Study of the process $e^+e^- \to K\overline{K}$ in the center-of-mass energy range 1004–1060 MeV with the CMD-3 detector at e^+e^- VEPP-2000 collider. *

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Abstract: The $e^+e^- \to K^0_S K^0_L$ and $e^+e^- \to K^-K^+$ cross sections have been measured in the center-of-mass energy range 1004–1060 MeV for 25 energy points with about 2÷3% systematic uncertainties. The analysis is based on 5.5 pb^{-1} of integrated luminosity collected with the CMD-3 detector at the VEPP-2000 e^+e^- collider. The measured cross section is approximated according to Vector Meson Dominance model as a sum of ϕ,ω,ρ-like amplitudes and their excitations, and $\phi(1020)$ meson parameters have been obtained.

Key words: hadrons, electron positron collider, kaon form factor

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1 Introduction

Investigation of e^+e^- annihilation into hadrons at low energies provides unique information about interaction of light quarks. Precise measurement of the $e^+e^- \to K\overline{K}$ cross section allows to study properties of the light vector mesons with J$^{PC} = 1^{--}$, and is required for the precise calculation of strong interaction contributions to (g-2)$_\mu$ and α(M$_Z$) values [1]. A significant deviation of coupling constants ratio $\frac{g_{\phi\to K^+K^-}}{g_{\phi\to K_S K_L}}$ from a theoretical prediction requires new comprehensive measurement of the cross sections [2].

The most precise previous study of the process has been performed by the CMD-2 [3, 4], SND [5] and BaBar [6, 7] detectors. In this paper we present new measurement of the $e^+e^- \to K^0_S K^0_L$ and $e^+e^- \to K^-K^+$ cross section, characterized by statistical advantage and performed in the center-of-mass energy $E_{c.m.}$ range 1004–1060 MeV at 25 energy points. Also the paper contains the results of the cross section interpretation according to the Vector Meson Dominance (VMD) model.

2 CMD-3 detector and data set

The Cryogenic Magnetic Detector (CMD-3) is installed in one of two interaction regions of VEPP-2000 collider [8], and is described elsewhere [9]. The detector tracking system consists of the cylindrical drift chamber (DC) and double-layer cylindrical multiwire proportional Z-chamber, both used for a trigger, and both are installed inside thin (0.2 X_0) superconducting solenoid with 1.3 T field. DC contains 1218 hexagonal cells and allows to measure charged particle momentum with 1.5-4.5% accuracy in the 100-1000 MeV/c range, and provides the

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measurement of the polar (θ) and azimuth (ϕ) angles with 20 mrad and 3.5-8.0 mrad accuracy, respectively. An amplitude information from the DC wires is used to measure the ionization losses dE/dx of charged particles with $\sigma_{dE/dx}$ ≈11-14% accuracy for minimun ionization particles (m.i.p.). A barrel liquid xenon (LXe) with 5.4 X_0 and CsI crystal with 8.1 X_0 electromagnetic calorimeters are placed outside the solenoid. The BGO crystals with 13.4 X_0 are used as the end-cap calorimeters. Return yoke of the detector is surrounded by the scintillation counters, which are required for cosmic events veto.

To study a detector response to investigated processes and obtain a detection efficiency, we have developed a Monte Carlo (MC) simulation of our detector based on GEANT4 [10] package, and all simulated events pass all our reconstruction and selection procedures. The MC simulation includes photon jet radiation by initial electron or positron, calculated according to Ref. [11].

The analysis is based on 5.5 pb^{-1} of integrated luminosity, collected in two scans of $\phi(1020)$ resonance region at 25 energy points in the $E_{c.m.}$=1004–1060 MeV range.

The beam energy E_{beam} has been monitored by using the Back-Scattering-Laser-Light system [12] which determines $E_{c.m.}$ at each energy point with about 0.06 MeV accuracy.

3 $e^+e^- \to K\overline{K}$ event selection

At energies under study K_S^0-meson can be produced only simultaneously with K_L^0-meson. So, signal identification of the process $e^+e^- \to K_S^0K_L^0$ is based on the detection of two pions from the $K_S^0 \to \pi^+\pi^-$ decay. The following requirements are applied to the events with found K_S^0 candidate:

• The longitudinal and transverse distances of the vertex position are required to have $|Z_{K_S^0}| < 10$ cm and $|\rho_{K_S^0}| < 6$ cm, respectively;

• Each track has momentum $130 < P_{\pi^\pm} < 320$ MeV/c corresponding to the kinematically allowed region for pions from the K_S^0 decay;

• Each track has the ionization losses $dE/dx_{\pi^\pm} < dE/dx_{m.i.p} + 3\times\sigma_{dE/dx_{m.i.p.}}$ to reject charged kaons and background protons. The last two requirements are illustrated in Fig. 1 by lines for all detected tracks at the energy point $E_{beam} = 505$ MeV;

• The total reconstructed momentum of the K_S^0 candidate, $P_{K_S^0}$, is required to be within five standard deviations from the norminal momentum at each energy point;

We determine number of signal events for data and simulation by approximation of two pion invariant mass, shown in the Fig. 2, by a sum of signal and background profiles. The signal shape is described by the sum of three Gaussian functions with parameters fixed from the simulation, but with additional gaussian smearing to account for the detector response. A background, predominantly caused by collider processes $e^+e^- \to \pi^+\pi^-2\pi^0, 4\pi^\pm, 3\pi, K^+K^-$ and cosmic muons, is described by second order polynomium function, and is presented in both data and MC-simulation. The background in simulation corresponds to tails of signal with wrong reconstructed parameters of pions. By varying shapes of the functions used, we estimate uncertainty in number of extracted signal events not more than 1.1%.

The detection efficiency $\epsilon(K_S^0K_L^0)$ is obtained by dividing number of MC simulated events after reconstruction and selections described above, to total number of generated $K_S^0K_L^0$ pairs. Figure 3 shows the obtained detection efficiency (squares) vs c.m. energy. The energy behavior as well as the absolute value (≈ 35%) is predominantly due to pions polar angle selection criterion.

The detection of the charged mode ($e^+e^- \to K^-K^+$) is based on the search of two central collinear tracks of kaons in DC with defined momentums approximately equaled to $\sqrt{E_{c.m.}^2/4 - m_{K^+}^2}$ with accuracy of detector resolution. Additional selection exploits that kaon track has ionization losses significantly larger than the ones of m.i.p. due to relatively small velocity of kaons under study $\beta = 0.2$-0.4 (see the Fig. 1). The level of remaining background is less than 0.5 %.

The collinear configuration of the process allows to test MC simulation by the determination of the efficiencies of each kaons in data as well as in MC. The experimental efficiencies of single positive and negative tracks ($\varepsilon(K^+)$, $\varepsilon(K^-)$) are shown by triangles in the Fig. 3 and increases from 78% to 90% across the energy region under study. The deviation of efficiencies of single tracks in data from MC is less then 1%. Circles in the figure corresponds to total simulated detection efficiency ($\varepsilon(K^+K^-)$) of K^+K^- final state, that is constituted by geometrical efficiency due to polar angle selection (≈ 73%) as well as by the values of $\varepsilon(K^+)$, $\varepsilon(K^-)$.

4 Cross section of $e^+e^- \to K\overline{K}$ and systematic uncertainties

The experimental Born cross section of the $e^+e^- \to K\overline{K}$ process has been calculated for each energy point according to the expression:

$$\sigma^{born} = \frac{N_{exp}}{\epsilon_{reg}\epsilon_{trig}L(1+\delta_{rad})}\delta^{en.disper.}, \qquad (1)$$

where ϵ_{reg} is a detection efficiency, ϵ_{trig} is a trigger efficiency, L is the integrated luminosity, $1+\delta_{rad}$ is a radiative correction, and $\delta^{en.disper.}$ represents a correction due to the energy dispersion of the electron-positron beams.

The trigger efficiency is studied using responses of

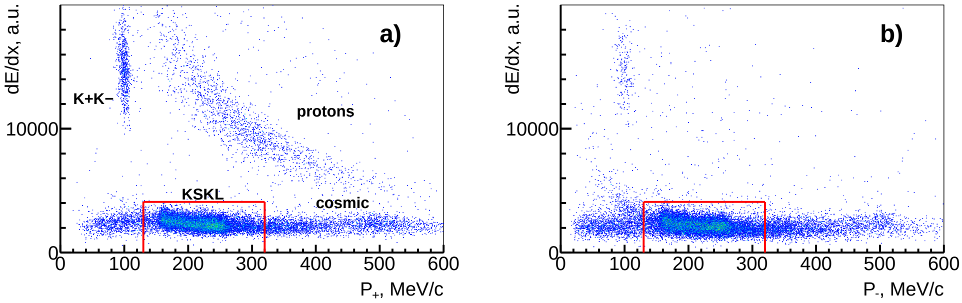

Fig. 1. The ionization losses vs momentum for positive (a) and negative (b) tracks for data at $E_{beam} = 505$ MeV. Lines show selections of pions from the K_S^0 decay.

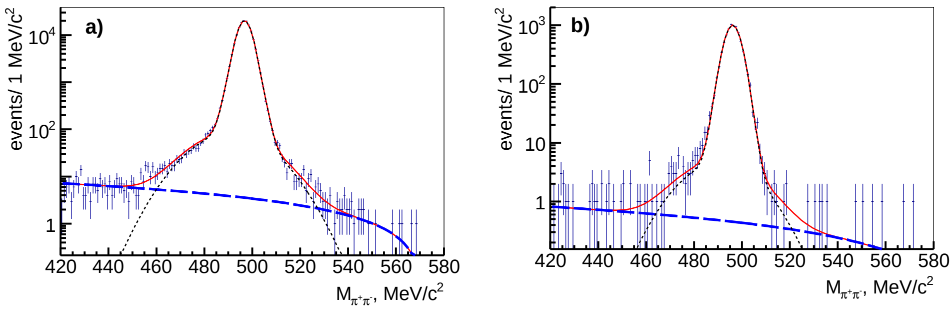

Fig. 2. The approximation of the invariant mass (solid line) of two pions at the beam energy 505 MeV for simulation (a) and data (b). The short dotted line corresponds to a signal profile, the long dotted line is for the background.

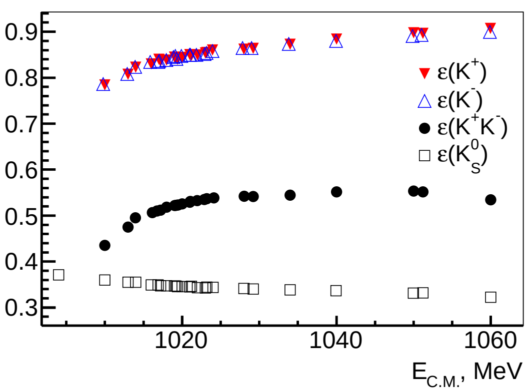

Fig. 3. The detection efficiency vs energy from simulation; The efficiencies of single traks of charged kaons ($\varepsilon(K^+)$, $\varepsilon(K^-)$); The efficiency of both kaons detection ($\varepsilon(K^+K^-)$) - circles; The efficiency of K_S-meson ($\varepsilon(K_S^0)$) - squares.

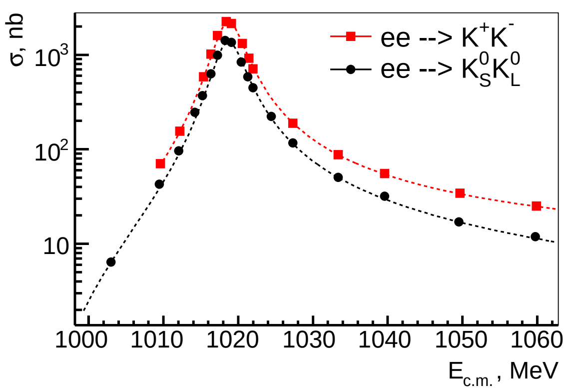

Fig. 4. Preliminary results of measurement of the $e^+e^- \to K^+K^-$ and $e^+e^- \to K_S^0K_L^0$ cross sections near the $\phi(1020)$ peak at CMD-3.

Table 1. Summary of systematic errors in the $e^+e^- \to K\overline{K}$ cross section measurement

source systematic error	$e^+e^- \to K_S^0 K_L^0$	$e^+e^- \to K^+K^-$
signal extraction	1.1	0.3
detection efficiency	1.0	3
radiative correction	0.3	0.3
energy dispersion correction	0.3	0.3
trigger efficiency	0.1	0.1
luminosity	1.0	1.0
total	1.8	3.2

two independent triggers, charged and neutral, for selected signal events, and is found to be close to unity $\epsilon_{trigg} = 0.998 \pm 0.001$. The integrated luminosity L is determined by the processes $e^+e^- \to e^+e^-$ and $e^+e^- \to \gamma\gamma$ with about 1% [15] accuracy. The initial state radiative correction $1+\delta_{rad}$ is calculated using structure function method with accuracy better than 0.3% [13]. The dispersion of the electron-positron c.m. energy is about 300 keV, significant in comparison with the width of ϕ meson, and we introduce the correction of the cross section, which has maximum value of 1.028 ± 0.007 for both channel in the peak of ϕ resonance. The resulting cross sections are shown in Fig. 4.

The uncertainty in $e^+e^- \to K_S^0 K_L^0$ cross section is dominated by signal extraction procedure used two pion mass approximation (Fig. 2). Moreover, MC simulation doesn't exactly reproduce all detector responses, and we perform additional study to obtain corrections for data-MC difference in the detection efficiency. We observe good data-MC agreement for the charged pion detection inefficiency ($\approx 1\%$), introduce no efficiency correction, and estimate uncertainty in the detection as 0.5%. By variation of corresponding selection criteria we estimate uncertainty due to the data-MC difference in the angular and momentum resolutions as 0.4%, and other selection criteria contribute 0.5%.

The uncertainty in $e^+e^- \to K^+K^-$ cross section is dominated by not exact knowledge of angular acceptance of kaons. This systematic uncertainty (3%) are examined using Z-chamber which surrounds DC. Unlike pions in neutral channel the charged pair of kaons have much more ionization losses and collinear configuration that leads to strong correlation in detector response to charged kaons tracks.

The systematic errors of the $e^+e^- \to K_S^0 K_L^0$ and $e^+e^- \to K^+K^-$ cross sections measurement, discussed above, are summarized in Table 1, and in total estimated as 1.8% and 3.2% respectively.

5 Cross section interpretation

Our data in the studied energy range allows to obtain $\phi(1020)$ parameters with good accuracy. We approximate the energy dependence of the cross section according to a vector meson dominance (VMD) model as a sum of ϕ, ω, ρ-like amplitudes [16]:

$$\sigma_{e^+e^-\to K\overline{K}}(s) = \frac{8\pi\alpha}{3s^{5/2}} p_K^3 \frac{Z(s)}{Z(m_{\phi^2})} \left| \frac{g_{\phi\gamma} g_{\phi KK}}{D_\phi(s)} \pm \frac{g_{\rho\gamma} g_{\rho KK}}{D_\rho(s)} + \frac{g_{\omega\gamma} g_{\omega KK}}{D_\omega(s)} + A_{\phi',\rho',\omega'} \right|^2, \quad (2)$$

where $s = E^2_{c.m.}$, p_K is a kaon momentum, Z(s) $= 1 + \frac{\pi\alpha}{2\beta}$ - the Sommerfeld-Gamov-Sakharov factor for charged kaons with velocity $\beta = \sqrt{1-4m_K/s}$, $D_V(s) = m_V^2 - s - i\sqrt{s}\Gamma_V(s)$, m_V, and Γ_V are mass and width of major intermediate resonances: $V = \rho(770), \omega(782), \phi(1020)$. The sign before ρ-amplitude is plus for charged channel and minos for neutral one due to quark structure of kaons and ρ-meson. The energy dependence of the decay width is expressed via sum of branching fractions and phase space energy dependence $P_{V\to f}(s)$ of all decay modes as (see [5, 16]):

$$\Gamma_V(s) = \Gamma_V \sum_{V\to f} B_{V\to f} \frac{P_{V\to f}(s)}{P_{V\to f}(m_V^2)}.$$

The coupling constants of the intermediate vector meson V with initial and final states can be presented as:

$$g_{V\gamma} = \sqrt{\frac{3m_V^3 \Gamma_{Vee}}{4\pi\alpha}};\ g_{VK\overline{K}} = \sqrt{\frac{6\pi m_V^2 \Gamma_V B_{VK\overline{K}}}{p_K^3(m_V)}},$$

where Γ_{Vee} and $B_{VK\overline{K}}$ are electronic width and decay branching fraction to pair of kaons.

In our approximation we use table values of mass, total width, and electronic width of $\rho(770)$ and $\omega(782)$: $\Gamma_{\rho\to ee} = 7.04 \pm 0.06$ keV, $\Gamma_{\omega\to ee} = 0.60 \pm 0.02$ keV [17]. The branching fractions of $\rho(770)$ and $\omega(782)$ to pair of kaons unknown, and we use the relation $g_{\omega K_S^0 K_L^0} = -g_{\rho K_S^0 K_L^0} =$

$g_{\phi K^0_S K^0_L}/\sqrt{2}$, based on the quark model with "ideal" mixing and exact SU(3) symmetry of u-,d-,s-quarks [16]. In order to take into account possible breaking of the assumption both $g_{\rho K^0_S K^0_L}$ and $g_{\phi K^0_S K^0_L}$ are multiplied to the union constant $r_{\rho/\omega}$.

The amplitude $A_{\phi',\rho',\omega'}$ denotes a contribution of excited $\omega(1420)$, $\rho(1450)$ and $\phi(1680)$ vector meson states to the $\phi(1020)$ mass region. Using BaBar [6, 7] data above 1.06 GeV for the $e^+e^- \to K^0_S K^0_L$ and $e^+e^- \to K^+K^-$ reactions we fix the contribution of higher energy states.

We fit the cross sections of $e^+e^- \to K^0_S K^0_L$ and $e^+e^- \to K^+K^-$ with float m_ϕ, Γ_ϕ, $\Gamma_{\phi\to e^+e^-} \times B_{\phi\to K^0_S K^0_L}$, $\Gamma_{\phi\to e^+e^-} \times B_{\phi\to K^+K^-}$ and $g_{\rho/\omega}$ parameters. The obtained fit is shown in the Fig. 4 with the following parameters, which contain statistical errors as well as systematic and model-dependent uncertainties:

$$\begin{aligned} m_\phi &= 1019.464 \pm 0.060 \text{ MeV/c}^2 \\ \Gamma_\phi &= 4.247 \pm 0.015 \text{ MeV} \\ \Gamma_{\phi\to ee} B_{\phi\to K^0_S K^0_L} &= 0.429 \pm 0.009 \text{ keV} \\ \Gamma_{\phi\to ee} B_{\phi\to K^+K^-} &= 0.679 \pm 0.022 \text{ keV} \\ r_{\rho/\omega} &= 0.76 \pm 0.11 \\ g_{V\to K^+K^-}/g_{V\to K^0_S K^0_L} &= 0.995 \pm 0.035 \end{aligned} \quad (3)$$

The difference of charged and neutral cross-sections for 24 energy points defined as $R_{c/n} = \sigma_{e^+e^-\to K^+K^-} \times \frac{p^3_{K^0}(s)}{p^3_{K^\pm}(s)} \times \frac{1}{Z(s)} - \sigma_{e^+e^-\to K^0_S K^0_L}$ is shown in Fig. 5. The difference $R_{c/n}$ is predominantly caused by interference term of resonance amplitudes of ϕ-meson and isovector ρ-meson. Shaded area corresponds to 1.8% and 3.2% systematic uncertainties in data for neutral and charged channel respectively. The result of discussed above fit is shown by solid line that leads to agreement $\chi^2 = 37$. It should be mentioned that the case with $A_{\phi',\rho',\omega'} = 0$ and naive theoretical prediction $g_{V\to K^+K^-} = g_{V\to K^0_S K^0_L}$, $r_{\rho/\omega}$ = 1 also gives an adequate description of experimental $R_{c/n}$. This case is characterized by $\chi^2 = 51$ and shown by short dotted line, while long dotted lines correspond to the same theoretical prediction with $r_{\rho/\omega}$ = 0.5 or 1.5 and strongly differ from data.

6 Conclusion and acknowledgements

Using pions from the $K^0_S \to \pi^+\pi^-$ decay and collinear charge kaons in DC we observe 6.5×10^5 and 1.6×10^6 events of the $e^+e^- \to K^0_S K^0_L$ and $e^+e^- \to K^+K^-$ processes respectively in the 1004–1060 MeV c.m. energy range, and measure its cross section with 1.8÷3.2% systematic error. Using VMD model the parameters of ϕ-meson are preliminary measured (3). The obtained deviation of ρ, ω amplitudes from naive theoretical prediction $r_{\rho/\omega} = 0.76\pm0.11$ allows to estimate the precision of used VMD-based phenomenological model as 25 %. Moreover, obtained ratio $g_{V\to K^+K^-}/g_{V\to K^0_S K^0_L} = 0.995\pm0.035$ demonstrates the precision of SU(2)-symmetry better than 3.5 %.

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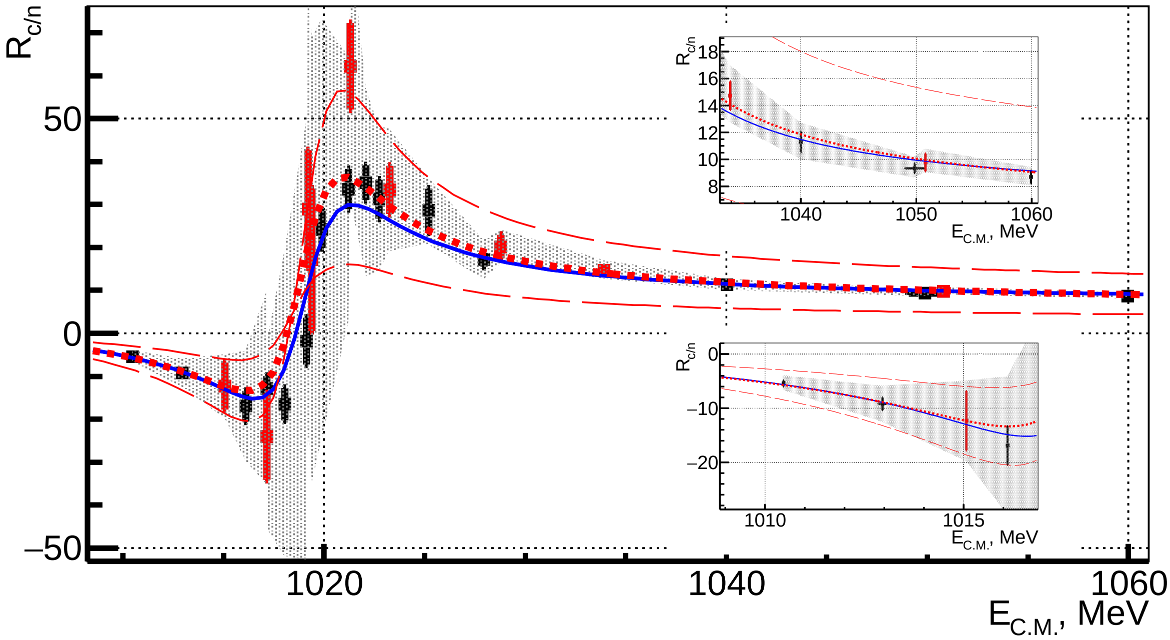

Fig. 5. The difference of charged and neutral cross-sections defined as $R_{c/n} = \sigma_{e^+e^-\to K^+K^-} \times \frac{p^3_{K^0}(s)}{p^3_{K^\pm}(s)} \times \frac{1}{Z(s)} - \sigma_{e^+e^-\to K^0_S K^0_L}$. Shaded area corresponds to systematic uncertainties in data, solid line - to fit of data, short dotted line - to theoretical prediction with $A_{\phi',\rho',\omega'} = 0$, $g_{V\to K^+K^-}/g_{V\to K^0_S K^0_L} = 1$ and $r_{\rho/\omega} = 1$ while long dotted lines - to the same theoretical prediction with $r_{\rho/\omega} = 0.5$ (1.5).