IL NUOVO CIMENTO **47 C** (2024) 160
DOI 10.1393/ncc/i2024-24160-6

Colloquia: HADRON2023

Further evidence for the lower-lying vector meson $\rho(1250)$ in the $e^+e^- \to \omega\pi^0$ process

T. Komada[1](*), T. Maeda[1], T. Tsuru[2] and K. Yamada[2]

[1] *Junior College Funabashi Campus, Nihon University - Chiba, Japan*
[2] *Research Institute of Science and Technology, College of Science and Technology, Nihon University - Tokyo, Japan*

received 21 December 2023

Summary. — Recently, strong evidence for the existence of the isovector vector meson with a mass around 1.26 GeV, or $\rho(1250)$, was presented from a unitary multichannel reanalysis of elastic $\pi\pi$-scattering data by Hammoud *et al.* In this work, we examine whether the $\rho(1250)$ observed in the $\pi\pi$-scattering process is also seen in the production process $e^+e^- \to \omega\pi^0$.

1. – Introduction

In the early 1970s, several evidences/signals for the $\rho(1250)$ were reported in the analysis of the $\omega\pi$ and $\pi\pi$ systems (see the mini-review of vector mesons in ref. [1, 2]). After that, this state was reported in the analysis of the $\bar{p}p$ annihilation, photoproduction, hadroproduction, and e^+e^- annihilation processes [3]. On the other hand, its existence was not confirmed in the analysis of the $\omega\pi$ system from the e^+e^- annihilation or τ decay [4-9]. Now, several results for evidences/signals around 1.25 GeV are listed under the $\rho(1450)$ in the Particle Data Group (PDG) tables [3] for their convenience, and are not recognized as a resonance state in the review "Spectroscopy of light meson resonances" by the PDG [3]. Although the existence of the $\rho(1250)$ is still controversial, it has an attractive interest [8, 10], since this state cannot be accommodated as a $q\bar{q}$ state in the conventional quark models.

Recently, the existence of the $\rho(1250)$ was reinforced with a multichannel and fully unitary S-matrix analysis of elastic $\pi\pi$ scattering data with crossing-symmetry constraints by Hammound *et al.* [11]. In this work, we examine whether this state is seen in the $e^+e^- \to \omega\pi^0$ process by using the vector meson dominance (VMD) model.

(*) E-mail: `komada.toshihiko@nihon-u.ac.jp`

2. – Analysis data and method

The combined data of the cross-sections for the $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$ process measured by SND [12, 13] and CMD-2 [14] and those for the $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ process measured by BABAR [15] are used to study isovector vector resonances in the energy region from threshold to 2 GeV.

The VMD model and intermediate $\omega(782)\pi^0$ state are assumed for the processes $e^+e^- \to \gamma^* \to$ "V" $\to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ or $\pi^0\pi^0\gamma$, where the symbol "V" denotes five intermediate states of the $\rho(770)$, $\rho(1250)$, $\rho(1450)$, $\rho(1600)$, and $\rho(1800)$. The $\omega(782)$ decays into either $\pi^+\pi^-\pi^0$ or $\pi^0\gamma$. The process is shown schematically in fig. 1(a). The direct process of γ^* into $\omega\pi^0$ is also taken into account, as shown in fig. 1(b).

The formula of the cross-section for the relevant processes is given by

$$\sigma_0(s) = \frac{4\pi\alpha^2}{s^{\frac{3}{2}}}\left(\frac{g_{\rho\omega\pi}}{f_\rho}\right)^2 \left| \frac{m_\rho^2\sqrt{F_\rho(s)}}{m_\rho^2 - s - i\sqrt{s}\Gamma_\rho(s)} + \sum_{i=1}^{4} \frac{A_i e^{i\theta_{\rho^{(i)}}} m_{\rho^{(i)}}^2 \sqrt{F_{\rho^{(i)}}(s)}}{m_{\rho^{(i)}}^2 - s - i m_{\rho^{(i)}}\Gamma_{\rho^{(i)}}} + \frac{A_{\mathrm{dir}} e^{i\theta_{\mathrm{dir}}}}{s} \right|^2 P_f(s), \tag{1}$$

where $g_{\rho\omega\pi}$ and f_ρ are the coupling constants for the transitions $\rho \to \omega\pi$ and $\rho \to \gamma^*$, respectively, and the resonances ρ, $\rho^{(1)}$, $\rho^{(2)}$, $\rho^{(3)}$, $\rho^{(4)}$ are assigned to $\rho(770)$, $\rho(1250)$, $\rho(1450)$, $\rho(1600)$, $\rho(1800)$, based on the results of ref. [11]. The form factors are introduced as

$$F_R(s) = \frac{2m_R^2}{m_R^2 + s}, \quad \text{for } R = \rho,\ \rho^{(i)}, \tag{2}$$

and assuming the ω resonance to be infinitely narrow

$$P_f(s) = \frac{1}{3} p_\omega^3(s) B_\omega, \tag{3}$$

where $p_\omega(s)$ is the three-momentum of $\omega(782)$ in the $\rho(770)$ at rest and B_ω is the branching ratios of $\omega \to \pi^0\gamma$ and $\omega \to \pi^+\pi^-\pi^0$, respectively, to be taken as 0.0835 and 0.892 [3].

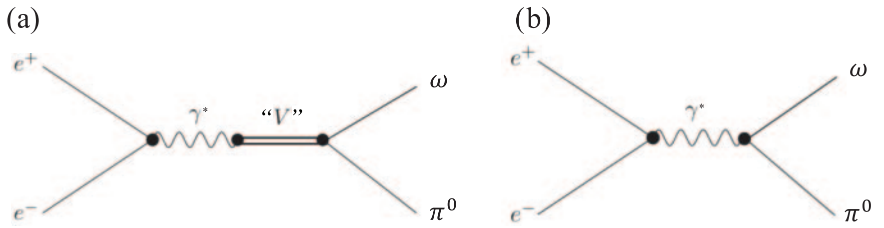

Fig. 1. – Feynman diagrams for the $e^+e^- \to \omega\pi^0$ process. (a) The contribution from the $e^+e^- \to$ "V" $\to \omega\pi^0$ process in the VMD model. (b) The contribution from the direct process of γ^* into $\omega\pi^0$.

The energy-dependent width of $\rho(770)$ is given by

$$\Gamma_\rho(s) = \left(\Gamma_\rho(m_\rho^2)\frac{m_\rho^2}{s}\frac{p_\pi^3(s)}{p_\pi^3(m_\rho^2)} + \frac{g_{\rho\omega\pi}^2}{12\pi}p_\omega^3(s)\right)\frac{2m_\rho^2}{m_\rho^2+s}, \tag{4}$$

where $p_\pi(s)$ is the three-momentum of each pion in $\rho(770) \to \pi^+\pi^-$. For the $\rho^{(i)}$ resonances constant widths are used.

The mass and width of $\rho(770)$ are fixed to their PDG values [3]. The $m_{\rho^{(i)}}$ and $\Gamma_{\rho^{(i)}}$ are treated as fitting parameters within the range of 3σ of the values of the analysis results of ref. [11]. The $r = g_{\rho\omega\pi}/f_\rho$, $A_{\rho^{(i)}}$, $A_{\rm dir}$ and $\theta_{\rm dir}$ are the fitting parameters. Each relative phase of $\theta_{\rho^{(i)}}$ is fixed to 0° or 180° in the present analysis.

3. – Results of the analysis

As preliminary results of our analysis, four solutions were found. Obtained values of the parameters are shown in table I. The relative phases of $\rho(1250)$ referred to $\rho(770)$ were obtained to be 180° for all solutions.

The solutions can be classified into two categories: 1) solutions I and II, which have indications of $\rho(1600)$; 2) solutions III and IV, where the contribution of $\rho(1600)$ can be considered negligible. The fit results of solution I and solution III are shown in fig. 2. The statistical significances of each amplitudes in the best solution, solution I, are listed in

Table I. – *Obtained values of the parameters.*

	Solution I	Solution II	Solution III	Solution IV
χ^2/ndf	212.6/117=1.82	215.2/117=1.84	219.3/117=1.87	233.6/117=2.00
$m_{\rho(1250)}$ (MeV)	1330	1344	1312	1343
$\Gamma_{\rho(1250)}$ (MeV)	333	325	333	333
$A_{\rho(1250)}$	6.50×10^{-2}	5.95×10^{-2}	7.79×10^{-2}	7.37×10^{-2}
$\theta_{\rho(1250)}$ (deg)	180	180	180	180
$m_{\rho(1450)}$ (MeV)	1486	1494	1470	1495
$\Gamma_{\rho(1450)}$ (MeV)	276	271	283	283
$A_{\rho(1450)}$	1.10×10^{-1}	1.28×10^{-1}	8.91×10^{-2}	1.02×10^{-1}
$\theta_{\rho(1450)}$ (deg)	180	180	180	180
$m_{\rho(1600)}$ (MeV)	1609	1609	1604	1596
$\Gamma_{\rho(1600)}$ (MeV)	151	151	146	127
$A_{\rho(1600)}$	7.46×10^{-3}	9.38×10^{-3}	$\simeq 0$	$\simeq 0$
$\theta_{\rho(1600)}$ (deg)	180	180	0	0
$m_{\rho(1800)}$ (MeV)	1819	1806	1731	1819
$\Gamma_{\rho(1800)}$ (MeV)	196	284	196	196
$A_{\rho(1800)}$	2.13×10^{-3}	$\simeq 0$	3.67×10^{-3}	3.37×10^{-4}
$\theta_{\rho(1800)}$ (deg)	180	0	0	180
r (GeV $^{-1}$)	3.18	2.92	3.67	3.34
$A_{\rm direct}$ (MeV^2)	7.71×10^{-2}	2.67×10^{-1}	1.85×10^{-1}	2.49×10^{-2}
$\theta_{\rm direct}$ (deg)	318	294	106	30.0

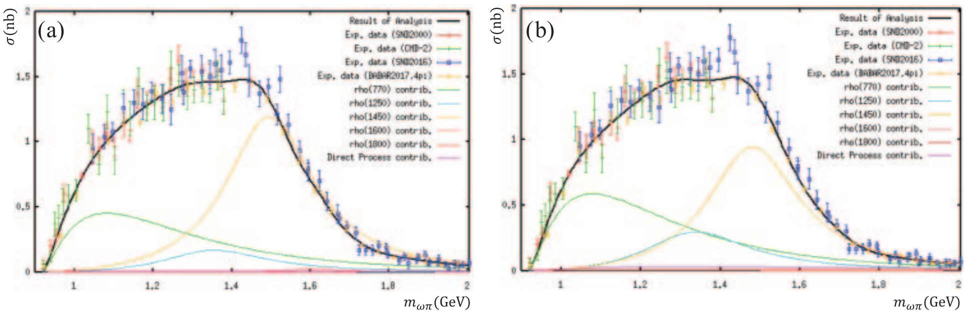

Fig. 2. – (a) and (b) Show the results of analyses for solutions I and II. The green, light blue, brown, pink curves represent the contributions from $\rho(770)$, $\rho(1250)$, $\rho(1450)$ and $\rho(1600)$, respectively. The black curves represent the fit results. The data measured in the process $e^+e^- \to \omega\pi^0 \to \pi^+\pi^-\pi^0\pi^0$ obtained by BABAR are scaled by the appropriate branching ratio.

TABLE II. – *Statistical significance of each amplitude.*

Amplitude	Significance
$\rho(1250)$	4.9σ
$\rho(1450)$	$> 10\sigma$
$\rho(1600)$	1.7σ
$\rho(1800)$	0.74σ
Direct process	1.9σ

table II. The existence of $\rho(1250)$ is confirmed with a significance of 4.9σ. The existence of $\rho(1450)$ is indispensable with a significance greater than 10σ. The $\rho(1600)$ and the direct process are each indicated with a significance of about 2σ. The $\rho(1800)$ is less significant with a significance of 0.7σ.

4. – Summary

We examined whether an isovector vector meson with a mass around 1.26 GeV, identified as $\rho(1250)$, is seen in the $e^+e^- \to \omega\pi^0$ process. It was found with the method of least squares that the cross-section line shape is described well by the coherent sum of five resonant amplitudes of the $\rho(770)$ and four higher-mass ρ-like vector mesons, $\rho^{(1)}$, $\rho^{(2)}$, $\rho^{(3)}$, and $\rho^{(4)}$, around 1.3 GeV, 1.5 GeV, 1.6 GeV, and 1.8 GeV, respectively, together with a nonresonant amplitude for the direct production process. These four resonances correspond to $\rho(1250)$, $\rho(1450)$, $\rho(1600)$, and $\rho(1800)$, which were found between 1 and 2 GeV by Hammound *et al.* [11]. Then, since the fitted mass and width of the $\rho^{(1)}$ resonance were similar to their obtained values, it would be associated with the $\rho(1250)$, which seems to offer further evidence about its existence.

* * *

We would like to express our gratitude to M. Ishida for initiating this work and making significant contributions. We also thank K. Takamatsu and S. Ishida for their crucial discussions from the early stages of this work, which were essential for advancing our research. We are grateful to I. Yamauchi, T. Matsuda and M. Oda for their useful comments and discussions.

REFERENCES

[1] Particle Data Group (Wohl C. G. *et al.*), *Rev. Mod. Phys.*, **56** (1984) S1.
[2] Particle Data Group (Yost G. P. *et al.*), *Phys. Lett. B*, **204** (1988) 1.
[3] Particle Data Group (Workman R. L. *et al.*), *Prog. Theor. Exp. Phys.*, **2022** (2022) 083C01.
[4] Kurdadze L. M. *et al.*, *JETP Lett.*, **37** (1983) 733.
[5] Dolinsky S. I. *et al.*, *Phys. Lett. B*, **174** (1986) 453.
[6] Dolinsky S. I. *et al.*, *Phys. Rep.*, **202** (1991) 99.
[7] Edwards K. W. *et al.*, *Phys. Rev. D*, **61** (2000) 072003.
[8] Achasov M. N. *et al.*, *Phys. Lett. B*, **486** (2000) 29.
[9] Akhmetshin R. R. *et al.*, *Phys. Lett. B*, **562** (2003) 173.
[10] Akhmetshin R. R. *et al.*, *Phys. Lett. B*, **466** (1999) 392.
[11] Hammoud N. *et al.*, *Phys. Rev. D*, **102** (2020) 054029.
[12] SND Collaboration (Achasov M. N. *et al.*), *Phys. Rev. D*, **94** (2016) 112001.
[13] SND Collaboration (Achasov M. N. *et al.*), *Phys. Lett. B*, **486** (2000) 29.
[14] CMD-2 Collaboration (Akhmetshin R. R. *et al.*), *Phys. Lett. B*, **562** (2003) 173.
[15] BABAR Collaboration (Lees J. P. *et al.*), *Phys. Rev. D*, **96** (2017) 092009.