

The $pp \rightarrow K^+ n \Sigma^+$ reaction near threshold

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Abstract

Inclusive K^+ production in proton-proton collisions has been measured at a beam energy of 2.16 GeV using the COSY-ANKE magnetic spectrometer. The resulting spectrum, as well as those corresponding to K^+p and $K^+\pi^+$ correlated pairs, can all be well described using consistent values of the total cross sections for the $pp \rightarrow K^+p\Lambda$, $pp \rightarrow K^+p\Sigma^0$, and $pp \rightarrow K^+n\Sigma^+$ reactions. While the resulting values for Λ and Σ^0 production are in good agreement with world data, our value for the total Σ^+ production cross section, $\sigma(pp \rightarrow K^+n\Sigma^+) = (2.5 \pm 0.6_{\text{stat}} \pm 0.4_{\text{syst}}) \mu\text{b}$ at an excess energy of $\varepsilon = 129 \text{ MeV}$, could only be reconciled with other recently published data if there were a highly unusual near-threshold behaviour.

Key words: Kaon production, Sigma production, Threshold effects

PACS: 13.75.-n, 14.20.Jn, 14.40.Aq, 25.40.Ve

The production of light hyperons in proton-proton collisions in the close-to-threshold region has been extensively studied at different experimental

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facilities. The energy dependence of the total cross sections for $pp \rightarrow K^+ p \Lambda$ and $pp \rightarrow K^+ p \Sigma^0$ has been well measured and both follow phase-space, though modified in the former case by the $p \Lambda$ final-state interaction (FSI) [1]. On the other hand, little information is available on the $pp \rightarrow K^+ n \Sigma^+$ reaction. The COSY-11 collaboration has recently published surprisingly high values for the total cross sections in this channel at excess energies of $\varepsilon = 13$ MeV and 60 MeV [2]. According to these measurements, the ratios of the total cross sections $R(\Sigma^+/\Sigma^0) = \sigma(pp \rightarrow K^+ n \Sigma^+)/\sigma(pp \rightarrow K^+ p \Sigma^0)$ at these two energies are 230 ± 70 and 90 ± 40 , respectively [3]. These experimental results are in striking contrast to published theoretical estimates [4]. However, it has recently been suggested that the inclusion in the production model of the previously ignored $\Delta^{++}(1620)1/2^-$ isobar, together with a strong $n \Sigma^+$ FSI, would allow one to achieve much better (factor 2–4) agreement with the COSY-11 data [5].

A model-independent estimate for $R(\Sigma^+/\Sigma^0)$ might be obtained from the isospin relation linking the different Σ production channels, the amplitudes for which satisfy:

$$f(pp \rightarrow K^+ n \Sigma^+) + f(pp \rightarrow K^0 p \Sigma^+) + \sqrt{2} f(pp \rightarrow K^+ p \Sigma^0) = 0. \quad (1)$$

This leads to a triangle inequality between the total cross sections [6]:

$$\begin{aligned} \left[\sqrt{\sigma(pp \rightarrow K^0 p \Sigma^+)} - \sqrt{2\sigma(pp \rightarrow K^+ p \Sigma^0)} \right]^2 &\leq \sigma(pp \rightarrow K^+ n \Sigma^+) \\ &\leq \left[\sqrt{\sigma(pp \rightarrow K^0 p \Sigma^+)} + \sqrt{2\sigma(pp \rightarrow K^+ p \Sigma^0)} \right]^2. \end{aligned} \quad (2)$$

At $\varepsilon \approx 129$ MeV (the excess energy corresponding to a proton beam energy of 2.16 GeV), $\sigma(pp \rightarrow K^0 p \Sigma^+)$ [7] is nearly equal to $\sigma(pp \rightarrow K^+ p \Sigma^0)$ [1] so that the inequality of Eq. (2) predicts that $R(\Sigma^+/\Sigma^0) < 6$ at this excess energy. The COSY-11 results exceed this limit by more than an order of magnitude, though they were obtained closer to threshold, where no other $K^0 p \Sigma^+$ data have been published¹.

The authors of Ref. [9] analysed published momentum spectra from inclusive K^+ production in pp collisions at different angles and beam energies, with the aim of extracting the contribution from the $K^+ n \Sigma^+$ channel. For K^+ missing-masses below the $N \Lambda \pi$ threshold, only contributions from the $K^+ p \Lambda$, $K^+ p \Sigma^0$, and $K^+ n \Sigma^+$ channels are relevant. It was assumed that production in the first two channels could be described by three-body phase-space, with possible modifications coming from the FSI. By subtracting these known contributions

¹ There are, however, data taken with the COSY-TOF detector and presented in PhD theses [8].

from the inclusive spectra, an estimate of the $pp \rightarrow K^+ n \Sigma^+$ cross section was deduced. The inclusive data available were restricted to relatively high excess energies, $\varepsilon > 170$ MeV, and had therefore no direct bearing on the COSY-11 results. However, the authors did conclude that there was no visible evidence for any strong $N\Sigma$ FSI.

Since one cannot *a priori* exclude an anomalous threshold behaviour associated with the isospin $I=\frac{1}{2}$ K^+n (and K^0p) system, as suggested in Ref. [5], further experimental studies of the $pp \rightarrow K^+ n \Sigma^+$ reaction are necessary to clarify the situation. We here present the analysis of new experimental data taken at a proton beam energy $T_p = 2.157$ GeV.

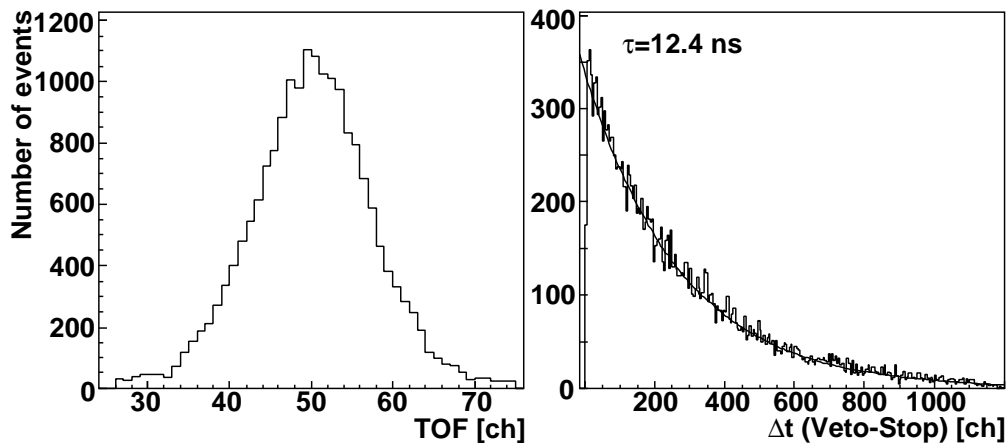


Fig. 1. The time of flight (TOF) between start and stop counters for inclusive K^+ production in pp collisions at 2.16 GeV (left panel). Time difference (Δt) between the detection of the K^+ meson in the stop counter and a decay π^+ or μ^+ in the corresponding veto counter of the same telescope (right panel). The solid line, which corresponds to the 12.4 ns lifetime of the K^+ , reproduces well the data.

The experiment was carried out using the magnetic spectrometer ANKE [10] at the COoler-SYNchrotron COSY-Jülich [11], with an internal cluster-jet target which had an average density of $\sim 2 \times 10^{14}$ cm $^{-2}$ [12]. Only two of the ANKE detection systems were needed for the analysis of these data. The positive side system (PD), used for the K^+ and π^+ detection, consists of 23 thin start counters, placed close to the vacuum chamber window, two multiwire proportional chambers (MWPCs), and 21 stop counters for time-of-flight (TOF) measurements. The experimental efficiency of particle identification was 98% using time of flight and 90% on average for MWPCs and was known with an accuracy of $\sim 1\%$. The first 15 stop counters are part of range telescopes used for the identification of the K^+ mesons. Each of these telescopes consists of a stop counter, energy-loss counter, two passive degraders and a veto counter. The thickness of the passive degraders in each telescope is chosen such that the K^+ deposits the maximum energy in the energy-loss counter and stops either at the edge of the counter or in the second passive degrader. Delayed signals for the kaon decay products are then registered by the so-called veto counter.

This method (see Fig. 1) allows one to identify the K^+ -mesons by suppressing a background that is up to 10^6 times higher. Such data by themselves are sufficient for the determination of the inclusive kaon spectrum. The efficiency of the kaon identification by this method, which varies between 10–30% depending on the telescope number, is known with an accuracy of 10–15%. Details of the particle identification analysis using the delayed–veto technique are to be found in Ref. [13].

The ANKE forward detector system (FD) [14] was used for both the K^+p correlation measurements and luminosity determination. The FD consists of two layers of plastic scintillator and a set of three multiwire proportional chambers placed downstream of the magnet. The efficiency of track reconstruction using FD MWPCs, which was about 85%, was known with an accuracy of approximately 1%. The luminosity was determined by selecting proton–proton elastic scattering events in the angular range $6.8^\circ < \theta_{\text{lab}} < 8.8^\circ$ on the basis of a dedicated pre–scaled trigger. This is described in some detail in Ref. [15], where the same data set was used for the investigation of ω -meson production. The overall systematic uncertainty in the absolute normalisation was estimated to be of the order of 6% [15]. It is estimated that the amount of background in the K^+p and $K^+\pi^+$ correlation spectra is less than 2%. For the acceptance calculations, a model of the ANKE system has been implemented within the GEANT4 simulation package [16]. This contributes an overall uncertainty of about 5%.

Information on Σ^+ production was obtained from three simultaneously measured observables, *viz.* the K^+p , $K^+\pi^+$ correlation spectra and the K^+ inclusive double–differential cross section, which we first briefly outline. The measured missing–mass spectrum of the detected K^+p pairs allows one to fix the strength of the different K^+ production channels at this energy. Since the decay $\Sigma^+ \rightarrow p\pi^0$ is also possible (branching ratio BR 51.6%), this spectrum also contains some information on the Σ^+ production total cross section, $\sigma(\Sigma^+)$.

The $pp \rightarrow K^+n\Sigma^+$ reaction can be cleanly identified either by using K^+n correlations, as at COSY-11 [2], or by detecting $K^+\pi^+$ pairs coming from the decay $\Sigma^+ \rightarrow \pi^+n$ (BR 48.3%). Although the $pp \rightarrow K^+n\Lambda\pi^+$ reaction is another potential source of $K^+\pi^+$ correlations, even at the much higher energy of 2.85 GeV its production is only about 4% of that of Σ^+ [6]. The contribution of this channel to the final distributions is therefore estimated to be less than 2%.

The inclusive K^+ double–differential cross section depends upon all possible production channels, though the contribution from the $pp \rightarrow K^+n\Sigma^+$ reaction at 2.16 GeV represents only a small fraction of the total. Therefore, within our systematic errors, only an upper limit for $\sigma(\Sigma^+)$ can be extracted from the inclusive data at this energy. Nevertheless, this spectrum does provide a valuable check on the consistency of the whole analysis by using simula-

tions where the individual weights of the channels are fixed by the total cross sections extracted from the correlation data.

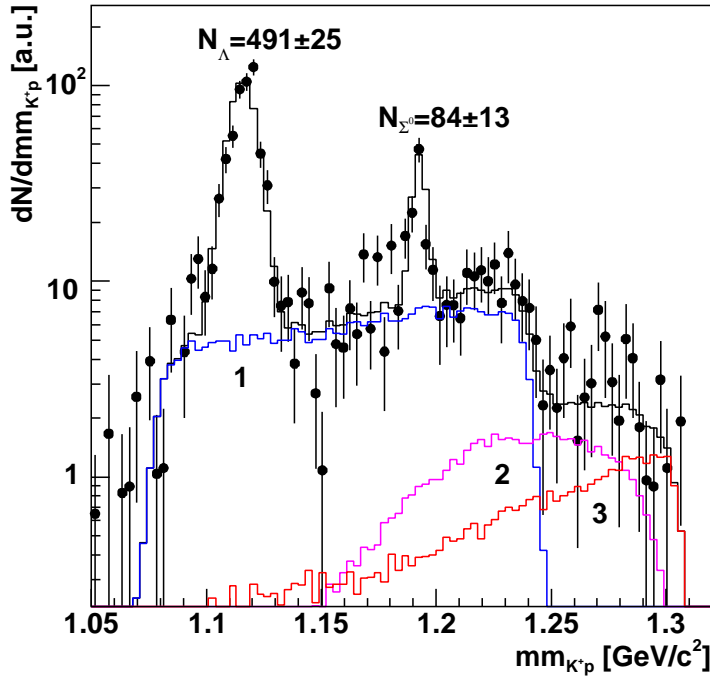


Fig. 2. Missing-mass distribution of K^+p pairs (mm_{K^+p}) produced in pp collisions at 2.16 GeV. Experimental data are shown by circles (resolution ~ 3 MeV/ c^2). The two peaks correspond to direct protons from the $pp \rightarrow K^+p\Lambda/\Sigma^0$ reactions. The continuum contributions of secondary protons arising from the $pp \rightarrow K^+p(\Lambda \rightarrow \pi^-p)$ (histogram 1), $pp \rightarrow K^+p(\Sigma^0 \rightarrow \gamma\Lambda \rightarrow \gamma\pi^-p)$ (histogram 2), and $pp \rightarrow K^+n(\Sigma^+ \rightarrow \pi^0p)$ (histogram 3) have been obtained in Monte Carlo simulations. The sum of all contributions, including the two direct peaks, is shown by the solid histogram.

The K^+p missing-mass spectrum presented in Fig. 2 shows two prominent peaks corresponding to Λ and Σ^0 production. In addition there is a continuum resulting from the detection of protons from the $\Lambda \rightarrow \pi^-p$ (BR 63.9%) and $\Sigma^0 \rightarrow \gamma\Lambda \rightarrow \gamma p\pi^-$ (BR 100%) decay, as well as a contribution from the $\Sigma^+ \rightarrow p\pi^0$ decay. This continuum is described well by our simulations.

Following the authors of Ref. [17], a simple model has been developed for the $pp \rightarrow K^+p\Lambda$ reaction. We here assume that (i) the $N^*(1650)$ -resonance is the dominant contribution for Λ production, (ii) the $p\Lambda$ FSI [1] has a significant effect on the experimental observables, (iii) use the angular distribution of the vertex-proton, as measured with the COSY-TOF detector [18]. A simple phase-space model has been used for the $pp \rightarrow K^+p\Sigma^0$ and $pp \rightarrow K^+n\Sigma^+$ reactions since there is no evidence for significant $p\Sigma^0$ or $n\Sigma^+$ FSI effects [1,9], and this is confirmed by our data.

The number of events extracted from the measured missing-mass spectrum of Fig. 2, together with our values for the total acceptances, luminosity, and

efficiencies, yields total cross sections of $\sigma(\Lambda) = (23.2 \pm 3.7_{\text{stat}} \pm 5.8_{\text{syst}}) \mu\text{b}$ and $\sigma(\Sigma^0) = (2.6 \pm 0.6_{\text{stat}} \pm 0.4_{\text{syst}}) \mu\text{b}$ for Λ and Σ^0 production, respectively. For the total cross sections calculations only the direct K^+p events are used, as their amount is precisely known (peaks in Fig. 2). These values are in agreement with the parameterisation of the world data (see Ref. [1]).

The high-mass part of the missing-mass spectrum in the Fig. 2 is sensitive to $R(\Sigma^+/\Sigma^0)$. A good description of the spectrum can be obtained if $R(\Sigma^+/\Sigma^0) \approx 1.5$. However our statistics do not permit us to draw meaningful conclusions on the associated error.

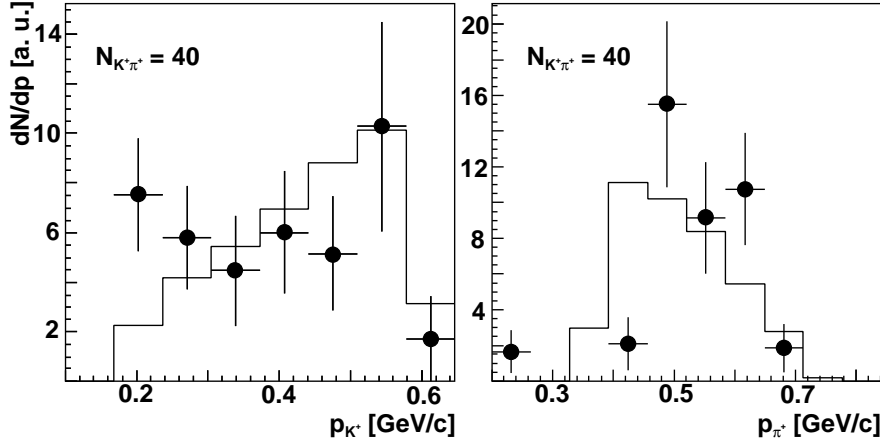


Fig. 3. Momentum distributions of K^+ and π^+ from the $pp \rightarrow K^+\pi^+X$ reaction at 2.16 GeV. The solid histograms correspond to simulations of the $pp \rightarrow K^+n(\Sigma^+ \rightarrow \pi^+n)$ reaction in the phase-space model.

The momentum distributions of the detected $K^+\pi^+$ pairs are presented in Fig. 3. Simulations carried out within the framework of the phase-space model show reasonable agreement with the experimental data. From the number of detected events the total cross section is determined to be:

$$\sigma_{\text{tot}}(\Sigma^+) = (2.5 \pm 0.6_{\text{stat}} \pm 0.4_{\text{syst}}) \mu\text{b},$$

where both the statistical and systematic uncertainties are indicated.

The ratio of the Σ^+ and Σ^0 count rates, $N_{\Sigma^+}/N_{\Sigma^0}$, is practically independent of the conditions of the experiment (luminosity, telescope efficiencies *etc.*). It can therefore be used to cross check the experimental value of $\sigma(\Sigma^+)$ extracted from the analysis of $K^+\pi^+$ correlations. The $\sigma(\Sigma^+)/\sigma(\Sigma^0)$ ratio depends on the acceptances (A) and number of detected events ($N_{K^+\pi^+}$ for the Σ^+ , and N_{K^+p} from direct proton for Σ^0):

$$\frac{\sigma(\Sigma^+)}{\sigma(\Sigma^0)} = \frac{N_{K^+\pi^+(\Sigma^+)}}{N_{K^+p(\Sigma^0)}} \times \frac{A_{K^+p(\Sigma^0)}}{A_{K^+\pi^+(\Sigma^+)}} \times \frac{1}{\text{BR}_{\Sigma^+ \rightarrow \pi^+n}} \quad (3)$$

Using the numbers of events extracted from the experimental spectra together with our estimates of the total acceptances, we obtain the following ratio of the Σ^+/Σ^0 total cross sections:

$$\frac{\sigma(\Sigma^+)}{\sigma(\Sigma^0)} = \frac{(40 \pm 7)}{(84 \pm 13)} \times \frac{4.5 \times 10^{-4}}{5.1 \times 10^{-4}} \times \frac{1}{0.48} = 0.9 \pm 0.2. \quad (4)$$

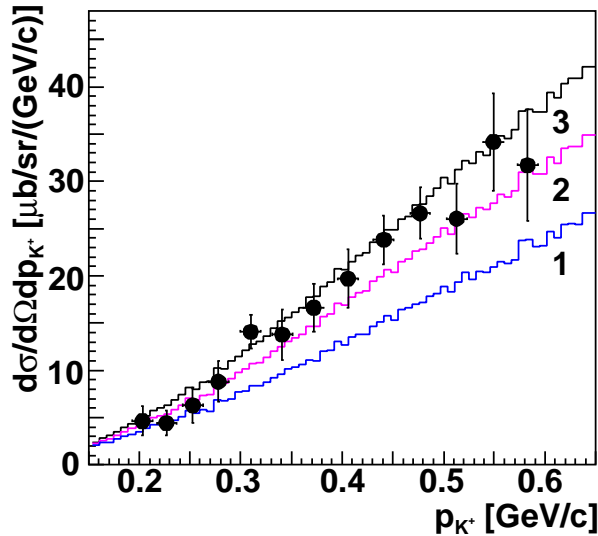


Fig. 4. Inclusive K^+ momentum spectrum for $\theta_K^{\text{lab}} < 4^\circ$ resulting from pp collisions at 2.16 GeV. The simulation of $pp \rightarrow K^+ p \Lambda$ with $\sigma(\Lambda) = 23.2 \mu\text{b}$ is shown by the histogram 1. The addition of the contribution from the $pp \rightarrow K^+ p \Sigma^0$ reaction using a total cross section of $\sigma(\Sigma^0) = 2.6 \mu\text{b}$ leads to the histogram 2. The total, corresponding to the further inclusion of the $pp \rightarrow K^+ n \Sigma^+$ reaction channel with $\sigma(\Sigma^+) = 2.5 \mu\text{b}$, is shown by the histogram 3.

Since the ratio is consistent with unity, the Σ^+ total cross section derived from Eq. (4) agrees with the value obtained directly from the $K^+ \pi^+$ data, as well as that estimated from the $K^+ p$ missing-mass spectrum. It is also reassuring that our simulation of the inclusive K^+ spectrum shown in Fig. 4 reproduces the experimental data so well. This means that the relation between the inclusive and correlation data seems to be well understood.

Our value of the Σ^+ production cross section falls well within the boundaries fixed by isospin invariance that are shown in Fig. 5. It is also in agreement with experimental data collected with the COSY-TOF detector at the same energy [19]. Compared to this the two COSY-11 points, which were taken even closer to the threshold, look extremely high.

In summary, we have presented new measurements of the $pp \rightarrow K^+ n \Sigma^+$ total cross section at 2.16 GeV that do not depend upon the detection of the final neutron. From the analysis of the $K^+ p$ and $K^+ \pi^+$ correlated pairs, total cross sections for the production of Λ , Σ^0 and Σ^+ have been extracted. The

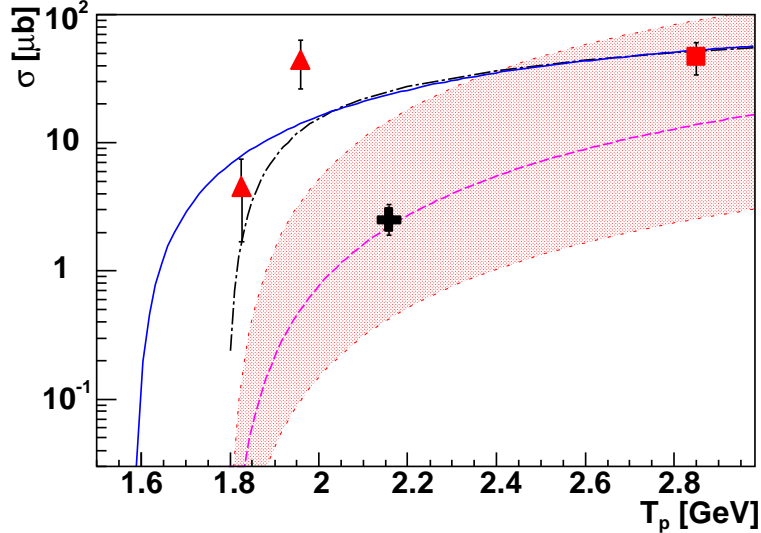


Fig. 5. Total cross sections as a function of beam energy. Our value for $\sigma(pp \rightarrow K^+ n \Sigma^+)$ at 2.16 GeV is shown by a cross. Total cross sections for $pp \rightarrow K^+ n \Sigma^+$ reaction measured by COSY-11 [2] and at higher energy in a bubble-chamber experiment [6] are represented by triangles and an square, respectively. The lines show the normalised three-body phase space dependence for the $pp \rightarrow K^+ p \Lambda$ (solid line) and $pp \rightarrow K^+ p \Sigma^0$ (dashed line) with FSI effects in the Λ case, as described in Ref. [1]. Both reproduce well the available experimental data. The estimate for the $pp \rightarrow K^+ n \Sigma^+$ total cross section from Ref. [5] is shown by the chain curve. The region restricted by the triangle inequality of Eq. (2) is shown by the hatched area.

values of $\sigma(\Lambda)$ and $\sigma(\Sigma^0)$ are in reasonable agreement with the trends of the experimental data defined at other energies. Our value of $\sigma(\Sigma^+)$ at $\varepsilon = 129$ MeV satisfies well the triangle inequality of Eq. (2). Furthermore, the inclusive double-differential cross section is well described using the values of the total cross sections for the individual K^+ production channels determined in this work from the correlation studies. This shows an overall consistency of the methodology.

Our data show that at $\varepsilon \approx 128$ MeV the Σ^+ and Σ^0 production rates are rather similar and the expectation would be that this would continue as the threshold is approached. However, the value of the total Σ^+ cross section reported by the COSY-11 collaboration at $\varepsilon = 60$ MeV is over an order of magnitude larger than ours. Taken at face value, the two measurements would imply a very large threshold anomaly. Even if this seems to be very unlikely, it can and must be checked, and this is possible with our method [20].

This work has been partially supported by BMBF, DFG(436 RUS 113/768), Russian Academy of Science, and COSY FFE. We thank the COSY machine crew for their support during the experiment. J.-J. Xie and B.-S. Zou kindly provided us with the numerical values of the calculations in Ref. [5]. Useful discussions with A. Sibirtsev and other members of the ANKE Collaboration

are gratefully acknowledged.

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