numbers owing to the unitary diagrams.

Concerning the hypotetical narrow $\tilde{\rho}(1200)$-resonance, we can say that it has a very small value of wave function "at zero" and doesn't look like the "standard" $q\bar{q}$-resonance. The mass of this resonance corresponds to the mass of the strange $K^*(1410)$-resonance discussed in the Part I of this work. Thus, if the existence of both these resonances will be confirmed, then it will demand prosecution of uncommon states, say hybrids.

4. Conclusion

The analysis of experimental data related to processes (1)-(3) indicates the satisfactory description of these processes by intermediate ρ^i/ω^i-resonances corresponding to the evaluated radial and orbital excitations of ρ/ω-meson. Paricularly, it confirms the existence of $\rho'/\omega'(1400)$ and $\rho''/\omega''(1600)$ resonances which were found earlier [4,6] (see, also review [5]). However, the parameters of these resonances are changed due to more precise measurements.

A rough estimation of a value of the wave function of $q\bar{q}$-system "at zero" for the $\rho'/\omega'(1400)$-resonance confirms the correspondence of this resonance to the first radial excition of ρ/ω-meson [7]. For the $\rho''/\omega''(1600)$-resonance the analogous estimation indicates some difficulty in the interpretation of this resonance as a D-wave orbital excitation of ρ/ω-meson. However, at present time we can hardly say about the discrepancy of that interpretation due to the existence of considerable uncertainties in the determination of the value of the wave function of this resonance "at zero".

Concerning higher-lying predicted resonances $\rho'''/\omega'''(1870)$, $\rho^{V}/\omega^{V}(2000)$ and $\rho^{V}/\omega^{V}(2230)$, we can only say that the assumption of their existence is not in contradicion with experimental data.

Lastly, it is possible that some fine subsrtucture in the behaviour of the cross section of process (1) at ~1200 MeV is connected with the existence of a narrow and slightly produced in this process $\tilde{\rho}/\tilde{\omega}(1200)$-resonance. The presence of this resonance is in accordance with the observation of the $K^*(1410)$-strange resonance*). Both these resonances are not accomodated within the $q\bar{q}$-model and should summon new, say, hybrid interpretation.

In conclusion, we would like to say that there is urgent necessity for more reliable confirmation of the existence of these superfluous resonances by more precise measurements of processes (1)-(3).

I would like to thank S. B. Gerasimov, V. A Meshcheryakov and M. K. Volkov for numerous discussions.

*) After this paper was completed I was informed about paper [9] where a ρ-resonance with mass 1266±14 MeV and width 166±35 MeV was observed in the $\pi^+\pi^-$-system produced in the reaction $K^- p \to \pi^+\pi^-\Lambda$ at 11 GeV with LASS spectrometer at SLAC. The existence of this resonance is discussed also in the paper [10].

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Говорков А.Б. E2-91-359

Об особенности спектра резонансов
легких мезонов
II. Анализ экспериментальных данных

Заново выполненный анализ экспериментальных данных по e^+e^-- аннигиляции в $\pi^0\omega$ и в $\pi^+\pi^-\pi^0$ указывает на возможность существования "лишнего" $\tilde{\rho}/\tilde{\omega}(1200)$-резонанса - нестранного партнера странного $K^*(1410)$-резонанса.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1991

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On the Subtleties of the Spectrum
of Light Meson Resonances
II. Data Analysis

A renewed analysis of the available experimental data on e^+e^--annihilation into $\pi^0\tilde{\omega}$ and $\pi^+\pi^-\pi^0$ hints at the existence of a superfluous $\tilde{\rho}/\tilde{\omega}(1200)$-resonances, non-strange partners of $K^*(1410)$.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

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