Resonances in $e^+e^-$ annihilation near 2.2 GeV

J. P. Lees, V. Poireau, and V. Tisserand
Laboratoire d'Annecy-le-Vieux de Physique des Particules (LAPP), Université de Savoie, CNRS/IN2P3, F-74941 Annecy-Le-Vieux, France

E. Grauges
Universitat de Barcelona, Facultat de Física, Departament ECM, E-08028 Barcelona, Spain

A. Palano
INFN Sezione di Bari and Dipartimento di Fisica, Università di Bari, I-70126 Bari, Italy

G. Eigen
University of Bergen, Institute of Physics, N-5007 Bergen, Norway

D. N. Brown and Yu. G. Kolomensky
Lawrence Berkeley National Laboratory and University of California, Berkeley, California 94720, USA

M. Fritsch, H. Koch, and T. Schroeder
Ruhr Universität Bochum, Institut für Experimentalphysik 1, D-44780 Bochum, Germany

R. Cheaib$^b$, C. Hearty$^{ab}$, T. S. Mattison$^b$, J. A. McKenna$^b$, and R. Y. So$^b$
Institute of Particle Physics$^a$; University of British Columbia$^b$,
Vancouver, British Columbia, Canada V6T 1Z1

V. E. Blinov$^{abc}$, A. R. Buzykjaev$^a$, V. P. Druzhinin$^{ab}$, V. B. Golubev$^{ab}$, E. A. Kozyrev$^{ab}$, E. A. Kravchenko$^{ab}$, A. P. Onuchin$^{abc}$, S. I. Serednyakov$^{ab}$, Yu. I. Skovpen$^{ab}$, E. P. Solodov$^{ab}$, and K. Yu. Todyshev$^{ab}$
Budker Institute of Nuclear Physics SB RAS, Novosibirsk 630090$^a$,
Novosibirsk State University, Novosibirsk 630090$^b$,
Novosibirsk State Technical University, Novosibirsk 630092$^c$, Russia

A. J. Lankford
University of California at Irvine, Irvine, California 92697, USA

B. Dey, J. W. Gary, and O. Long
University of California at Riverside, Riverside, California 92521, USA

A. M. Eisner, W. S. Lockman, and W. Panduro Vazquez
University of California at Santa Cruz, Institute for Particle Physics, Santa Cruz, California 95064, USA

D. S. Chao, C. H. Cheng, B. Echenard, K. T. Flood, D. G. Hitlin, J. Kim, Y. Li, T. S. Miyashita, P. Ongmongkol, F. C. Porter, and M. Röhrken
California Institute of Technology, Pasadena, California 91125, USA

Z. Huard, B. T. Meadows, B. G. Pushpawela, M. D. Sokoloff, and L. Sur$^c$
University of Cincinnati, Cincinnati, Ohio 45221, USA

J. G. Smith and S. R. Wagner
University of Colorado, Boulder, Colorado 80309, USA

D. Bernard and M. Verderi
Laboratoire Leprince-Ringuet, Ecole Polytechnique, CNRS/IN2P3, F-91128 Palaiseau, France

D. Bettoni$^a$, C. Bozzi$^a$, R. Calabrese$^{ab}$, G. Cibinetto$^{ab}$, E. Fioravanti$^{ab}$, I. Garzia$^{ab}$, E. Luppi$^{ab}$, and V. Santoro$^a$
INFN Sezione di Ferrara$^a$; Dipartimento di Fisica e Scienze della Terra, Università di Ferrara$^b$, I-44122 Ferrara, Italy

A. Calcaterra, R. de Sangro, G. Finocchiaro, S. Martellotti,
N. Neri$^a$ and F. Palombo$^{ab}$
INFN Sezione di Milano$^a$; Dipartimento di Fisica, Università di Milano$^b$, I-20133 Milano, Italy

L. Cremaldi, R. Godang$^c$ and D. J. Summers
University of Mississippi, University, Mississippi 38677, USA

P. Taras
Université de Montréal, Physique des Particules, Montréal, Québec, Canada H3C 3J7

G. De Nard and C. Sciacca
INFN Sezione di Napoli and Dipartimento di Scienze Fisiche, Università di Napoli Federico II, I-80126 Napoli, Italy

G. Raven
NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands

C. P. Jessop and J. M. LoSecco
University of Notre Dame, Notre Dame, Indiana 46556, USA

K. Honscheid and R. Kass
Ohio State University, Columbus, Ohio 43210, USA

A. Gaz$^a$, M. Margoni$^{ab}$, M. Posocco$^a$, G. Simi$^{ab}$, F. Simonetto$^{ab}$, and R. Stroili$^{ab}$
INFN Sezione di Padova$^a$; Dipartimento di Fisica, Università di Padova$^b$, I-35131 Padova, Italy

S. Akar, E. Ben-Haim, M. Bomben, G. R. Bonneaud, G. Calderini, J. Chauveau, G. Marchiori, and J. Ocariz
Laboratoire de Physique Nucléaire et de Hautes Energies, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, F-75252 Paris, France

M. Biasini$^{ab}$, E. Manoni$^a$, and A. Rossi$^a$
INFN Sezione di Perugia$^a$; Dipartimento di Fisica, Università di Perugia$^b$, I-06123 Perugia, Italy

G. Batignani$^{ab}$, S. Bettarini$^{ab}$, M. Carpinelli$^{ab}$, G. Casarosa$^{ab}$, M. Chrzaszcz$^a$, F. Forti$^{ab}$, M. A. Giorgi$^{ab}$, A. Lusiani$^{ac}$, B. Oberho$^{ab}$, E. Paoloni$^{ab}$, M. Rama$^a$, G. Rizzo$^{ab}$, J. J. Walsh$^a$, and L. Zani$^{ab}$
INFN Sezione di Pisa$^a$; Dipartimento di Fisica, Università di Pisa$^b$; Scuola Normale Superiore di Pisa$^c$, I-56127 Pisa, Italy

A. J. S. Smith
Princeton University, Princeton, New Jersey 08544, USA

F. Anulli$^a$, R. Faccini$^{ab}$, F. Ferrarotto$^a$, F. Ferroni$^a$, A. Pilloni$^{ab}$, and G. Piredda$^a$
INFN Sezione di Roma$^a$; Dipartimento di Fisica, Università di Roma La Sapienza$^b$, I-00185 Roma, Italy

C. Bünger, S. Dittrich, O. Grünberg, M. Heß, T. Leddig, C. Voß, and R. Waldi
Universität Rostock, D-18051 Rostock, Germany

T. Adye and F. F. Wilson
Rutherford Appleton Laboratory, Didcot, Didcot, Oxon, OX11 0QX, United Kingdom

S. Emery and G. Vasseur
IRFU, CEA, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France

M. V. Purohit and J. R. Wilson
SLAC National Accelerator Laboratory, Stanford, California 94309 USA
Using the initial-state radiation method, the $e^+e^-\rightarrow K_S K_L$ cross section from 1.98 to 2.54 GeV is measured in a data sample of $469 \text{ fb}^{-1}$ collected with the BABAR detector. The results are used in conjunction with previous BABAR results for the $e^+e^-\rightarrow K^+K^-$, $e^+e^-\rightarrow \pi^+\pi^-$, $e^+e^-\rightarrow \pi^+\pi^-\eta$, and $e^+e^-\rightarrow \omega\pi\pi$ cross sections to investigate the nature of the resonance structure recently observed by the BESIII experiment in the $e^+e^-\rightarrow K^+K^-$ cross section.

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*Now at: Wuhan University, Wuhan 430072, China  
†Deceased  
‡Now at: University of Huddersfield, Huddersfield HD1 3DH, UK
I. INTRODUCTION

Recently, a precise measurement of the $e^+e^- \rightarrow K^+K^-$ cross section in the center-of-mass (c.m.) energy range $E = 2.00-3.08$ GeV was performed by the BESIII Collaboration [1]. In this cross section, a clear interference pattern was observed near 2.2 GeV. To explain this pattern, BESIII inferred the existence of a resonance with a mass of 2239 ± 7 ± 11 MeV/$c^2$ and a width of 140 ± 12 ± 21 MeV. In the Particle Data Group (PDG) table [2] there are two vector resonances with a mass near 2.2 GeV/$c^2$: $\phi(2170)$ and $\rho(2150)$. The first is observed in three reactions: $e^+e^- \rightarrow \phi(2170)$ [3, 4], $J/\psi \rightarrow \eta\phi(2170)$ [5, 6], and $e^+e^- \rightarrow \eta\phi(2170)$ [7], but only in the decay mode $\phi(2170) \rightarrow \phi(1020) f_0(980)$. As shown in Ref. [1], the parameters of the resonance structure observed in the $e^+e^- \rightarrow K^+K^-$ cross section differ from the $\phi(2170)$ PDG parameters by more than 3$\sigma$ in mass and more than 2$\sigma$ in width. The isovector resonance $\rho(2150)$ is not well established. The PDG lists three $e^+e^-$ annihilation processes in which evidence for its existence is seen: $e^+e^- \rightarrow f_1(1275)\pi^+\pi^-$, $e^+e^- \rightarrow \eta'\pi^+\pi^-$, and $e^+e^- \rightarrow \pi^+\pi^-$. In the first two reactions, wide ($\Gamma \sim 300$ MeV) resonance-like structures are observed near the reaction thresholds [8]. A completely different structure is seen in the third process. A resonance with mass and width 2254 ± 22 MeV/$c^2$ and 109 ± 76 MeV, respectively, is needed to describe the interference pattern in the $e^+e^- \rightarrow \pi^+\pi^-$ cross section [9]. Note that the parameters of this resonance are very similar to those mentioned above for the $e^+e^- \rightarrow K^+K^-$ reaction from BESIII.

Any resonance in the $e^+e^- \rightarrow K^+K^-$ cross section should also be present in $e^+e^- \rightarrow KS\bar{K}L$. The most precise data on this reaction near 2 GeV were obtained by the BABAR Collaboration [10]. In this previous work, the $e^+e^- \rightarrow KS\bar{K}L$ cross section was measured up to 2.2 GeV. Above 2 GeV, the cross section was found to be consistent with zero within the statistical uncertainties of around 20 pb. In the present work we expand the energy region of the BABAR $KS\bar{K}L$ measurement up to 2.5 GeV. The new $KS\bar{K}L$ measurements, in conjunction with previous BABAR results for other exclusive $e^+e^-$ processes, are used to investigate the nature of the structure observed by BESIII in $e^+e^- \rightarrow K^+K^-$.  

II. FIT TO THE BESIII AND BABAR $e^+e^- \rightarrow K^+K^-$ DATA

In Fig. 1 we show BESIII [1] and BABAR [11] data on the dressed Born cross section for the process $e^+e^- \rightarrow K^+K^-$ in the energy region of interest. The dressed cross section used to obtain resonance parameters is calculated from the bare cross section ($\sigma_b$) listed in Refs. [1, 11] as $\sigma = \sigma_b R_{VP}/C_{FS}$, where $R_{VP}$ is the factor taking into account the vacuum polarization correction, while $C_{FS}$ is the final-state correction (see, e.g., Ref. [12]). The latter, in particular, takes into account extra photon radiation from the final state. In the energy region of interest, 2.00–2.5 GeV, $R_{VP} \approx 1.04$ and $C_{FS} = 1.008$. The BESIII and BABAR data on the dressed $e^+e^- \rightarrow K^+K^-$ cross section are fitted by a coherent sum of resonant and nonresonant contributions

$$\sigma(E) = \frac{M_R^2\beta(E)^3}{E^2\beta(M_R)^3} \sqrt{\sigma_R}BW(E) + e^{i\varphi}P(E)^2, \quad (1)$$

where $\beta(E) = \sqrt{1 - 4m_K^2/E^2}$, $m_K$ is the charged kaon mass, $BW(E) = M_R\Gamma_R/(M_R^2 - E^2 - i\Gamma_R)$ is the Breit-Wigner function describing the resonant amplitude, $M_R$, $\Gamma_R$, and $\sigma_R$ are the resonance mass, width, and peak cross section, $P(E)$ is a second-order polynomial describing the nonresonant amplitude, and $\varphi$ is the relative phase between the resonant and nonresonant amplitudes. The fit result is shown in Fig. 1. The fit yields $\chi^2/\nu = 55.8/40$ ($P(\chi^2) = 5\%$) and the fit parameters are listed in Table I.

The systematic uncertainties in the resonance param-
eters come mainly from uncertainties in the description of the resonance and nonresonance shapes. The uncertainty due to the absolute c.m. energy calibration is negligible \cite{11}. For the signal shape we study the effect of the imaginary parts, we multiply the function \( a(E)/\sqrt{E^2 - b^2} \) inspired by the vector-meson dominance model, where \( a \) and \( b \) are fitted parameters, while small deviations from the main dependence are described by a quadratic polynomial. The nonresonance amplitude may have an energy-dependent imaginary part originating from vector resonances lying below 2 GeV. Using the results of Ref. \cite{13}, we estimate that its fraction reaches 10% at 2 GeV and decreases to 5% at 2.5 GeV. To study the effect of the imaginary parts, we multiply the function \( P(E) \) in Eq. (1) by a factor of \( 1 \pm iG(E) \), where \( G(E) \) is a linear function decreasing from 0.05–0.15 at \( E = 2 \) GeV to zero at 2.5 GeV. The deviations from the nominal parameter values listed in Table I are taken as the estimates of the systematic uncertainties given in Table I. The systematic uncertainty in the parameter \( \sigma_R \) includes also the correlated systematic uncertainty in the \( e^+e^- \rightarrow K^+K^- \) cross section, which is 2.5% (6%) for the BESIII (BaBar) data.

Our values for the resonance mass and width are close to the values 2239 ± 7 ± 11 MeV/\( c^2 \) and 140 ± 12 ± 21 MeV obtained in Ref. \cite{11}. We also perform the fit to the BaBar data only. The resulting parameters are \( M_R = 2201 \pm 19 \) MeV/\( c^2 \), \( \Gamma_R = 70 \pm 38 \) MeV, and \( \sigma_R = 42^{+99}_{-16} \) pb. The resonance significance in the BaBar data estimated from the \( \chi^2 \) difference for the fits with and without the resonance contribution is 3.5\( \sigma \).

III. THE \( e^+e^- \rightarrow K_S K_L \) CROSS SECTION IN THE 2.0–2.5 GEV ENERGY RANGE

The data analysis presented in this paper is based on methods developed for the measurement of the \( e^+e^- \rightarrow K_S K_L \) cross section in Ref. \cite{10}. The data set, with an integrated luminosity of 469 fb\(^{-1} \) \cite{13}, was collected with the BaBar detector \cite{15} at the SLAC PEP-II asymmetric-energy \( e^+e^- \) storage ring at the \( \Upsilon(4S) \) resonance and 40 MeV below this resonance. The initial-state-radiation (ISR) technique is used, in which the cross section for the process \( e^+e^- \rightarrow K_S K_L \) is determined from the \( K_S K_L \) invariant mass spectrum measured in the reaction \( e^+e^- \rightarrow K_S K_L \gamma \).

The selection criteria for \( e^+e^- \rightarrow K_S K_L \gamma \) events are described in detail in Ref. \cite{10}. We require the detection of all the final-state particles. The ISR photon candidate must have an energy in the c.m. frame greater than 3 GeV. The \( K_S \) candidate is reconstructed using the \( K_S \rightarrow \pi^+\pi^- \) decay mode. Two oppositely charged tracks not identified as electrons are fitted to a common vertex. The distance between the reconstructed \( K_S \) decay vertex and the beam axis must be in the range from 0.2 to 40.0 cm. The cosine of the angle between a vector from the beam interaction point to the \( K_S \) vertex and the \( K_S \) momentum in the plane transverse to the beam axis is required to be larger than 0.9992. The invariant mass of the \( K_S \) candidate must be in the range 0.482–0.512 GeV/\( c^2 \). The \( K_L \) candidate is a cluster in the calorimeter with energy deposition greater than 0.2 GeV. To suppress background, we also require the event to not contain extra charged tracks originating from the interaction region or extra photons with energy larger than 0.5 GeV.

The ISR photon, \( K_S \), and \( K_L \) candidates are subjected to a three-constraint kinematic fit to the \( e^+e^- \rightarrow K_S K_L \gamma \) hypothesis with the requirement of energy and momentum balance. Only the angular information is used in the fit for the \( K_L \) candidate. If there are several \( K_L \) candidates in an event, the \( K_S K_L \gamma \) combination giving the smallest \( \chi^2 \) value is retained. The particle parameters after the kinematic fit are used to calculate the \( K_S K_L \) invariant mass \( m(K_S K_L) \), which is required to satisfy 1.06 < \( m(K_S K_L) \) < 2.5 GeV/\( c^2 \).

The \( \chi^2 \) distribution from the fit for the selected events is shown in Fig. 2 in comparison with the simulated signal and background distributions. The background is dominated by the ISR processes \( e^+e^- \rightarrow K_S K_L \pi^0 \gamma, K_S K_L \eta \gamma \), and \( K_S K_L \eta^{\prime} \gamma \). The condition \( \chi^2 < 10 \) is applied to select signal events. The control region \( 10 < \chi^2 < 20 \) is used to estimate and subtract background.

The numbers of signal (\( N_s \)) and background (\( N_b \)) events in the signal region (\( \chi^2 < 10 \)) are determined as

\[
N_s = N_1 - N_b, \quad N_b = (N_2 - aN_s)/b, \tag{2}
\]

where \( N_1 \) and \( N_2 \) are the numbers of selected data events in the signal and control regions, and \( a = 0.20 \pm 0.01 \) and \( b = 0.87 \pm 0.09 \) are the \( N_2/N_1 \) ratios for signal and background, respectively.

The value of the coefficient \( a \) is determined from the simulated signal \( \chi^2 \) distribution. For the mass region of interest \( 2.0 < m(K_S K_L) < 2.5 \) GeV/\( c^2 \), where the number of signal events is small, the \( aN_s \) term in the expression for \( N_b \) is negligible. The coefficient \( b \) is determined in two ways: either using background simulation, or from the difference between the data and simulated signal distributions in Fig. 2. The signal distribution is normalized to the number of data events with \( \chi^2 < 3 \) after subtrac-
tion of the background estimated from simulation. The average of the two $b$ values is quoted above. Their difference (10%) is taken as an estimate of the systematic uncertainty in $b$. As shown in Ref. [10], the background $m(K_S K_L)$ distribution obtained using Eq. (2) is found to be in reasonable agreement with the same distribution obtained from simulation.

The background estimated from the control region decreases monotonically with increasing $m(K_S K_L)$ and is well approximated by a smooth function. Figure 3 shows the $m(K_S K_L)$ distribution for data events from the signal region. The curve represents the estimated background distribution.

The uncertainty in the background is 12%, which includes the 10% uncertainty in the parameter $b$ in Eq. (2) and a 6% uncertainty in the background approximation. We do not see a significant signal of $K_S K_L$ events over background. The $e^+ e^- \rightarrow K_S K_L$ cross section in the mass region $1.96 < m(K_S K_L) < 2.56$ GeV/$c^2$ obtained from the mass spectrum in Fig. 3 after background subtraction is shown in Fig. 4 (left). The details on the detection efficiency and ISR luminosity can be found in Ref. [10]. The numerical values of the $e^+ e^- \rightarrow K_S K_L$ cross section, with statistical and systematic uncertainties, are listed in Table I. The systematic uncertainties arise mainly from the background subtraction and are fully correlated between different $m(K_S K_L)$ intervals.

A fit to the cross section data with a constant yields $\chi^2/\nu = 11.7/13$, where $\nu$ is the number of degrees of freedom. The average value of the $e^+ e^- \rightarrow K_S K_L$ cross section between 1.98 and 2.54 GeV/$c^2$ is found to be $(4 \pm 5 \pm 5)$ pb, which is therefore consistent with zero. The dashed curve in Fig. 4 (left) represents the cross section for the resonance with the parameters listed in Table I. Formally, from the $\chi^2$ difference between the two hypotheses in Fig. 4 (left) the resonance interpretation can be excluded at 2.3$\sigma$. However, possible destructive interference between the resonant and nonresonant $e^+ e^- \rightarrow K_S K_L$ amplitudes may significantly weaken this constraint. We also must take into account the uncertainty in the background subtraction and the statistical uncertainty in the resonance cross section obtained from the fit to the $e^+ e^- \rightarrow K^+ K^-$ data. To do this we fit the mass spectrum shown in Fig. 3 with a sum of signal and background distributions. The background distribution shown in Fig. 3 is multiplied by a scale factor $r_{bkg}$, which is allowed to vary within a 12% uncertainty around unity.

The signal cross section is described by Eq. (1) with a constant nonresonant amplitude $P(E) = \sqrt{\sigma_{NR}}$ and the parameter $\sigma_R$ varied around the value listed in Table I. From the fit we determine $\sigma_{NR}$ and $\varphi$. The result of the fit is shown by the curve in Fig. 4 (right). The fitted value of the parameter $r_{bkg}$ is 0.94. Therefore, the points in Fig. 4 (right) lie slightly higher than those in Fig. 4 (left). The fit yields $\chi^2/\nu = 11.0/12$ and the following values of parameters:

$$\sigma_{NR} = 7.3^{+7.4}_{-5.3} \text{ pb, } \varphi = (-69 \pm 23)^\circ. \quad (3)$$

We conclude that the $\bar{B}B$ data on the $e^+ e^- \rightarrow K_S K_L$ cross section do not exclude the existence of the resonance with the parameters listed in Table I, but restrict the possible range of allowed values of the relative
As discussed in the introduction, the mass and width of the resonance observed in the process $e^+e^- \rightarrow K_S K_L$ near 2.2 GeV are close to the parameters of the state seen in the $e^+e^- \rightarrow \pi^+\pi^-$ cross section measured by $\bar{B}A\bar{B}A\bar{R}$ [9]. The latter cross section in the energy range 2.00–2.55 GeV is shown in Fig. 5 (left). An interference pattern in the energy region near 2.25 GeV is also seen in the energy dependence of the $e^+e^- \rightarrow \pi^+\pi^-\eta$ cross section recently measured by $\bar{B}A\bar{B}A\bar{R}$ [10] and shown in Fig. 5 (right). We perform a simultaneous fit to the $e^+e^- \rightarrow \pi^+\pi^-$ and $\pi^+\pi^-\eta$ data. The cross sections are described by formulas similar to Eq. (1). For the $\pi^+\pi^-\eta$ channel, the phase space factor $\beta(E)/\beta(M_R)^3$ in Eq. (1) is replaced by the factor $p_\eta(E)^3/p_\eta(M_R)^3M_R/E [11]$, where $p_\eta$ is the $\eta$-meson momentum calculated in the model of the $\rho(770)\eta$ intermediate state. The nonresonant amplitude is described by the function $a/(E^2-b^2)$ inspired by the vector-meson dominance model. The ten fitted parameters are the mass ($M_R$) and width ($\Gamma_R$) of the resonance, the peak cross sections ($\sigma(e^+e^- \rightarrow R \rightarrow \pi^+\pi^-)$ and $\sigma(e^+e^- \rightarrow R \rightarrow \pi^+\pi^-\eta)$), and $a$, $b$, and $\varphi$ for the two channels. The result of the fit is shown in Fig. 5 by the solid curves. The fit parameters obtained are listed in the second column of Table II. The fit yields $\chi^2/\nu = 14.0/12$ ($P(\chi^2) = 0.30$). The significance of the resonance calculated from the difference in $\chi^2$ with and without the

| $m(K_S K_L)$ (GeV/c²) | $\sigma$ (pb) | $m(K_S K_L)$ (GeV/c²) | $\sigma$ (pb) |
|------------------------|--------------|------------------------|--------------|
| 1.98–2.02              | 12.5 ± 25.2 ± 9.2 | 2.26–2.30              | –4.1 ± 21.0 ± 4.6 |
| 2.02–2.06              | 15.8 ± 21.8 ± 8.1 | 2.30–2.34              | –0.6 ± 17.7 ± 4.3 |
| 2.06–2.10              | 0.4 ± 22.5 ± 7.2  | 2.34–2.38              | 4.3 ± 13.5 ± 4.0  |
| 2.10–2.14              | –13.4 ± 19.3 ± 6.5 | 2.28–2.42              | –26.6 ± 16.0 ± 3.8 |
| 2.14–2.18              | 26.9 ± 19.6 ± 5.9 | 2.42–2.46              | –4.8 ± 16.0 ± 3.6 |
| 2.18–2.22              | 26.8 ± 19.6 ± 5.4 | 2.46–2.50              | 32.1 ± 15.7 ± 3.5 |
| 2.22–2.26              | –8.6 ± 20.3 ± 5.0 | 2.50–2.54              | 2.0 ± 14.1 ± 3.3 |
resonance contributions is 4.6σ. The systematic uncertainties in the resonance parameters are determined as described in Sec. [11].

We also perform a simultaneous fit to the BESIII and BaBar $e^+e^- \rightarrow K^+K^-$ data and the BaBar $e^+e^- \rightarrow \pi^+\pi^-$ and $\pi^+\pi^-\eta$ data. The $e^+e^- \rightarrow K^+K^-$ cross section is parametrized as described in Sec. [II]. The fit parameters obtained are listed in the third column of Table [III]. The energy dependence of the total $e^+e^- \rightarrow \pi^+\pi^-$ and $\pi^+\pi^-\eta$ cross sections are similar to those (Table I) obtained in the fit to the $e^+e^- \rightarrow K^+K^-$ data alone. The results of the fit for $e^+e^- \rightarrow \pi^+\pi^-$ and $\pi^+\pi^-\eta$ cross sections are shown in Fig. [5] by the dashed curves. The $\chi^2/\nu$ calculated using the $\pi^+\pi^-$ and $\pi^+\pi^-\eta$ data is 17.2/14 ($P(\chi^2) = 0.25$). We conclude that it is very likely that the interference patterns observed in the three cross sections discussed above are manifestations of the same isovector resonance, $\rho(2230)$. It is interesting to note that the decay rates of this state to $K^+K^-$, $\pi^+\pi^-$, and $\pi^+\pi^-\eta$ are all similar.

V. TWO-RESONANCE FIT

The isovector state discussed in the previous section is expected to have an $\omega$-like isoscalar partner with a similar mass. An indication of an isoscalar resonance structure near 2.25 GeV is seen in the $e^+e^- \rightarrow \omega \pi^+\pi^-$ and $e^+e^- \rightarrow \omega \pi^0\pi^0$ cross sections measured by BaBar [8][13]. The energy dependence of the total $e^+e^- \rightarrow \omega \pi\pi$ $(\omega \pi^+\pi^- + \omega \pi^0\pi^0)$ cross section in the energy region of interest is shown in Fig. [6]. It is fitted by a coherent sum of resonant and nonresonant contributions. We assume that the process $e^+e^- \rightarrow \omega \pi\pi$ proceeds via the $\omega f_0(500)$ intermediate state. Therefore, the factor $\beta(E^3/\beta(M_R)^3$ in Eq. [1] is replaced by the s-wave phase-space factor $p_{\omega}(E)/p_{\omega}(M_R)$, where $p_{\omega}$ is the $\omega$-meson momentum in $e^+e^- \rightarrow \omega f_0(500)$. It should be noted that the phase-space factor for the other possible intermediate state, $b_1(1235)\pi$, has a similar energy dependence in the energy region of interest. The nonresonant amplitude is described by the function $a/(E^2 - b^2)$. The fit yields $\chi^2/\nu = 6.8/6$. The result of the fit is shown in Fig. [6] by the solid curve. The fitted resonance mass $(2265 \pm 20$ MeV/c²) and width $(75^{+125}_{-27}$ MeV) are similar to the parameters of the isovector state in Table [III]. Since different intermediate mechanisms (e.g., $\omega f_0$ and $b_1\pi$) contribute to the $\omega \pi\pi$ final state, the resonant and nonresonant amplitudes may be not fully coherent. Inclusion in the fit of an incoherent contribution describing up to 50% of the nonresonant cross section has an insignificant impact on the fitted resonance mass and width. The dashed curve in Fig. [6] is the result of the fit to data with a second-order polynomial. The $\chi^2/\nu$ for this fit is 18.1/9. From the $\chi^2$ difference between the two fits we estimate that the significance of the resonance signal in the $e^+e^- \rightarrow \omega \pi\pi$ cross section is 2.6σ.

From isospin invariance, the isovector amplitude enters the $e^+e^- \rightarrow K^+K^-$ and $e^+e^- \rightarrow K_SK_L$ amplitudes with opposite sign (in contrast to the isoscalar case) [10]:

$$A(e^+e^- \rightarrow K^+K^-) = A_{I=0} + A_{I=1},$$

$$A(e^+e^- \rightarrow K_SK_L) = A_{I=0} - A_{I=1}. \quad (4)$$
TABLE III: The parameters for the fit to the $e^+e^- \rightarrow \pi^+\pi^-$ and $\pi^+\pi^-\eta$ cross section data (second column), and to the $e^+e^- \rightarrow K^+K^-, \pi^+\pi^-$, and $\pi^+\pi^-\eta$ cross section data (third column). The quoted uncertainties are statistical and systematic, respectively.

| $\pi^+\pi^-$ and $\pi^+\pi^-\eta$ | $K^+K^-, \pi^+\pi^-$, and $\pi^+\pi^-\eta$ |
|-----------------------------------|-----------------------------------------------|
| $M_R$ (MeV/c$^2$) | $\Gamma_R$ (MeV) | $\sigma(e^+e^- \rightarrow R \rightarrow K^+K^-)$ (pb) | $\sigma(e^+e^- \rightarrow R \rightarrow \pi^+\pi^-)$ (pb) | $\sigma(e^+e^- \rightarrow R \rightarrow \pi^+\pi^-\eta)$ (pb) | $\varphi(e^+e^- \rightarrow K^+K^-)$ (deg) | $\varphi(e^+e^- \rightarrow \pi^+\pi^-)$ (deg) | $\varphi(e^+e^- \rightarrow \pi^+\pi^-\eta)$ (deg) | $\chi^2/\nu$ |
| 2270 ± 20 ± 9 | 116$^{+90}_{-60}$ ± 50 | 41 ± 6 ± 4 | 36$^{+27}_{-20}$ ± 4 | 27$^{+14}_{-11}$ ± 4 | 140 ± 8 ± 9 | 147 ± 30 ± 10 | 188 ± 19 ± 9 | 217 ± 24 ± 9 | 251 ± 15 ± 9 | 13.96/12 | 17.2/14 |

The quark model predicts [19] that the isoscalar amplitude related to the $\omega$-like resonance is one-third the amplitude of the corresponding $\rho$-like state and that these amplitudes have the same sign in the $e^+e^- \rightarrow K^+K^-$ channel. If the $\rho$- and $\omega$-like resonances have similar masses and widths, we expect the resonance amplitude in the $e^+e^- \rightarrow K_SK_L$ reaction to be about two times smaller than that in $e^+e^- \rightarrow K^+K^-$. This weakens the constraints on the nonresonant $e^+e^- \rightarrow K_SK_L$ cross sections and the interference phase, relation (3), obtained in the fit to the $e^+e^- \rightarrow K_SK_L$ data in Sec. VI. Repeating this fit with the resonance amplitude smaller by a factor of two, we obtain $\chi^2/\nu = 10.6/12$ and the parameters

$$\sigma_{NR} = 5.0_{-1.8}^{+8.2}, \quad \varphi = (-51_{-41}^{+56})^{`\circ}. \tag{5}$$

The fit with zero nonresonant cross section also has an acceptable $\chi^2$ value, 12.1/14. We conclude that the two-resonance fit allows a simultaneous description of the $e^+e^- \rightarrow K^+K^-$ and $e^+e^- \rightarrow K_SK_L$ data without strong constraints on the interference parameters in the $e^+e^- \rightarrow K_SK_L$ channel.

Finally, we fit the $e^+e^- \rightarrow K^+K^-$, $e^+e^- \rightarrow \pi^+\pi^-$, and $e^+e^- \rightarrow \pi^+\pi^-\eta$ data using the model described in Sec. VI with an additional contribution from the $\phi(2170)$ resonance. The $\phi(2170)$ mass and width are fixed at their PDG values [2]. The inclusion of the $\phi(2170)$ has an insignificant impact on the quality of the fit. The fitted value of the $\phi(2170)$ peak cross section is found to be consistent with zero, $0.8_{-0.8}^{+2.9}$ pb.

VI. SUMMARY

In this paper, we present measurements of the $e^+e^- \rightarrow K_SK_L$ cross section in the center-of-mass range from 1.98 to 2.54 GeV. The measured cross section is consistent with zero and does not exhibit evidence for a resonance structure. The $K_SK_L$ data are analyzed in conjunction with BESIII [1] and BaBar [11] data on the $e^+e^- \rightarrow K^+K^-$ cross section, and with BaBar data on the $e^+e^- \rightarrow \pi^+\pi^-\eta$ [9], $\pi^+\pi^-\eta$ [10], $\omega\pi^+\pi^- + \omega\eta\pi^0$ [8] [12] cross sections to examine properties and better elucidate the nature of the resonance structure observed by BESIII in the $e^+e^- \rightarrow K^+K^-$ cross section near 2.25 GeV [1].

The interference patterns seen in the $e^+e^- \rightarrow \pi^+\pi^-$ and $e^+e^- \rightarrow \pi^+\pi^-\eta$ data near 2.25 GeV provide 4.6$\sigma$ evidence for the existence of the isovector resonance $\rho(2230)$. Its mass and width are consistent with the parameters of the resonance observed in the $e^+e^- \rightarrow K^+K^-$ channel.

All three cross sections are well described by a model with $\rho(2230)$ mass and width $M = 2232 \pm 8 \pm 9$ MeV/c$^2$ and $\Gamma = 133 \pm 14 \pm 4$ MeV.
Any resonance in the $e^+e^- \to K^+K^-$ cross section should also be manifest in the $e^+e^- \to K_SK_L$ cross section. The BABAR data on the $e^+e^- \to K_SK_L$ cross section do not exclude the existence of the $\rho(2230)$ resonance, but strongly restrict the possible range of allowed values of the relative phase between the resonant and nonresonant $e^+e^- \to K_SK_L$ amplitudes. This restriction may be significantly weakened by inclusion in the fit of an additional isoscalar resonance with a nearby mass. An indication of such a resonance with $2.6\sigma$ significance is seen in the $e^+e^- \to \omega\pi\pi$ cross section.

Further study of the resonance structures near 2.25 GeV can be performed at the BESIII experiment, where the cross sections for $e^+e^- \to \pi^+\pi^-\eta$, $\omega\pi^+\pi^-$, $\omega\pi^0\pi^0$ and other exclusive processes in the energy range between 2 and 2.5 GeV may be measured with high accuracy.

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