CMD-2 and SND results on the $\rho$, $\omega$ and $\phi$.

M.N. Achasov \textsuperscript{a b} \textsuperscript{*}

\textsuperscript{a}Budker Institute of Nuclear Physics, Siberian Branch of the Russian Academy of Sciences, 11 Lavrentyev, Novosibirsk, 630090, Russia

\textsuperscript{b}Novosibirsk State University, 630090, Novosibirsk, Russia

The review of experimental results of the light vector mesons parameters studies with CMD-2 and SND detectors at VEPP-2M $e^+e^-$ collider in the energy region $360 \leq \sqrt{s} \leq 1380$ MeV is given.

1. Introduction

During the last 35 years the cross section of the $e^+e^-$ annihilation was studied in the energy region $\sqrt{s} \approx 0.4 - 190$ GeV at $e^+e^-$ colliders in CERN, DESY, KEK, SLAC, Cornell, Novosibirsk, Orsay, Frascati, Beijing. The energy range of the VEPP-2M collider (Novosibirsk, BINP SB RAS) \cite{1} lays below 1.4 GeV in the beginning of the energy scale. Besides VEPP-2M, the low energy region were studied in experiments at ACO, DCI (Orsay) and ADONE (Frascati) $e^+e^-$ colliders. The VEPP-2M had finished its operation in year 2000 and now is being reconstructed into VEPP-2000 \cite{2}. At B-factory PEP-II (SLAC) the cross sections of the processes $e^+e^\rightarrow$ hadrons are measured using radiative return method in the energy region from the reactions thresholds up to $\Upsilon(4S)$ mass \cite{3,4}. The $\phi$-factory DAΦNE (Frascati) produces experimental data in the narrow energy region around $\sqrt{s} \simeq 1020$ MeV. The radiative return method is also used there for the cross sections measurements below 1 GeV \cite{5}.

At the VEPP-2M energy region the $e^+e^\rightarrow$ hadrons processes cross sections are described with 1\% accuracy by the vector mesons dominance model (VDM). In the VDM framework the virtual photon transits into the vector meson ($\rho, \omega, \phi$ or their excited states) with quantum numbers $I^G(J^{PC}) = 1^+(1^{--})$ or $0^-(1^{--})$, which in its turn decays to hadrons (fig.1).

Studies of the $e^+e^\rightarrow$ hadrons processes allow to determine parameters of the vector mesons $\rho, \omega, \phi$ and their excitations, provide information about interference between mesons and reactions dynamics.

2. Experiment

From 1995 to 2000 the CMD-2 \cite{6} and SND \cite{7} detectors simultaneously operated at the VEPP-2M $e^+e^-$ collider in the energy range $\sqrt{s}$ from 360 to 1400 MeV. The VEPP-2M luminosity varies in the range from $\sim 10^{30} \text{cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 360$ MeV to $\sim 10^{30} \text{cm}^{-2}\text{s}^{-1}$ at $\sqrt{s} = 1$ GeV. The total integrated luminosity collected by each detector is about 30 pb$^{-1}$.
SND detector contains several subsystems. The tracking system includes two cylindrical drift chambers. The three-layer electromagnetic calorimeter is based on NaI(Tl) crystals. The muon/veto system consists of plastic scintillation counters and two layers of streamer tubes. CMD-2 detector contains tracking system which includes a cylindrical drift chamber and double-layer multiwire proportional chamber (z-chamber). The photons energy and angles are measured by using the barrel CsI and endcap BGO calorimeters installed inside the superconductive solenoid with a 1 T magnetic field. The muon system consists of two layers of streamer tubes. The detailed descriptions of the detectors are given in Ref. [37].

CMD-2 and SND can detect and completely reconstruct events containing both neutral and charged particles.

The experiments were performed using energy scan method. After events reconstruction and analysis the cross section of the process \( e^+e^- \rightarrow \text{hadrons} \) is fitted by theoretical expression:

\[
\sigma = \frac{N}{IL \varepsilon \delta_{rad} \delta_s},
\]

where \( N \) is the process events number, \( IL \) is the integrated luminosity (measured by using reactions with well known cross sections: \( e^+e^- \rightarrow e^+e^- \) and \( \gamma\gamma \)), \( \varepsilon \) is the detection efficiency (obtained from Monte-Carlo simulation), \( \delta_{rad} \) is the radiative correction which takes into account the photons emission by initial and in some cases by final state particles, \( \delta_s \) is the correction due to the beam energy spread.

In order to obtain the vector mesons parameters the measured cross section of the process \( e^+e^- \rightarrow X \), where \( X \) denotes the final hadron system, is fitted by theoretical expression:

\[
\sigma(s) = \frac{4\pi\alpha}{s^{3/2}} \frac{\Gamma_V m_V^3}{P(s)} \sum_{V=\rho, \omega, \phi, ...} \frac{\sigma(V \rightarrow X)}{D_V(s)} e^{iq_V} \left| \frac{\sqrt{\sum_{\omega=\rho, \omega, \phi, ...} \Gamma_{\omega} m_{\omega} \sigma(V \rightarrow \omega)}}{P(m_{\omega})} \right|^2.
\]

Here \( P_X(s) \) is a phase space factor including dynamics of the vector meson transition to the final state, \( m_V \) and \( \Gamma_V \) are the meson mass and full width, \( \sigma(V \rightarrow X) = 12\pi B(V \rightarrow X) B(V \rightarrow e^+e^-)/m_V^2, D_V(s) \) is the vector meson \( V \) propagator, \( \phi_V \) is the interference phase. The parameters \( m_V, \Gamma_v \), \( B(V \rightarrow e^+e^-), \phi_V \) are obtained form the fit.

CMD-2 and SND experiments have obtained quite important results on the \( \rho, \omega, \phi \) rare decays (relative probabilities less than \( 10^{-3} \)). The well known decays \( \rho \rightarrow \pi^0\gamma \) [33,34], \( \rho \rightarrow \eta\gamma \) [9,10,11,12], \( \omega \rightarrow \pi^0\pi^0\gamma \) [13,14,15], \( \phi \rightarrow \pi^+\pi^-\gamma \) were also studied. The eight decays \( \phi \rightarrow f_0\gamma \) [17,18,19,22,23], \( \phi \rightarrow a_0\gamma \) [20,21,22], \( \phi \rightarrow \eta\gamma \) [24,25,26,27,28], \( \phi \rightarrow \omega\eta \) [29,30,31], \( \phi \rightarrow \pi^+\pi^-\pi^0\pi^- \) [32], \( \rho \rightarrow \pi^0\pi^0\pi^0 \) [31,33], \( \rho \rightarrow \pi^+\pi^-\pi^0 \) [33] were observed for the first time. In this paper the vector mesons main decays and parameters studies are reviewed.

3. Cross sections of \( e^+e^- \rightarrow \text{hadrons annihilation} \)

The \( e^+e^- \rightarrow \pi^+\pi^- \) cross section in the VEPP-2M energy region measured in various experiments [36,37,38,39,10,11,12,13,14,15] is shown in fig. 2. For the data description the \( \rho, \omega, \rho' \) mesons are required. The CMD-2 data have 0.6 – 0.8 % systematic error below and 1.2 – 4.2 % above 1 GeV. SND measured the cross section below 1 GeV with accuracy 1.3 – 3.4 %. SND and CMD-2 results are in agreement with each other and with the CMD and OLYA measurements. However they are in conflict with KLOE measurement.

The \( e^+e^- \rightarrow \pi^+\pi^-\pi^0 \) process was studied with SND in the energy region \( \sqrt{s} \) from 600 to 1380 MeV [34,41,45,46] (fig. 3). The curve is the result of the fit taking into account \( \omega, \phi, \rho, \omega' \) and \( \omega'' \). The systematic accuracy of the measurement is 3.4 - 5.4 %. In experiments at VEPP-2M the clear evidence of the broad resonance structure at \( \sqrt{s} = 1100 - 1400 \) MeV, which is identified as \( \omega' \) resonance, was obtained. SND measurements were confirmed by BABAR radiative return method result [3]. The \( e^+e^- \rightarrow \rho\pi \rightarrow \pi^+\pi^-\pi^0 \) transition dominates in this reaction [15,16,17]. In the energy region above the \( \phi \)-meson mass the transition \( e^+e^- \rightarrow \omega\pi^0 \rightarrow \)
\[\pi^+\pi^-\pi^0,\] predicted in Ref. [49], was observed and studied [46]. The intermediate state different from these two (maybe \(e^+e^-\rightarrow \rho^0\pi^0\)) was observed by KLOE and CMD-2 in the \(\phi\)-meson energy region [48,50]. CMD-2 has reported \(\Delta\) and \(\gamma\) decays [36] and KLOE [5] data are shown.

CMD-2 and SND measured the cross sections of the \(e^+e^-\rightarrow \pi^0\gamma\) and \(e^+e^-\rightarrow \eta\gamma\) processes. The systematic errors of the CMD-2 and SND measurements of the \(e^+e^-\rightarrow \pi^0\gamma\) cross section are 6\% and 3\% respectively [9,10,11,12,13,14,15,16,17]. The energy dependence of the cross section (fig.5) is described by \(\rho,\omega,\phi\) mesons contributions. The \(e^+e^-\rightarrow \eta\gamma\) process was studied by using events with the \(\eta\rightarrow \pi^0\pi^0\pi^0,\pi^+\pi^-\pi^0,\gamma\gamma\) decays [9,10,11,12,13,14,15,16,17]. The systematic errors depend on energy and at the \(\phi\)-meson region they are about 3-7\%. The cross section energy dependence is shown in fig.6. For the data description the \(\phi,\rho,\omega,\rho'\) resonances are needed.

The \(e^+e^-\rightarrow K^+K^-\) process cross section measured by SND [14,15], CMD-2 [51,52] and OLYA [59] in the energy region \(\sqrt{s}\) below 1380 MeV is shown in fig.7. In the energy region \(\sqrt{s} > 1060\) MeV the SND and CMD-2 data are preliminary.

The systematic accuracies of the CMD-2 and SND measurements in the \(\phi\)-meson energy range are 3-4\% and 7\% respectively.

The \(e^+e^-\rightarrow K_S K_L\) cross section was measured by using \(K_S\rightarrow \pi^0\pi^0\) and \(\pi^+\pi^-\) decays. The cross section measured by SND [14] and CMD-2 [60,61] in the vicinity of the \(\phi\)-meson (fig.8) has systematic errors 3.3\% and 1.7\% respectively. The results of different experiments are in agreement. The measurements above \(\phi\)-meson were reported by SND and CMD-2 in Ref. [12,61,62].

The \(e^+e^-\rightarrow K\bar{K}\) data near the \((1020)\)-meson peak can be described by taking into account the \(\phi,\rho,\omega\) amplitudes only. The \(\rho\) and \(\omega\) coupling constants agree with the naive quark model predictions. At higher energies the \(\phi'\) contribution should be added to the reactions amplitudes.

The \(e^+e^-\rightarrow \pi^+\pi^-\pi^+\pi^-\) and \(e^+e^-\rightarrow \pi^+\pi^-\pi^0\pi^0\) processes have the largest cross sections in the energy region \(\sqrt{s} > 1\) GeV. The CMD-2 [53] and CLEO-2 [54] had shown that in the VEPP-2M energy region in the \(e^+e^-\rightarrow \pi^+\pi^-\pi^+\pi^-\) process the \(\rho\pi\pi\) and in the \(e^+e^-\rightarrow \pi^+\pi^-\pi^0\pi^0\) the \(\rho\pi\pi\) and \(\omega\pi\pi\) mechanisms are dominant. Moreover the dynamics of the \(e^+e^-\rightarrow \rho\pi\pi\) reaction can be described with \(a_1\pi\) intermediate state. The SND analysis confirmed these
Figure 4. The $e^+e^- \rightarrow \pi^+\pi^-\pi^0$ cross section measured by SND [44,46,34]. The curve is the fit with the $\omega, \phi, \rho, \omega', \omega''$ resonances.

Figure 5. The $e^+e^- \rightarrow \pi^0\gamma$ cross section. The SND (*) [12] and CMD-2 (●) [9] data are shown.

Figure 6. The $e^+e^- \rightarrow \eta\gamma$ cross section. The SND (*) [12] and CMD-2 (●) [9] data are shown.

Figure 7. The $e^+e^- \rightarrow K^+K^-$ cross section. The OLYA (○) [59], SND (*) [44,12] and CMD-2 (●) [51,58] data are shown.

Figure 8. The $e^+e^- \rightarrow K_SK_L$ cross section. The SND (*) [11] and CMD-2 (●) [60] are shown.

Figure 9. The $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ cross section. The DM2 (○) [66], SND (*) [65], CMD-2 (●) [67] and BABAR (□) [4] data are shown.
conclusions. The $e^+e^- \rightarrow \pi^+\pi^-\pi^+\pi^-$ cross section measured by DM2, SND, CMD-2 and BABAR is shown in Fig. The results agree with each other. The $e^+e^- \rightarrow \omega\pi^0$ was steadied in two final states $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^+\pi^-\pi^0\pi^0$ and $e^+e^- \rightarrow \omega\pi^0 \rightarrow \pi^0\pi^0\pi^0\gamma$ by both SND and CMD-2. These results are in agreement also.

The fit to the experimental data shows that within the measurement accuracy the $e^+e^- \rightarrow hadrons$ cross sections can be described by VDM taking into account $\rho, \omega, \phi$-mesons and their excited states $\rho', \omega', \phi', \ldots$.

4. Light vector mesons parameters

The parameters of the light vector mesons $\rho, \omega, \phi$ (Tab. 1) were extracted from the measured cross sections. The CMD-2 and SND averaged values together with the results of the other measurements are shown in Tab. 1. The $\rho$-meson parameters were obtained from the study of the $e^+e^- \rightarrow \pi^+\pi^-\pi^0\pi^0\gamma$ and $\pi^+\pi^-\pi^0\pi^0$ processes cross sections analysis. The results of the CMD-2 and SND have accuracy comparable or better than the other experiments. In particular, the accuracy of the $G$-parity suppressed decay $\omega \rightarrow \pi^+\pi^-\pi^0$ was improved by factor 3.

The accuracy of the parameters $B(\phi \rightarrow e^+e^-)B(\phi \rightarrow \eta\gamma)$ and $B(\phi \rightarrow e^+e^-)B(\phi \rightarrow K_SK_L)$ was improved also. Using the CMD-2 and SND results the $B(\phi \rightarrow e^+e^-) = (2.90 \pm 0.04) \times 10^{-4}$ was obtained. This value deviates from the KLOE result $B(\phi \rightarrow e^+e^-) = (3.10 \pm 0.05) \times 10^{-4}$ by three standard deviations.

The light vector mesons $\rho, \omega, \phi$ are studied rather well. About $\omega', \rho', \phi', \ldots$ we know with certainty that such resonances exist. However their parameters are not well established and their nature is not clear due to poor accuracy of experimental data, large width of these states and model uncertainty in their description. The pa-

| $\rho$-parameters | CMD-2 | SND |
|-------------------|-------|-----|
| $\Gamma(\rho^0, \rho^+\rho^-)$, MeV | 0.07 | 0.08 |
| $G(\rho^0, \rho^+\rho^-)$, keV | 715.0 | 782.8 |
| $\Gamma(\rho^0, \rho^\to\pi^+\pi^-\pi^0\pi^0\gamma)$, MeV | 2.90 | 3.10 |
| $\Gamma(\rho^0, \rho^\to\pi^+\pi^-\pi^0\pi^0$ | 3.10 | 3.00 |

Table 1. The average values of the $\rho, \omega, \phi$-mesons parameters measured by CMD-2 and SND in comparison with other experimental results.
The cross section of the $\omega'$ and $\omega''$ were measured in the energy region $|\omega| \approx 10$ times higher than analogous values for $\omega$. The $\omega'$ and $\omega''$ were estimated from combined analysis of the $e^+e^-\rightarrow \pi^+\pi^-\pi^0$ process cross section measured by SND and of the DM-2 data on the $e^+e^-\rightarrow \omega\pi\pi$ reaction (Tab. 2).

Using the leptonic widths obtained from the fit the following ratios can be obtained in the framework of the nonrelativistic quark model:

$$\frac{|\Psi_S^S(0)|^2}{|\Psi_S^S(0)|^2} = \left(\frac{m_{\omega'}}{m_{\omega}}\right)^2 \cdot \frac{\Gamma(\omega'\rightarrow e^+e^-)}{\Gamma(\omega\rightarrow e^+e^-)} \sim 4,$$

and

$$\frac{|\Psi_S^{S''}(0)|^2}{|\Psi_S^{S''}(0)|^2} = \left(\frac{m_{\omega''}}{m_{\omega}}\right)^2 \cdot \frac{\Gamma(\omega''\rightarrow e^+e^-)}{\Gamma(\omega'\rightarrow e^+e^-)} \sim 5,$$

where $\Psi_S^S(0)$ is the radial wave function of the $q\bar{q}$ bound state at the origin. These ratios are about 10 times higher than analogous values for the $\sigma$ and $b\bar{b}$ states:

$$|\Psi_S^{S}(S^2S)(0)/\Psi_S^{S}(S^2S)(0)|^2 \approx 0.57, |\Psi_S^{S}(S^2S)(0)/\Psi_S^{S}(S^2S)(0)|^2 \approx 0.44,$$

$$|\Psi_S^{S}(S^2S)(0)/\Psi_S^{S}(S^2S)(0)|^2 \approx 0.43.$$ These results can indicate to the unusual nature of the $\omega'$, $\omega''$. More precise data and deeper analysis are required however, to draw final conclusions.

### 5. Conclusion

In the 1995-2000 the experiments with CMD-2 and SND detectors at VEPP-2M were fulfilled. The cross section of the $e^+e^-\rightarrow \pi^+\pi^-\pi^0$ annihilation in hadrons were measured in the energy region $\sqrt{s} = 360 - 1380$ MeV. Results of these experiments determine nowadays the accuracy of the light vector mesons parameters determination. They are one of the main source of information about particle physics at low energies.

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### Table 2

The $\omega'$ and $\omega''$ parameters obtained from the SND and DM-2 data analysis.

| $V$ | $m_V$, MeV | $\Gamma_V$, MeV | $\sigma(V \rightarrow 3\pi)$, nb | $\sigma(V \rightarrow \omega\pi\pi)$, nb | $\Gamma(V \rightarrow e^+e^-)$, |
|-----|------------|-----------------|-------------------------------|---------------------------------|-----------------------------|
| $\omega'$ | $1400 \pm 50 \pm 130$ | $870 \pm 390 \pm 450$ | $4.9 \pm 1.0 \pm 1.6$ | $\sim 570$ | 
| $\omega''$ | $1770 \pm 50 \pm 60$ | $490 \pm 390 \pm 130$ | $5.4 \pm 2.0 \pm 3.9$ | $1.9 \pm 0.4 \pm 0.6$ | $\sim 860$ |
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