Threshold K, η, and η' mesons production in pp interaction*

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The near threshold total cross sections for the $pp \to pp\eta'$ and $pp \to ppK^+K^-$ reactions has been measured at the COSY - 11 facility. Possible production mechanisms are discussed. The energy dependence of the total cross section for the both reactions disagrees with predictions based on the phase space volume and the proton-proton final state interaction.

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1. Introduction

In context of the extensive experimental and theoretical studies of the η and K^+ production [1, 2, 3] it is natural to ask about the production mechanism of their partners in the pseudoscalar meson nonet, namely the mesons η' and K^-.

The study of the $pp \to ppK^+K^-$ reaction may deliver information not only about the production mechanisms, but also about the structure of the $f_0(980)$ and $a_0(980)$ resonances, which decay into K^+K^- pairs and which are at present intensively investigated [4]. It is discussed whether these resonances are genuine mesons, four quark states $qq\bar{q}\bar{q}$, exotic hybrids, hadronic K^+K^- molecules, or a mixture of glueball and $q\bar{q}$ states.

Till now there are no theoretical calculations which would predict the total cross section or other observables for the $pp \to ppK^+K^-$ reaction depending on the assumed -above listed- hypotheses. However, there exist predictions for the $\pi\pi \to K\bar{K}$ scattering, based on the Jülich meson exchange model [5], which indicate that the total cross section for this reaction increases by about factor of 20 when including a strong $K\bar{K}$ interaction into the calculations. If for the $pp \to ppK^+K^-$ reaction the calculations will reveal a similar difference then already a measurement of the total cross section could decide whether a produced K^+K^- pair can form a hadronic molecule.

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The K^+ possesses antistrangeness and hence its production can be associated with the creation of the hyperon, for example Λ. That is why close to threshold its production in proton-proton collisions should be much more copious with respect to the threshold production of the K^- meson, which requires a simultaneous creation of the K^+. On the other hand measurements of the heavy-ion collisions performed at GSI [6] revealed that the yield of K^- and K^+ mesons at the corresponding center-of-mass excess energies are similar. This observation suggests that medium effects can act differently on the K^+ and K^- production in the nuclear matter [7]. However, any conclusion will not be possible without the knowledge of the cross sections for the elementary production of K^+ and K^- near their respective thresholds in the $pp \to p\Lambda K^+$ and $pp \to ppK^+K^-$ reactions.

Both these reactions are studied at the COSY-11 facility. The results for the $pp \to p\Lambda K^+$ reaction can be found in the contribution of K. Kilian to this conference and in references [1]. Some results on the $pp \to ppK^+K^-$ will be presented in the last section, which is preceded by the discussion of the production mechanisms of the η' meson in proton-proton collisions.

According to the SU(3)-flavour classification η and η' mesons are mixtures of the SU(3)-singlet state $\eta_1 = \frac{1}{\sqrt{3}}(u\bar{u}+d\bar{d}+s\bar{s})$ and eighth component of the SU(3)-octet state $\eta_8 = \frac{1}{\sqrt{6}}(u\bar{u} + d\bar{d} - 2s\bar{s})$. The mixing angle implies univocally the strange and nonstrange quark contents of the η and η' mesons. Specifically, the up to date mixing angle averaged over all present experimental results ($\Theta = -15.5^o$) yields:

$$\eta = cos\Theta \cdot \eta_8 - sin\Theta \cdot \eta_1 = 0.77 \cdot \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) - 0.63 \cdot s\bar{s},$$

$$\eta' = sin\Theta \cdot \eta_8 + cos\Theta \cdot \eta_1 = 0.63 \cdot \frac{1}{\sqrt{2}}(u\bar{u} + d\bar{d}) + 0.77 \cdot s\bar{s}. \quad (1)$$

The similar amount of strange and nonstrange quarkonium in both η and η' mesons suggests that the masses of these particles should be similar. In reality, however, the η' is almost two times heavier than the η meson indicating that the structure of η and/or η' is more complicated than concluded from the mixture of the SU(3)-flavour states.

There exist many theoretical models, mainly connected with the proposal of G.'t Hooft [8] based on the "U(1) anomaly", trying to explain the large η' meson mass. For example, one considers the two-gluon annihilation process $gg \longleftrightarrow q\bar{q}$ as a contribution to the SU(3)-flavour singlet state [9, 26]. Because of the small pseudoscalar mixing angle such an additional gluon-induced interaction should mainly affect the properties of the η' which is predominantly built out of the SU(3)-flavour singlet state. In order to reproduce the observed η' mass, a gluonium component ranging between 29% and 53% is required [10].

Since the η' meson can couple directly to gluons one plausible production mechanism of this meson in the proton-proton interaction, suggested by N. Nikolaev, can be a fusion of gluons emitted from the two colliding protons, which is complementary to meson exchange current and would probe the gluonic content of the η' meson [11].

2. Possible mechanisms of the $pp \to pp\eta'$ reaction

Similarly as pions [12], the η' meson can be produced via mechanisms depicted in Figures 1a-d. Since the η' is much heavier than the π^0 meson and its production requires much larger four momentum transfer, it is expected that the creation through the heavy meson exchange, as illustrated in Figure 1c, will be even more significant than in the π^0 case.

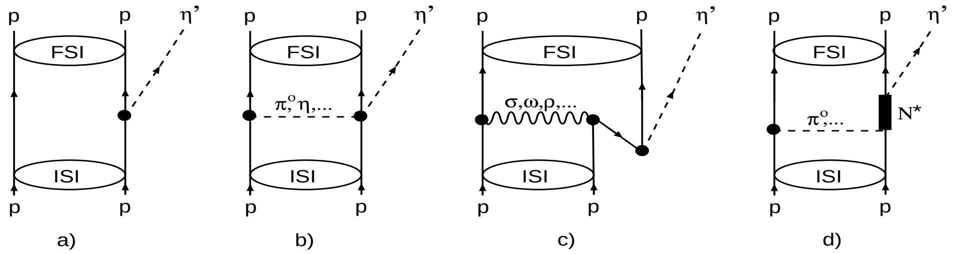

Fig. 1. Feynman diagrams for the $pp \to pp\eta'$ reaction near threshold: **(a)** direct term, **(b)** "rescattering" term, **(c)** production through the heavy-meson exchange, **(d)** excitation of an intermediate resonance.

The resonant production, via the excitation of an $S - wave$ resonance, can contribute already at the reaction threshold. However, in contrary to the η meson case, none such resonance is known, which may decay into an S-wave $\eta' N$ system [1]. Therefore one does not expect that the production via the excitation of the baryonic resonance will be appreciable. The only resonance which could be considerd here is the $D_{13}(2080)$ [13] [2]. However, due to its spin $\frac{3}{2}$, its contribution should be suppressed in the close to threshold $pp \to pp\eta'$ reaction. At present we can not observe an appreciable influence of a probable N^* resonance on the total cross section energy dependence, because the range of the covered excess energy is smaller than $\sim$ 8.5 MeV (see Figure 3) which is to be compared with a typical resonance width of

[1] In the *relativized quark model* approach one predicts many nonstrange baryon resonances which should decay into η' [14]. For instance, $S_{11}(2030)$, $D_{13}(2055)$, $D_{13}(2080)$, $S_{11}(2090)$ or $D_{13}(2095)$.

[2] The study of the $\gamma p \to \eta' p$ reaction revealed the existence of the $\mathbf{D_{13}(2080)}$ resonance [13, 27], which can decay into η' and proton.

about 100 MeV. However, the absolute values for the total cross section should differ significantly, depending whether the production is resonant or not. Unfortunately, till now, there exist no quantitative predictions of the production cross section for the $pp \to pp\eta'$ reaction. At present, even the contribution to the total cross section from the direct production process, shown in Figure 1a, can not be established because of the large uncertainty of the coupling constant for the $pp\eta'$ vertex.

Additionally to the mechanisms which govern the π^0 or η production, in case of the η' meson two other processes, shown in Figure 2 are proposed [11, 15, 16]. According to Figure 2a the η' meson would be emitted by a virtual ω, ρ, or σ meson, which couples strongly to the η'. The strong coupling is manifested by the decay of the η' into $\rho\gamma$ or $\omega\gamma$. The emission showed in diagram 2a may be understood as an inverse process to the η' decay. For instance, the $\omega\omega\eta'$ vertex is determined by the $\eta' \to \omega\omega^* \to \omega\gamma$ decay [3], whereas the $\sigma\eta\eta'$ corresponds to the $\eta' \to \pi\pi\eta$ decay, with σ describing the two pions.

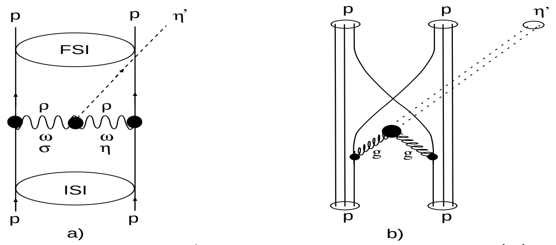

Fig. 2. Diagrams for the $pp \to pp\eta'$ reaction near threshold: **(a)** emission from the virtual particle, **(b)** production via a fusion of gluons.

Since the η' meson is essentially built out of the SU(3)-flavour singlet state η_1, which can couple to the purely gluonic states [25], it can also be produced in the fusion of gluons emitted from the exchanged quarks of the colliding protons, as shown in Figure 2b [11]. An evaluation of the contribution of this production mechanism to the total cross section would enable the insight into a probable gluonic contents of the η' meson. Unfortunately, at present there are no theoretical calculations concerning this mechanism. There are some plans to evaluate the meson-exchange mechanisms based on the measurements of the $\gamma p \to p\eta'$ reaction, where a gluon fusion is not expected. Next, having the parameters for the meson-exchange graphs fixed one could calculate the cross section for the $pp \to pp\eta'$ reaction. The probable discrepancy between the prediction based on the meson-exchange currents and the experimental data would reveal information about the gluons fusion mechanism [15].

[3] ω^* denotes the virtual ω

3. Proton-proton final state interaction

In analogy with the *Watson-Migdal* approximation [17] for two body processes, it can be assumed that the complete transition amplitude of a production process $M_{pp\to pp\eta'}$ factorizes approximately as [2]:

$$M_{pp\to pp} \approx M_0 \cdot M_{FSI} \tag{2}$$

where, M_0 accounts for all possible production processes, and M_{FSI} describes the elastic interaction of the protons and the η' meson in the exit channel.

An exact evaluation of the production amplitude M_0 would require the knowledge of all appropriate coupling constants and the form factors needed for the calculations of the production amplitudes illustrated by the diagrams in Figures 1 and 2. On the other hand, the exact calculation of the M_{FSI} amplitude, would require the usage of the Faddeev formalism and the knowledge of the proton-proton and proton-η' forces.

Thus, in a first approximation it is assumed that the production amplitude M_0 is constant over the entire phase space near threshold, and that only proton-proton elastic scattering takes place in the exit channel.

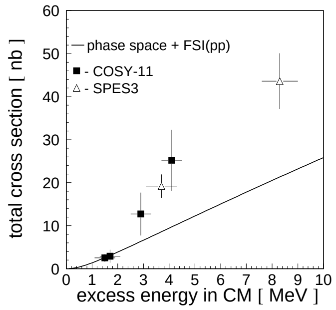

Fig. 3. Energy dependence of the total cross section as given by the phase space factors and the proton-proton final state interaction (solid line). The experimental values of the total cross section for the $pp \to pp\eta'$ reaction are indicated by filled squares (COSY-11 [18]) and by open triangles (SPES3 [19]). The shown errors take account of both, statistical and systematical uncertainties.

Sufficiently close to threshold, the amplitude corresponding to the ${}^3P_0 \to {}^1S_0$ transition in the proton-proton system has a dominant contribution to the $pp \to pp\eta'$ reaction. Therefore, it is enough to consider the ${}^1S_0$ - wave scattering of the outgoing protons.

The solid line in Figure 3 shows the anticipation of these assumptions with a value of M_0 adjusted to the experimental points at excess energies lower than 2 MeV.

In case of the $pp \to pp\eta$ reaction, a similar deviation of the energy dependence for the total cross section from the predictions based on the phase space and the proton-proton final state interaction was taken as an evidence for the η-proton interaction [2, 20]. Albeit η-proton interaction is much weaker than the proton-proton one (compare $a_{p\eta} = (0.5 + i0.3)\ fm$ [2, 21] with $a_{pp} = -7.82\ fm$), it becomes important through the interference terms, since the M_{FSI} amplitude is coherent in terms involving the various final pair interactions [2].

Thus, we may speculate that at very low energies the proton-η' interaction is repulsive, and hence caused the suppression of the total cross section very close to threshold. On the other hand, the observed deviation of the experimental points from the solid line may be attributed to the increase of the primary production amplitude with the increasing excess energy. At present, however, we can not prove any of these hypotheses.

4. $pp \to ppK^+K^-$

The $pp \to ppK^+K^-$ reaction is studied by means of the COSY-11 detection system [22] by measuring momentum and velocity of both protons and K^+ meson, whereas the K^- is identified via the missing mass method [23]. Additionally, the signals from the K^- mesons are registered by the position sensitive silicon pad detector at the inner region of the dipole magnet [24].

Figure 4a shows the invariant mass of the measured K^+ meson versus the missing mass of the identified ppK^+ subsystem, obtained at the excess energy $Q = 9.8\ MeV$. Events corresponding to the $pp \to ppK^+K^-$ reaction are expected at the crossing point of the lines shown in the figure, which indicate the mass of the K mesons.

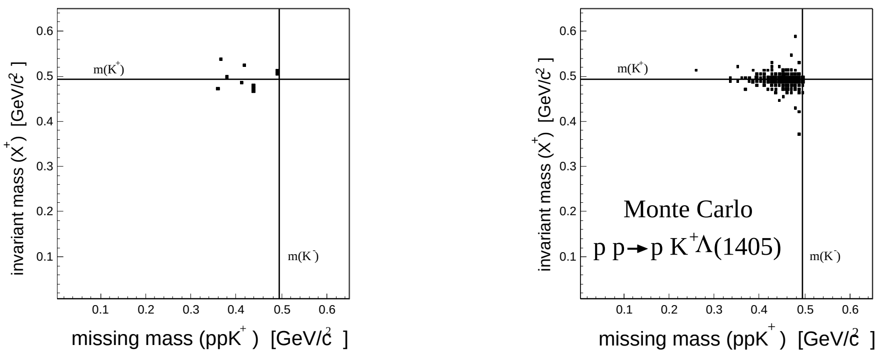

Fig. 4. Invariant mass of the third particle versus the missing mass in the ppK^+ system. **(a)** Experiment at $Q = 9.8\ MeV$, **(b)** Monte Carlo simulations at $Q = 9.8\ MeV$.

The resolution of the mass measurement of the COSY - 11 detection system is proved to be about 1 MeV [18, 1], which implies that expected spread of the K^- mass should be of this order of magnitude. We observe, however, that it is by about a factor of 50 larger!

One of the possible explanations is that one of the measured protons originates from the decay of the $\Lambda(1405)$ or an other resonance, see Figure 4b. This would imply that most of the observed events do not correspond to the direct K^+K^- production but rather to the $pp \to pK^+\Lambda(1405) \to pK^+p\pi\pi\gamma$ reaction. At present, this and other possibilities are intensively studied using the additional information of the position of the negatively charged particles registered by the array of silicon pad detectors.

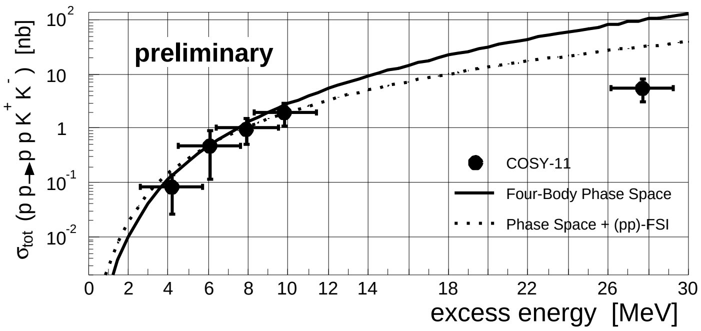

Fig. 5. Upper limit of the cross section for the $pp \to ppK^+K^-$ reaction at different excess energies in the threshold region.

Being aware of this still not solved problems we only can estimate the total cross section for the measured $pp \to ppK^+X$ reaction. The preliminary result is depicted in Figure 5. The shown values of the cross section can be treated as upper limits for the $pp \to ppK^+K^-$ reaction.

It is worth noting, that similarly as in the $pp \to pp\eta$ and $pp \to pp\eta'$ reactions the energy dependence of the total cross section disagrees with the predictions based on the phase space and the proton-proton final state interaction, suggesting a significant influence of the K^+K^- interaction.

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