Study of the process $e^+e^- \rightarrow K^0_LK^0_S$ in the c.m. energy range 1.05–1.38 GeV with CMD-2

R.R. Akhmetshin a, V.M. Aulchenko a,b, V.Sh. Banzarov a, L.M. Barkov a,b, S.E. Baru a, N.S. Bashtovoy a, A.E. Bondar a,b, D.V. Bondarev a, A.V. Bragin a, S.K. Dhawan c, S.I. Eidelman a,b, D.A. Epifanov a,b, G.V. Fedotovich a,b, N.I. Gabyshev a, D.A. Gorbachev a,b, A.A. Grebeniuk a, D.N. Grigoriev a,b, V.W. Hughes c, F.V. Ignatov a,b, S.V. Karpov a, V.F. Kazanin a,b, B.I. Khazin a,b, I.A. Koop a,b, P.P. Krokovny a,b, A.S. Kuzmin a,b, I.B. Logashenko a, P.A. Lukin a, A.P. Lysenko a, K.Yu. Mikhailov a, I.N. Nesterenko a,b, V.S. Okhapkin a, A.V. Pak a,b, A.A. Polunin a, A.S. Popov a, B.L. Roberts d, N.I. Root a, A.A. Ruban a, N.M. Ryskulov a, A.G. Shamov a, Yu.M. Shatunov a, B.A. Shwartz a,b, A.L. Sibidanov a,b, V.A. Sidorov a, A.N. Skrinsky a, I.G. Snopkov a, E.P. Solodov a,b, P.Yu. Stepanov a, A.I. Sukhanov a, J.A. Thompson e, Yu.V. Yudin a, S.G. Zverev a

a Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia
b Novosibirsk State University, Novosibirsk 630090, Russia
c Yale University, New Haven, CT 06511, USA
d Boston University, Boston, MA 02215, USA
e University of Pittsburgh, Pittsburgh, PA 15260, USA

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Abstract

The process $e^+e^- \rightarrow K^0_LK^0_S$ has been studied with the CMD-2 detector using about 950 events detected in the center-of-mass energy range from 1.05 to 1.38 GeV. The cross section exceeds the expectation based on the contributions of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons only.

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E-mail address: p.a.lukin@inp.nsk.su (P.A. Lukin).
1. Introduction

The investigation of the process $e^+e^- \rightarrow K^0_L K^0_S$ is important for a number of physics problems. Since both $I = 0$ and $I = 1$ vector mesons can decay into a kaon pair, one can search for excitations of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ by measuring the cross section of the process in the energy range above the $\phi(1020)$ meson [1]. The isovector part of the cross section of the process $e^+e^- \rightarrow K\bar{K}$ (both $K^+K^-$ and $K^0_L K^0_S$ final states should be taken) can be related to the $\tau^- \rightarrow K^-K^0\nu_e$ decay by using conservation of vector current [2]. Assuming the hypothesis of factorization it can be also used to account for the contribution of vector current [2].


2. Detector and experiment

The CMD-2 detector has been described in detail elsewhere [10]. Its tracking system consists of the cylindrical drift chamber (DC) [11] surrounding the interaction point, and proportional Z-chamber (ZC) [12] for precise polar angle measurement, both also used for the trigger. Both chambers are inside a thin (0.38 $X_0$) superconducting solenoid [13] with a field of 1 T. The barrel electromagnetic calorimeter [14] is placed outside the solenoid and consists of 892 CsI crystals. The muon-range system [15] of the detector, also located outside the solenoid, is based on streamer tubes. The endcap electromagnetic calorimeter [16] based on BGO crystals makes the detector almost hermetic for photons.

The data sample used in the analysis was collected in two scans of the center-of-mass energy range 1.05–1.38 GeV. In the first scan the beam energy was increased from 530 to 690 MeV with a 10 MeV step, while in the second one it was decreased from 685 to 525 MeV with the same energy step.

3. Data analysis

Events of the process $e^+e^- \rightarrow K^0_L K^0_S$ were detected by using a subsequent decay of the $K^0_S$ meson into a pair of charged pions.

The following selection criteria were used:

- There are two oppositely charged tracks from the vertex closest to the beam. Track momenta, assuming that tracks are pions, satisfy the conditions:
  
  \[ p_\pi^{\text{min}} < p_\pi < p_\pi^{\text{max}} + 20, \]

  where $p_\pi^{\text{min}}$, $p_\pi^{\text{max}}$ are minimum and maximum kinematically possible momenta of a pion from the $K^0_S \rightarrow \pi^+\pi^-$ decay in MeV/c.

- The track polar angles are:
  
  \[ 0.95 < \theta_1,2 < \pi - 0.95. \]

- The maximum of the track ionization losses is
  
  \[ \max\left(\frac{dE}{dx}\right)_1, \frac{dE}{dx}_2 < 2.2\left(\frac{dE}{dx}\right)\text{MIP}, \]

  where $\frac{dE}{dx}\text{MIP}$ is the ionization loss of a minimum ionizing particle (see Fig. 1(a) for events from the energy range $1.05 < \sqrt{s} < 1.09$ GeV). The cut is used to remove $K^+K^-$ events as well as events of “beam-wall” interactions.
Fig. 1. Distributions used for the selection of $e^+e^- \rightarrow K_0^0\bar{K}_0^0$ events: (a) particle ionization losses versus the invariant mass of two tracks; (b) $Z$-coordinate of the vertex versus the distance from the beam point to the vertex in the $\rho$–$\phi$ plane; (c) missing momentum (the histogram is simulation, the points are experimental events); (d) invariant mass of two tracks.

- The acollinearity angle for pions in the $R$–$\phi$ plane is
  
  \[ 0.2 < |\pi_2 - \phi_1 - \phi_2| < 3.0, \]

  and the space angle between pion tracks is

  \[ \psi > 0.5, \]

  By these criteria events with collinear particles and particles going close to each other were rejected.

- The $Z$-coordinate of the vertex is less than 7.0 cm and the radius of the vertex in the $R$–$\phi$ plane ($R_{vtx}$) satisfies the condition:

  \[ 0.07 < R_{vtx} < 1.3 \text{ cm}, \]  

  as shown in Fig. 1(b) for the energy range $1.05 < \sqrt{s} < 1.09 \text{ GeV}.

In the energy region above the $\phi(1020)$, production of a neutral kaon pair is often accompanied by emission of a hard photon by initial electrons (“return to resonance” effect). The distribution of the missing momentum of two tracks defined as $P_{\text{mis}} = |\vec{P}_1 + \vec{P}_2|$ is shown in Fig. 1(c) for $\sqrt{s} = 1.07 \text{ GeV}$. In agreement with the Monte Carlo simulation, the left peak in Fig. 1(c) corresponds to “return to resonance” events, while the right one describes events without hard photon emission. In the present Letter events with “return to resonance” were excluded from analysis by the requirement

\[ |P_{\text{mis}} - \sqrt{E_{\text{beam}}^2 - m_{K^0}^2}| < 40 \text{ MeV/c}, \]

where 40 MeV/c corresponds to five standard deviations of the experimental resolution for the $P_{\text{mis}}$ value.
The selection criteria are shown in Fig. 1(c) by the vertical lines.

The number of events was determined from a fit of the invariant mass distribution with a sum of two Gaussians describing the signal and a smooth function describing background. For the fitting procedure, the data sample was subdivided into three energy bins: 1.05–1.19, 1.20–1.29 and 1.30–1.38 GeV. The approximation above was performed in each of the three bins and the parameters obtained were later fixed during the approximation at each energy point within the corresponding bin. An example of such an approximation in the energy range 1.05–1.19 GeV is shown in Fig. 1(d).

After background subtraction and application of the cuts described above, $948 \pm 33 \, K^0_L K^0_S$ events were selected.

At each energy point the cross section is determined from the following formula:

$$ \sigma = \frac{N}{L \varepsilon (1 + \delta_{\text{rad}})}, $$

where $N$ is the number of selected events, $\varepsilon$ is the detection efficiency, $L$ is the integrated luminosity determined from events of Bhabha scattering at large angles [17], and $(1 + \delta_{\text{rad}})$ is a radiative correction due to initial state radiation [18]. The detection efficiency $\varepsilon = \varepsilon_{\text{rec}} \varepsilon_{\text{trig}} \varepsilon_{\text{geom}}$, where $\varepsilon_{\text{rec}}$ is the reconstruction efficiency, $\varepsilon_{\text{trig}}$ is the trigger efficiency, and $\varepsilon_{\text{geom}}$ is the acceptance.

The reconstruction efficiency ($\varepsilon_{\text{rec}}$) was determined from the experimental data [19]. To this end “test” events, in which a $K^0_L$ produced a cluster in the CsI calorimeter, were selected. Using the angles of this cluster as well as the angles of the clusters produced by pions from the $K^0_S \rightarrow \pi^+ \pi^-$ decay and requiring one track in DC, one obtains a clean sample of events for efficiency determination. Analysis shows that the reconstruction efficiency is energy independent.

A similar procedure was used to determine the trigger efficiency ($\varepsilon_{\text{trig}}$) [19]. The acceptance ($\varepsilon_{\text{geom}}$) was determined from Monte Carlo simulation.

The beam energy at each point was evaluated from the value of the magnetic field in the dipole magnets [20]. The systematic uncertainty was estimated to be $\Delta E / E = 4 \times 10^{-4}$ from the analysis of the long-term stability of energy [17]. The number of events, integrated luminosity, detection efficiency, radiative correction and cross section at each energy point are listed in Table 1. It is this cross section (the “dressed” one) that should be used in the approximation of the energy dependence with resonances. For applications to various dispersion integrals such as the leading order hadronic contribution to the muon anomalous magnetic moment, one should use the “bare” cross section. Following the procedure in Ref. [21], the latter is obtained from the “dressed” one by multiplying it by the vacuum polarization factor $|1 - \Pi(s)|^2$, where $\Pi(s)$ is the photon polarization operator calculated taking into account the effects of both leptonic and hadronic vacuum polarization.

Fig. 2 shows the energy dependence of the cross section obtained in this work together with the results of our study of the $\phi \rightarrow K^0_L K^0_S$ decay from [22] (the data in the 1.00–1.04 GeV energy range). Also shown are the results of the previous experiments that studied the process $e^+ e^- \rightarrow K^0_L K^0_S$ above the $\phi$ meson region. Good agreement between the results of all measurements is observed.

The energy dependence of the cross section was approximated in the frame of Vector Dominance Model [23] with the contributions of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons according to the follow-
Table 1

The c.m. energy, number of events, integrated luminosity, detection efficiency, radiative correction, “dressed” cross section, vacuum polarization factor and “bare” cross section of the process $e^+ e^- \rightarrow K_L^0 K_S^0$. The first error in the cross section value is statistical and the second is systematic one.

| $\sqrt{s}$, GeV | $N$ | $L$, nb$^{-1}$ | $\epsilon$ | $1 + \delta_{\text{rad}}$ | $\sigma$, nb | $|1 - \Pi(s)|^2$ | $\sigma_{0}$, nb |
|-----------------|-----|---------------| -------------|-----------------|---------|-----------------|---------|
| 1.050           | 310.9 ± 17.8 | 117.7 ± 0.7 | 0.151 | 0.996 | 17.56 ± 1.00 ± 1.97 | 0.948 | 16.65 ± 0.95 ± 1.87 |
| 1.060           | 124.1 ± 11.3 | 76.8 ± 0.6 | 0.146 | 0.950 | 11.65 ± 1.06 ± 0.64 | 0.953 | 11.10 ± 0.97 ± 0.61 |
| 1.070           | 76.1 ± 8.9 | 81.8 ± 0.5 | 0.141 | 0.926 | 7.13 ± 0.84 ± 0.35 | 0.956 | 6.82 ± 0.80 ± 0.33 |
| 1.080           | 39.3 ± 6.6 | 59.6 ± 0.5 | 0.136 | 0.914 | 5.30 ± 0.90 ± 0.26 | 0.958 | 5.08 ± 0.86 ± 0.25 |
| 1.090           | 53.0 ± 7.5 | 85.2 ± 1.3 | 0.132 | 0.909 | 5.18 ± 0.73 ± 0.25 | 0.959 | 4.97 ± 0.70 ± 0.24 |
| 1.100           | 29.0 ± 5.5 | 75.7 ± 0.5 | 0.128 | 0.906 | 4.35 ± 0.81 ± 0.21 | 0.961 | 4.19 ± 0.78 ± 0.20 |
| 1.110           | 33.5 ± 6.1 | 83.3 ± 0.5 | 0.124 | 0.905 | 3.58 ± 0.65 ± 0.29 | 0.962 | 3.44 ± 0.62 ± 0.28 |
| 1.120           | 18.5 ± 3.9 | 59.4 ± 0.7 | 0.120 | 0.905 | 2.82 ± 0.75 ± 0.23 | 0.963 | 2.71 ± 0.72 ± 0.22 |
| 1.130           | 14.7 ± 3.2 | 62.8 ± 0.5 | 0.116 | 0.905 | 2.23 ± 0.63 ± 0.18 | 0.963 | 2.15 ± 0.61 ± 0.18 |
| 1.140           | 25.8 ± 5.7 | 87.4 ± 0.5 | 0.113 | 0.905 | 2.85 ± 0.61 ± 0.23 | 0.964 | 2.75 ± 0.59 ± 0.22 |
| 1.150           | 17.8 ± 4.1 | 63.2 ± 0.5 | 0.109 | 0.906 | 2.85 ± 0.62 ± 0.23 | 0.965 | 2.75 ± 0.60 ± 0.21 |
| 1.160           | 17.2 ± 3.8 | 113.0 ± 0.7 | 0.106 | 0.906 | 1.58 ± 0.44 ± 0.14 | 0.965 | 1.52 ± 0.42 ± 0.13 |
| 1.170           | 13.9 ± 3.2 | 71.8 ± 0.5 | 0.103 | 0.907 | 2.07 ± 0.59 ± 0.17 | 0.966 | 2.00 ± 0.57 ± 0.16 |
| 1.180           | 15.1 ± 3.6 | 114.9 ± 0.7 | 0.100 | 0.907 | 1.45 ± 0.42 ± 0.12 | 0.966 | 1.40 ± 0.41 ± 0.12 |
| 1.190           | 20.9 ± 3.6 | 132.5 ± 1.1 | 0.097 | 0.908 | 1.79 ± 0.44 ± 0.15 | 0.966 | 1.72 ± 0.42 ± 0.14 |
| 1.200           | 20.9 ± 3.6 | 270.1 ± 1.1 | 0.094 | 0.909 | 0.85 ± 0.23 ± 0.07 | 0.967 | 0.82 ± 0.23 ± 0.07 |
| 1.225           | 26.9 ± 5.3 | 286.7 ± 1.5 | 0.089 | 0.910 | 1.16 ± 0.24 ± 0.11 | 0.967 | 1.12 ± 0.24 ± 0.11 |
| 1.250           | 123.5 ± 5.3 | 492.3 ± 2.3 | 0.083 | 0.912 | 0.57 ± 0.14 ± 0.05 | 0.968 | 0.55 ± 0.14 ± 0.05 |
| 1.275           | 1827.0 ± 8.8 | 466.6 ± 1.5 | 0.079 | 0.913 | 0.55 ± 0.14 ± 0.05 | 0.968 | 0.53 ± 0.14 ± 0.05 |
| 1.296           | 202.9 ± 5.2 | 589.2 ± 2.7 | 0.075 | 0.915 | 0.50 ± 0.14 ± 0.05 | 0.968 | 0.48 ± 0.14 ± 0.05 |
| 1.325           | 112.9 ± 6.4 | 994.9 ± 3.1 | 0.071 | 0.916 | 0.17 ± 0.09 ± 0.02 | 0.968 | 0.16 ± 0.09 ± 0.02 |
| 1.368           | 20.7 ± 6.5 | 1338.7 ± 3.4 | 0.066 | 0.919 | 0.25 ± 0.08 ± 0.02 | 0.968 | 0.24 ± 0.08 ± 0.02 |

The energy dependence of the total width for a meson $V$ was chosen as in [24]. Masses, total widths and branching ratios of the resonances were taken from [25]. The following value of the cross section at the $\phi$ meson peak was obtained from the fit:

$$\sigma(\phi \rightarrow K_L^0 K_S^0) = 1376 \pm 6 \pm 23 \text{ nb},$$

$$\chi^2/\text{n.d.f} = 94.64/56 = 1.69.$$

The value of the peak cross section is exactly equal to that from our $\phi \rightarrow K_L^0 K_S^0$ study [22]. The relatively large value of the $\chi^2$ arises from the energy range above 1.13 GeV where, as seen from Fig. 2, most of the experimental points lie above the approximation curve. One of the possible explanations for the observed excess could be higher resonances contributing to the production of pairs of neutral kaons. This assumption is confirmed by the combined analysis of our results with those from the D01 detector obtained
in the energy range 1.4–2.18 GeV [1], see Fig. 3. To describe the energy dependence of the cross section at √s ~ 1.6 GeV, the following amplitude was added to the amplitudes of the ρ(770), ω(782) and φ(1020) mesons

\[ A_X = \sqrt{m_X^2 - s + i \sqrt{s} \Gamma_X} \ e^{i \delta_X}. \]

The parameters \( \sigma(X \rightarrow K^0_S K^0_S) \), \( M_X \), \( \Gamma_X \), \( \delta_X \) as well as the cross section at the \( \phi \) meson peak were obtained from the approximation

\[ \sigma(\phi \rightarrow K^0_L K^0_L) = 1375 \pm 6 \pm 23 \text{ nb}, \]
\[ \sigma(X \rightarrow K^0_S K^0_S) = 0.73 \pm 0.33 \text{ nb}, \]
\[ M_X = 1623 \pm 20 \text{ MeV}/c^2, \]
\[ \Gamma_X = 139 \pm 60 \text{ MeV}, \]
\[ \delta_X = 160^\circ \pm 42^\circ, \]
\[ \chi^2/\text{n.d.f} = 56.42/62 = 0.91. \]

The value of the cross section at the \( \phi \) meson peak changes from 1376 to 1375 nb after the contribution of a higher resonance is taken into account. This change agrees with the estimation of the systematic uncertainty of the cross section (of about 1.5 nb) due to the model dependence of the cross section value [26].

The approximation is shown in Fig. 3 by the solid line. The theoretical curve describing the contributions of the \( \rho(770) \), \( \omega(782) \) and \( \phi(1020) \) mesons only, is shown in Fig. 3 by the dotted line. One can see that after adding the amplitude \( A_X \), the quality of the approximation of the experimental data is much better.

The values obtained for the mass and width of the X state are consistent with those of the \( \phi(1680) \) meson [25]. However, as noted above, both isovector and isoscalar states could contribute to the cross section of the neutral kaon production in the energy range 1.0–2.0 GeV. To identify unambiguously the nature of the observed enhancement as well as to determine the relative weights of the \( I = 0 \) and \( I = 1 \) final states, one should simultaneously study both \( K^0_S K^0_S \) and \( K^+ K^- \) final states with a significantly higher data sample, particularly in the energy range above 1.4 GeV. The detailed investigation of other final states of \( e^+ e^- \) annihilation in this energy range will be also needed to shed light on the spectroscopy of the light quark resonances in the vector sector. Such studies will be possible at the VEPP-2000 collider [27] now under construction at the Budker Institute of Nuclear Physics.

The main sources of the systematic uncertainties are listed in Table 2. The uncertainty caused by the selection criteria was estimated by varying the cuts for pion momenta, acollinearity angle \( |\Delta \varphi| \) and \( Z \)-coordinate of the vertex by one standard deviation. It showed that the cross section changed by 3.5% below 1.1 GeV and by 6% above this energy. To estimate the uncertainty due to the background shape, the invariant mass distribution of two tracks was approximated in a narrow mass range from 400 to 600 MeV/c^2, the parameters of the function describing background were

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Fig. 3. The cross section of the process \( e^+ e^- \rightarrow K^0_L K^0_S \) in the energy range \( \sqrt{s} = 1.05–2.2 \text{ GeV} \) compared to the Vector Dominance Model predictions: \( \rho(770) \), \( \omega(782) \), \( \phi(1020) \) mesons (the dotted curve) and \( \rho(770) \), \( \omega(782) \), \( \phi(1020) \) and \( X \) (the solid curve).
4. Conclusion

Using 948 ± 33 reconstructed events detected by the CMD-2, the cross section of the process $e^+ e^- \rightarrow K^+_0 K^-_0$ was determined in the energy range from 1.05 to 1.38 GeV. This is the most precise measurement of this cross section by now. It is shown that in the energy range $\sqrt{s} > 1.13$ GeV the obtained energy dependence of this cross section could not be explained by the Vector Dominance Model with the contributions of the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons only, so that higher resonances should be taken into account. The addition of an amplitude corresponding to a resonance with mass and width close to those of the $\phi(1680)$ meson and interfering with the $\rho(770)$, $\omega(782)$ and $\phi(1020)$ mesons substantially improves the description of the observed energy dependence. To obtain the detailed information about the spectroscopy of higher resonances, new experiments are needed which will be performed at the VEPP-2000 collider.

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