The production of $K^+K^-$ pairs in proton-proton collisions below the $\phi$ meson threshold

Q. J. Ye,1,2† M. Hartmann,2 D. Chiladze,2,3 S. Dymov,4,5 A. Dzyuba,6 H. Gao,1 R. Gebel,2 V. Hejny,2 A. Kacharava,2 B. Lorentz,2 D. Mchedlishvili,2,3 S. Merzlakov,2,5 M. Mielke,7 S. Mikirtytchians,2,6 H. Ohm,2 M. Papenbrock,7 A. Polyanskij,2,8 V. Serdyuk,2,5 H. J. Stein,2 H. Ströher,2 S. Trusov,9,10 Yu. Valdau,11 C. Wilkin,12 and P. Wüstner13

1Department of Physics and Triangles University Nuclear Laboratory, Duke University, Durham, NC 27708, USA
2Institut für Kernphysik and Julich Centre for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany
3High Energy Physics Institute, Tbilisi State University, GE-0186 Tbilisi, Georgia
4Physikalisches Institut, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany
5Laboratory of Nuclear Problems, Joint Institute for Nuclear Research, RU-141980 Dubna, Russia
6High Energy Physics Department, Petersburg Nuclear Physics Institute, RU-188350 Gatchina, Russia
7Institut für Kernphysik, Universität Münster, D-48149 Münster, Germany
8Institute for Theoretical and Experimental Physics, RU-117218 Moscow, Russia
9Institut für Kern- und Hadronenphysik, Helmholtz-Zentrum Dresden-Rossendorf, D-01314 Dresden, Germany
10Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, RU-119991 Moscow, Russia
11Helmholtz-Institut für Strahlen- und Kernphysik, Universität Bonn, D-53115 Bonn, Germany
12Physics and Astronomy Department, UCL, London WC1E 6BT, United Kingdom
13Zentralinstitut für Elektronik, Forschungszentrum Jülich, D-52425 Jülich, Germany

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I. INTRODUCTION

The original motivation for the study of kaon-pair production in the $pp \rightarrow ppK^+K^-$ reaction near threshold was the investigation of the structure of the scalar mesons $a_0(980)$ or $f_0(980)$. Such measurements were initially performed by the COSY-11 collaboration at several different excess energies below the $\phi$-meson production threshold. However, their results showed that scalar meson production cannot in fact be the dominant driving mechanism in kaon pair production and that the data can be explained without the explicit inclusion of the $a_0/f_0$. Furthermore, they showed that the $K^-p$ and $K^-pp$ invariant mass spectra were strongly distorted, presumably by the $K^-p$ final state interaction (FSI). This was most apparent in the ratio of the differential cross sections in terms of the $K^-p$ and $K^+p$ invariant masses.

The $pp \rightarrow ppK^+K^-$ reaction was also investigated with higher statistics above the threshold for the production of the $\phi$ meson, mainly with the aim of investigating the properties of that meson. After removing the $\phi$ contribution in the spectra, it was clear that the $K^-p$ and $K^-pp$ distributions in the non-$\phi$ data were both strongly influenced by the $K^-p$ interaction. It has been suggested that this is connected with the production of the $\Lambda(1405)$ excited hyperon, which might be treated as a $\bar{K}N$ quasi-bound state with a width that overlaps the $\bar{K}N$ threshold. This idea was put on a quantitative footing by assuming that the $\Lambda(1405)$ was formed through the decay $N^* \rightarrow K^+\Lambda(1405)$. The strength and details of the $\bar{K}N$ interaction are clearly important elements in the interpretation of possible kaon nuclear systems, such as the deeply bound $K^-pp$ states.

In addition to the $K^-p$ FSI, and one between the two protons, the data also showed an enhancement at low $K^+K^-$ invariant masses with some possible structure at the $K^0\bar{K}^0$ threshold. Though the effects are small, they might be influenced by the $a_0(980)$ or $f_0(980)$ scalar mesons. However, the investigation of this region was hampered by the need to separate the non-$\phi$ from the $\phi$ contribution and the fact that the data were spread over a very wide range of $K^+K^-$ invariant masses. Measure-
ments below the $\phi$ threshold can provide useful information on these interesting FSI effects without suffering the distortion of the $\phi$ meson. However, the limited statistics in the low-energy COSY-11 data [2–4] are insufficient for the reaction below the $\phi$ threshold. A combined analysis of all the results below the $\phi$ threshold can provide useful information on these interesting FSI effects without suffering the distortion of the $\phi$ meson. However, the limited statistics in the low-energy COSY-11 data [2–4] are insufficient for detailed studies.

Previous measurements of the $pp \rightarrow ppK^+K^-$ reaction were carried out at the COSY-ANKE magnetic spectrometer at $\varepsilon = 51$, 67, and 108 MeV [6–8], where the $\phi$ threshold is at $\varepsilon = 32.1$ MeV. Here the excess energy is defined as $\varepsilon = \sqrt{s} - 2(m_p + m_K)c^2$, where $\sqrt{s}$ is the total center-of-mass energy and $m_p$ and $m_K$ are the particle masses in the final state. Because of the limited acceptance of this spectrometer, an ansatz has to be made regarding the distribution of events over the four-body phase space in order to convert count rates into cross sections. This was done assuming that the distortions were the products of those present in the two-particle subsystems. All the ANKE non-$\phi$ data seemed to be consistent with an effective scattering length of $a_{K^-p} = (0+1.5)i$ fm with no obvious influence of an energy dependence associated with an effective range term. The dominance of the imaginary part is not unexpected because of the strong couplings to the $\Sigma\pi$ and $\Lambda\pi$ channels but, due to the presence of two other final-state particles, this parameter is not necessarily an intrinsic feature of the isolated $K^-p$ system.

The ANKE measurements at three excess energies also showed some enhancement at low $K^+K^-$ invariant masses but with at least a break of slope at the $K^0\bar{K}^0$ threshold. A combined analysis of all the results in this region [7, 8] shows that the data can be understood in terms of a final state interaction involving both $K^+K^-$ elastic scattering plus a contribution from the $K^+K^- \rightarrow K^0\bar{K}^0$ charge exchange. Although suggestive, the data are not sufficient to draw firm conclusions.

In this paper we present much more precise $pp \rightarrow ppK^+K^-$ differential cross section data at a beam energy of $T_p = 2.568$ GeV ($\varepsilon = 23.9$ MeV) obtained using the COSY-ANKE spectrometer. With high statistics on the reaction below the $\phi$-meson threshold, we could study the effects of the final state interactions in the $K^-p$ and $K^+K^-$ systems in greater details.

The paper is organized as follows. We first describe the experimental setup and data analysis in Sec III. Given that the procedures involved are similar to those employed at higher energies [6, 8], this can be quite brief. The fitting of the phenomenological parametrization to the raw $pp \rightarrow ppK^+K^-$ data in order to make acceptance corrections is also described here. The resulting differential cross sections and total cross section for the $pp \rightarrow ppK^+K^-$ reaction are presented in Sec IV followed by our conclusions in Sec V.

II. EXPERIMENT AND DATA ANALYSIS

The measurement of the $pp \rightarrow ppK^+K^-$ reaction was performed at an internal target station of the Cooler Synchrotron (COSY) of the Forschungszentrum Jülich [13]. The ANKE spectrometer [14, 15], which consists of three dipole magnets, registers positively and negatively charged ejectiles in the side detection systems, with the fast positively charged particles being detected in the forward detector. Particle identification relies on time-of-flight measurements [6, 17, 18] from START and STOP counters, and momentum information obtained from the multiwire proportional chambers.

![Figure 1: The $pK^+K^-$ missing-mass distribution in the $pp \rightarrow pK^+K^-X$ reaction at $T_p = 2.568$ GeV. The hatched histogram shows the cuts imposed for the selection of the non-detected proton. The solid line, which is a second-order polynomial fit, was used to estimate the background contribution under the proton peak.](image)
be about 5%, which was subtracted from the peak using weighted data from the side bands, as parameterized by the solid line. Any ambiguity in this procedure, which is less than 3%, is one source of systematic uncertainty.

The uncertainty in the real part is large and strongly correlated with the imaginary part. To allow easy comparison with the analysis of the higher energy data \( \text{[6, 8]} \), the effective scattering length was taken to be purely imaginary. The uncertainty in the real part is large and strongly correlated with the imaginary part. To allow easy comparison with the analysis of the higher energy data \( \text{[6, 8]} \), the effective scattering length was taken to be purely imaginary.

The \( \bar{K}K \) scattering lengths for isospin-one and zero were taken as in our previous work \( \text{[7]} \) and the ratio of the \( I = 1 \) and \( I = 0 \) production amplitudes of \( s \)-wave \( KK \) pairs was parameterized as \( C e^{i \phi} \). The best fit was obtained with \( C = 0.54 \pm 0.03 \) and \( \phi = -112^\circ \pm 4^\circ \), which are consistent with our earlier evaluation \( \text{[7, 8]} \) based on the above \( \phi \) threshold data. The resulting descriptions of the experimental data in Fig. 2 are very good and certainly sufficient for evaluating the acceptance corrections.

The luminosity needed in the analysis was determined with an overall systematic uncertainty of 9% by measuring \( pp \) elastic scattering in the forward detector \( \text{[6]} \). This was checked by simultaneous studies of the beam current and Schottky spectra \( \text{[18]} \), which could fix the absolute luminosity with a systematic uncertainty of 6%. Within these uncertainties the two methods agreed but, in order to be coherent with our previous work, the luminosity extracted from the \( pp \) elastic scattering data was used in the final analysis.

### III. RESULTS

The differential cross section for the \( pp \rightarrow pp \bar{K}K \) reaction at an excess energy \( \varepsilon = 23.9 \text{ MeV} \) is shown in Fig. 3 as a function of the \( K^+K^- \) invariant mass. Also shown are simulations based on a four-body phase space and this distorted by the final state interactions in the \( K^+K^- \), \( pp \), and \( K^-p \) systems within the product ansatz.
of Eq. (1). This was done separately with effective scattering lengths of $a_{K^-p} = 1.5i$ fm and $a_{K^-p} = 2.45i$ fm.

The most striking features in the data are the strength near the $K^+K^-$ threshold and the dip at $M_{K^+K^-} \approx 0.995 \text{ GeV}/c^2$, which corresponds precisely to the $K^0\bar{K}^0$ production threshold [7]. This is compelling evidence for a cusp effect coming from the $K^0\bar{K}^0 \rightarrow K^+K^-$ transitions. To investigate this phenomenon in greater detail, the $K^+K^-$ invariant mass distribution was divided by a simulation where only the final state interactions in the $pp$ and $K^-p$, with $a_{K^-p} = 2.45i$ fm, were considered. The best fit to the data shown in Fig. 3 is achieved with a contribution from the isospin-zero channel that is about three times stronger than the isospin-one. This finding is consistent with our earlier result [2]. The deviations apparent in Figs. 3 and 4 at high $K^+K^-$ invariant masses might be connected with the approximations made in our coupled-channel model [2].

Previous analyses of the $pp \rightarrow ppK^+K^-$ reaction at different excess energies [1, 6, 8, 10] have all shown a strong preference for low values of the $K^-p$ and $K^-pp$ invariant masses, $M_{K^-p}$ and $M_{K^-pp}$. To study this further, we have evaluated differential cross sections as functions of these invariant masses and also the ratios:

$$R_{Kp} = \frac{d\sigma/dM_{K^-p}}{d\sigma/dM_{K^+p}},$$

$$R_{Kpp} = \frac{d\sigma/dM_{K^-pp}}{d\sigma/dM_{K^+pp}}.$$  \hfill (2)

The corresponding experimental data and simulations are shown in Figs. 5 and 6. Both $R_{Kp}$ and $R_{Kpp}$ display the very strong preferences for lower invariant masses seen in the earlier data. The low mass enhancements in Figs. 5 and 6 clearly indicate once again that the $pp \rightarrow ppK^+K^-$ reaction cannot be dominated by the undistorted production of a single scalar resonance $a_0$ or $f_0$. Within a four-body phase space simulation both ratios should be constant and equal to one and such a simulation also fails to describe the $M_{Kp}$ and $M_{Kpp}$ distributions. Whereas the inclusion of a $K^-p$ FSI with an effective scattering length $a_{K^-p} = 1.5i$ fm improves the situation, it overestimates the data in the high invariant mass regions for both $R_{Kp}$ and $R_{Kpp}$. With the larger effective scattering length $a_{K^-p} = 2.45i$ fm, these ratios, as well as the individual differential cross sections, can be well reproduced. Within the product ansatz of Eq. (1) the $K^-p$ final state interaction effectively becomes stronger at lower excess energies. This illustrates the limitations of this simple ansatz to the complex four-body dynamics.

Although the $K^-p$ elastic final state interaction describes well the vast bulk of the data shown in Figs. 5 and 6, it is interesting to note that there seems to be a small but significant deviation between the $K^-p$ data and simulation in Fig. 6 at low invariant masses. Since the $K^0n$ threshold is at $1.437 \text{ GeV}/c^2$, this suggests that the data

![FIG. 3: (Color online) The $pp \rightarrow ppK^+K^-$ differential cross section at $\varepsilon = 23.9 \text{ MeV}$ as a function of the $K^+K^-$ invariant mass. The dotted curve shows the four-body phase space simulation whereas the inclusion of the final state interactions through Eq. (1) gives the dashed curve for $a_{K^-p} = 1.5i$ fm and the red solid curve $a_{K^-p} = 2.45i$ fm. The dot-dashed curve was obtained by considering only the $pp$ and $K^-p$ final state interactions with $a_{K^-p} = 2.45i$ fm.](image1.png)

![FIG. 4: Ratio of the measured $pp \rightarrow ppK^+K^-$ differential cross section at $\varepsilon = 23.9 \text{ MeV}$ as a function of the $K^+K^-$ invariant mass to a simulation that includes only $K^-p$ and $pp$ final state interactions (shown by the dot-dashed curve in Fig. 3). In addition to the current data (solid circles), weighted averages of previous measurements (open squares and circles) are also presented. The solid curve represents the best fit in a model that includes elastic $K^+K^-$ FSI and $K^0\bar{K}^0 \rightarrow K^+K^-$ charge-exchange [7]. The best fits neglecting charge exchange and including only this effect are shown by the dashed and dot-dashed curves, respectively.](image2.png)
in this region might also be influenced by $K^-p = \bar{K}^0n$ channel coupling.

Due to the low statistics, the COSY-11 data at 10 and 28 MeV \(^4\,^9\) cannot distinguish between predictions based on effective scattering lengths of $a_{K^-p} = 1.5i$ fm and $a_{K^-p} = 2.45i$ fm. This illustrated for the $R_{Kp}$ ratio in Fig. 4 but this lack of sensitivity is equally true for $R_{Kpp}$.

The $pp \rightarrow ppK^+K^-$ differential cross section, shown in Fig. 3 as a function of the $K^+K^-$ invariant mass, was used to determine the value of the total cross section, $\sigma = 6.66 \pm 0.08 \pm 0.67$ nb, where the first error is statistical and the second systematic. The systematic effects considered here arise from the background subtraction, acceptance correction, tracking efficiency correction, and luminosity determination.

The total cross section result is plotted in Fig. 8 along with previous measurements from DISTO \(^5\), COSY-11 \(^2\,^4\,^9\), and ANKE \(^6\,^8\). The new point seems high compared to the COSY-11 result at $\varepsilon = 28$ MeV, though one has to take into account the limited statistics of these data. This value had already been increased by 50% compared to that originally published \(^4\). This was achieved through a re-analysis of the data that in-
FIG. 7: (Color online) The ratio $R_{Kp}$ for the $pp \rightarrow ppK^+K^-$ reaction measured by COSY-11 at (a) $\varepsilon = 10$ MeV and (b) 28 MeV [19]. The dotted histograms represent the four-body phase-space simulations, whereas the red solid and dashed lines represent the theoretical calculations taking into account $K^-p$, $pp$ and $K^+K^-$ final state interactions with $a_{K^-p} = 2.45i$ fm and $1.5i$ fm, respectively. Adjacent to each graph is a plot of the $M_{Kp}$ distribution, which shows the distribution of the $Kp$ invariant mass.

IV. DISCUSSION AND CONCLUSIONS

The production of $K^+K^-$ pairs has been measured in the $pp \rightarrow ppK^+K^-$ reaction channel at an excess energy of $\varepsilon = 23.9$ MeV. Even taking its 4.3 MeV/c$^2$ width into account, this is well below the central $\phi$-meson threshold at 32.1 MeV. The reaction was identified in ANKE through a triple coincidence of a $K^+K^-$ pair and a forward-going proton, with an additional cut on the $K^+K^-$ missing-mass spectrum. The high statistics and low excess energy allow us to produce a detailed $K^+K^-$ invariant mass distribution below the $\phi$ threshold.

The distortion of both the $K^-p$ and $K^-pp$ spectra, which are even stronger than in our higher energy data, can be explained quantitatively within the product ansatz of Eq. (11) with an effective $K^-p$ scattering length $a_{K^-p} \approx 2.45i$ fm. This is to be compared with the $1.5i$ fm obtained from the analysis of data measured above the $\phi$ production threshold. A full treatment of the dynamics of the four-body $ppK^+K^-$ channel is currently imprac-
tical. As a consequence, an energy dependence of \( a_{K^-p} \) is possible because this is merely an effective parameter within a very simplistic description of the four-body final state interaction. The strong \( K^-p \) final state interaction may be connected with the \( \Lambda(1405) \) in the production process and it has been suggested \[11\] that the production of non-\( \phi \) kaon pairs proceeds mainly through the associated production \( pp \to K^+p\Lambda(1405) \). This would also lead to deviations from the simple product ansatz for the final state interactions, not least because an attraction between the \( \Lambda(1405) \) and the proton would involve three final particles.

Our results show a very strong preference for low \( K^-pp \) masses and this effect seems to be even more marked than in the higher energy data \[6, 8\]. Although this might be connected with the ideas of a \( K^-p \) final state \[12, 22–24\], it must be stressed that our data were measured far above threshold. They should not therefore be taken as necessarily implying that the \( K^- \) will bind with two protons.

There is strong evidence for a cusp effect arising from the \( K^0\bar{K}^0 \to K^+\bar{K}^- \) transitions. Our analysis within a coupled-channel description suggests that, with the values of the \( KK \) scattering lengths used, the production of isospin-zero \( KK \) pairs dominates. Though this is consistent with results extracted from data taken above the \( \phi \) threshold \[3, 8\], there is clearly room for some refinement in the model. On the other hand, the structure of the \( K^-p \) invariant mass spectrum of Fig. 3 in the 1437 MeV/c\(^2\) region suggests that there might be important coupling also between the \( K^-p \) and \( K^0n \) systems.

It is evident that the interactions in the four-body \( ppK^+K^- \) final state are extremely complex. Nevertheless, the energy dependence of the total cross section can be well described above the \( \phi \) threshold by introducing the effects of the \( pp, K^+K^- \) and \( K^-p \) final state interaction with an effective scattering length of \( a_{K^-p} = 1.5i \) fm. This would, however, have to be increased to have any hope of fitting the lower energy data. Further theoretical work is required to clarify the reaction mechanisms.

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