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Eta physics at threshold

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Abstract. The production of η- and η'-mesons in elementary nucleon-nucleon collisions has been investigated at the synchrotrons CELSIUS, COSY and SATURNE. The high-quality proton beam with low emittance and small momentum spread permits to study the creation of these mesons very close to the kinematical threshold, where —due to the rapid growth of the phase space volume— the total cross-section increases by orders of magnitude over a few MeV range of the excess energy. The magnitude and energy dependence of the total cross-section as well as the occupation distribution of the phase space serve as observables for investigating the mechanisms underlying the production processes and the interaction of mesons with nucleons. The precise data on the η and η' creation via the $pp \to pp\eta(\eta')$ reactions allowed to settle the general features of the η- and η'-meson production and revealed the sensitivity of the mentioned observables to the nucleon-nucleon-meson final-state interaction. The particular production properties, like for example, the determination of the dominating exchange processes which lead to the excitation of the S_{11} nucleon isobar in the case of η creation, must be established by confrontation with other observables. The present status of this investigation with an emphasis on the results of the COSY-11 Collaboration is briefly presented. The available data are interpreted in view of the production mechanism and the meson-nucleon interaction.

PACS. 13.60.Le Meson production – 13.75.-n Hadron-induced low- and intermediate-energy reactions and scattering (energy ≤ 10 GeV) – 13.85.Lg Total cross sections – 25.40.-h Nucleon-induced reactions

1 Manifestation of the η-nucleon-nucleon interaction

In the last decade, large experimental as well as theoretical efforts were concentrated on the study of the creation of η- and η'-mesons via the hadronic interactions. Measurements of the production of these mesons in the elementary nucleon-nucleon collision have been performed in the vicinity of the kinematical threshold where only one partial wave in both initial and final state is expected to contribute to the production process. For example, in case of the proton-proton collision the dominance of the $^3P_0 \to Ss$ transition is expected up to an excess energy of about 40 MeV and 100 MeV for η- and η'-meson, respectively [1]. This simplifies significantly the interpretation of the data, yet still appears to be challenging due to the three-particle final-state system with a complex hadronic potential. The determined energy dependences of the total cross-section for η' [2,3] and η [3,4] mesons in proton-proton collisions are presented in figs. 1 and 2. Comparing the data to the arbitrarily normalized phase-space integral (dashed lines) reveals that the proton-proton FSI enhanced the total cross-section by more than one order of magnitude for low excess energies. One recognizes also that in the case of the η'-meson the calculation —assuming that the on-shell proton-proton amplitude exclusively determines the phase-space population— describes the data very well (solid line). This indicates that the proton-η' interaction is too small to be observed within the present accuracy [5]. In the case of the η-meson the increase of the total cross-section for very low and very high energies is much larger than expected from the final-state interaction between protons. The excess at higher energies can

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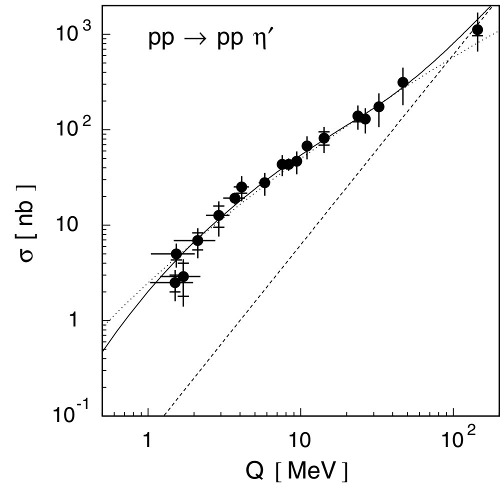

Fig. 1. Total cross-section for the $pp \to pp\eta'$ reaction as a function of the centre-of-mass excess energy Q. Data are from refs. [2,3]. The solid line shows the phase-space distribution with inclusion of proton-proton strong and Coulomb interactions. The dotted line indicates the parametrization of reference [6] with $\epsilon = 0.3$ and the dashed line indicates a phase-space integral normalized arbitrarily. Figure and title are adapted from ref. [1].

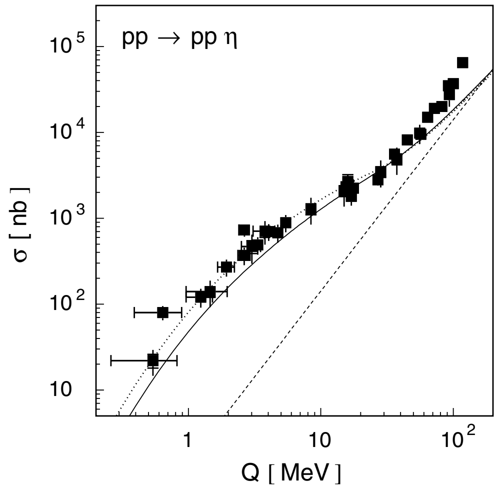

Fig. 2. Total cross-section for the $pp \to pp\eta$ reaction as a function of the centre-of-mass excess energy Q. Data are from refs. [3,4]. The dashed line indicates a phase-space integral normalized arbitrarily. The phase-space distribution with inclusion of proton-proton strong and Coulomb interactions fitted to the data in the excess energy range between 15 and 40 MeV is shown as the solid line. Additional inclusion of the proton-η interaction is indicated by the dotted line. The scattering length $a_{p\eta} = 0.7\,\mathrm{fm} + i\,0.4\,\mathrm{fm}$ and the effective range parameter $b_{p\eta} = -1.50\,\mathrm{fm} - i\,0.24\,\mathrm{fm}$ [7] have been arbitrarily chosen. The figure and caption are adapted from ref. [1].

be assigned to the onset of higher partial waves, and the enhancement at threshold can be plausibly explained by the influence of the attractive interaction between the η-meson and the proton.

Though the simple phenomenological treatment —based on factorization of the transition amplitude into the constant primary production and the on-shell incoherent pairwise interaction among particles— works well for the energy dependence of the total cross-section, it fails completely as far as the description of the differential cross-section is concerned (see the thin solid line in fig. 3).

This discrepancy is rather too large to be utterly caused by the underestimation of the S-wave proton-η interaction. An explanation could be a contribution from P-wave proton-proton interaction [8] or a significant influence of the off-shell effects of the interaction between outgoing particles. Indeed, a much better description of the differantial cross-section shown in fig. 3 is achieved when the enhancement due to the proton-proton FSI is modeled by the inverse of the squared Jost function instead of the on-shell amplitude of the elastic proton-proton scattering (see thick solid line in fig. 3). The Jost function accounts for the off-shell effects of the interacting particles, however it gives wrong energy dependence of the total cross-section, and unfortunately it depends rather strongly on the potential model [9,1] and applied formalism [10]. Therefore, in the framework of this phenomenology it is not possible —with a satisfactory accuracy— to separate the contribution of the proton-η interaction from other effects in a model-independent way. Thus, more sophisticated theoretical calculations are required. An estimation of the nucleon-η scattering parameters has successfully been performed by comparing the close-to-threshold data of the η-meson photoproduction on a deuteron [11] to the calculations performed to the first-order rescattering in the two-body subsystems [12]. The recent investigation of Fix and Arenhövel [13] shows, however, that the three-body dynamics contribute substantially to the total and differential cross-sections of the η photoproduction on the deuteron, and thus it cannot be neglected in the quantitative analysis.

Data of the η-NN system created via the hadronic interaction of nucleons still awaits a strict theoretical explanation. The hitherto performed analysis of the energy dependence of the total cross-section reveals the sensitivity of the data to the η-nucleon interaction. Clearly, further comparative studies of the η-nucleon-nucleon system created in photo- and hadro-production should lead to a better determination of the η-nucleon potential and specifically should be helpful in distinguishing between effects due to the production dynamics and the final-state interaction among the produced particles.

2 Production dynamics

It is rather well established that close to threshold the energy dependence of the total cross-section is due to the interaction among the outgoing particles and that the entire production dynamics manifests itself only in a single constant which determines the magnitude of the total cross-section [1]. Therefore, in spite of the precise measurements of the total cross-section for the creation of η- and η'-mesons in proton-proton as well as of η-meson in

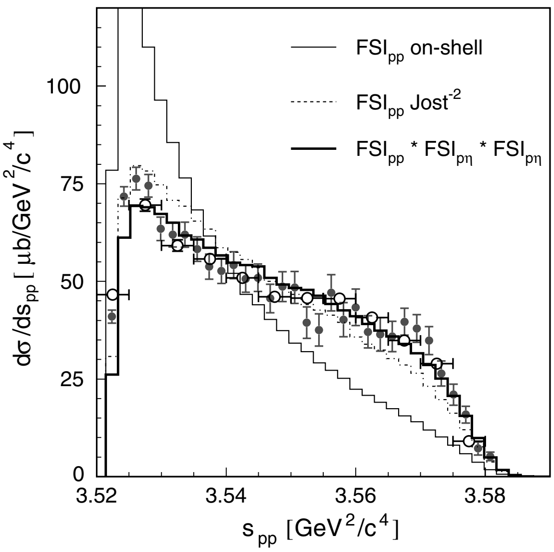

Fig. 3. Experimental distribution of the square of the proton-proton invariant mass (s_{pp}) determined experimentally for the $pp \to pp\eta$ reaction at the excess energy of $Q = 15.5$ MeV by the Collaborations COSY-11 [14] (closed circles) and TOF [15] (open circles). The TOF data have been normalized to give the same total cross-section as those of the COSY-11. The integral of the phase space weighted by the proton-proton on-shell scattering amplitude and by the inverse of the proton-proton squared Jost function [16] is represented by the thin solid and dashed line, respectively. The thick solid line shows the result of the calculations where the occupation density of the phase space was weighted by the inverse of the Jost function multiplied by the square of the proton-η scattering amplitude. The latter was calculated taking arbitrarily the scattering length $a_{p\eta} = 0.7\,\text{fm} + i\,0.4\,\text{fm}$. The lines have been normalized in amplitude to the data.

proton-neutron collisions there are still a lot of ambiguities in the description of the mechanism underlying the production process. It is generally anticipated [17–19] that the η-meson is produced predominantly via the excitation of the S_{11} baryonic resonance $N^*(1535)$, whose creation is induced through the exchange of the virtual π, η, ρ, σ and ω mesons; however, at present it is still not established what are the relative contributions originating from a particular meson. Measurements of the total cross-section in different isospin channels put some more limitations to the models, yet still the η-meson production in the $pp \to pp\eta$ and $pn \to pn\eta$ can be equally well described by, *e.g.*, assuming the ρ-meson exchange dominance [18] or by taking contributions from the pseudoscalar and vector meson exchanges [19]. Therefore, for a full understanding of the production dynamics the determination of polarisation observables is mandatory. Already the precise measurement of the beam analyzing power could exclude one of the above-mentioned possibilities. The first measurement of that quantity has been recently performed [20], but for a conclusive inference a better accuracy of the data is required.

Until now it was also not possible to determine unambiguously the mechanism of the production of the η'-meson [1]. Model uncertainties and in practice only one number —namely the magnitude of the total cross-section of the $pp \to pp\eta'$ reaction— serving as input for theory are by far not sufficient to distinguish between the mesonic, nucleonic or resonant production currents [21]. The understanding of that mechanism on the hadron and quark-gluon level will shed a light on the structure of the η'-meson. A possibly large glue content of the η' wave function and the dominant flavour-singlet combination of its quarks component may cause that the dynamics of its production process in nucleon-nucleon collisions is significantly different from that responsible for the production of other mesons. A creation of that meson via a fusion of gluons excited in the interaction region should lead to the same production yield in proton-proton and proton-neutron collisions, because gluons do not distinguish between flavours [22]. Therefore, it is interesting to determine experimentally the ratio $R_{\eta'} = \sigma(pn \to pn\eta')/\sigma(pp \to pp\eta')$ and to compare it to the already known value of $R_\eta \approx 6.5$ [23]. In the extreme case when the η'-meson is created only from glue excited in the interaction region the ratio $R_{\eta'}$ should be close to unity after the correction for the final- and initial-state interactions between the interacting nucleons [22]. On the contrary, a production mechanism dominated by the isovector meson exchange would yield a significantly larger ratio as already observed in the case of the η-meson. The appropriate experiments are in preparation at the COSY-11 facility [24] and the first feasibility study has already been accomplished sucessfully.

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