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Energy dependence of the near-threshold total cross-section for the $pp \rightarrow pp\eta'$ reaction

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Abstract

Total cross sections for the $pp \rightarrow pp\eta'$ reaction have been measured in the excess energy range from $Q = 1.53$ MeV to $Q = 23.64$ MeV. The experiment has been performed at the internal installation COSY-11 [1] using a stochastically cooled proton beam of the COoler SYnchrotron COSY [2] and a hydrogen cluster target [3,4]. The determined energy dependence of the total cross section weakens the hypothesis of the S-wave repulsive interaction between the η' meson and the proton [5,6]. New data agree well with predictions based on the phase-space distribution modified by the proton-proton final-state-interaction (FSI) only. © 2000 Published by Elsevier Science B.V. All rights reserved.

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Recently, total cross sections for the production of the η' meson in the collision of protons close to the reaction threshold have been published [7,8] for the first time. Two independent experiments performed at the accelerators SATURNE and COSY have delivered consistent results. The data has triggered off an interest in explaining the unknown dynamics of the $pp \rightarrow pp\eta'$ reaction [9–14]. The determined total

cross sections are about a factor of thirty smaller than the ones for the $pp \rightarrow pp\eta$ reaction [7,15–18] at the corresponding values of excess energy. Trying to explain this large difference Hibou et al. [7] showed that calculations within a one-pion exchange model, where the parameters were adjusted to fit the total cross section for the $pp \rightarrow pp\eta$ reaction, underestimate the η' cross sections by about a factor of two.

This discrepancy suggests that short-range production mechanisms as for example heavy meson exchange, mesonic currents [9], or more exotic processes like the production via a fusion of gluons [19] may contribute significantly to the creation of η and η' mesons [13]. Such effects are likely, since the momentum transfer required to create these mesons is much larger than for the pion production, and already in case of the $pp \rightarrow pp\pi^0$ reaction a significant short-range heavy meson exchange contribution is necessary in order to obtain agreement with experimental results [20,21]. On the other hand, Sibirtsev and Cassing [12] concluded that the one-pion exchange model, including the proton-proton final state interaction (pp-FSI), reproduces the magnitude of the experimental data and hence, the other exchange currents either play no role or cancel each other.

It is well established that the η meson is predominantly produced via the excitation of an intermediate baryonic resonance $S_{11}(1535)$ [15,22–26]. Both, the large difference in the production cross sections for η and η' mesons, and the lack of experimentally established baryonic resonances, which would decay into η' , suggest that the $pp \rightarrow pp\eta'$ reaction occurs without an excitation of the colliding protons. Indeed, as demonstrated by Gedalin et al. [11], the magnitude of the close-to-threshold η' production can be explained without a resonant production term. However, for the η' -photoproduction off protons [27–29] the excitation function is described by an assumed coherent excitation of two possible resonances [27] ($S_{11}(1897)$ and $P_{11}(1986)$), which decay into η' and proton. Anticipating this hypothesis, recently Nakayama et al. [9] have shown that it is also possible to explain the magnitude and energy dependence of the close-to-threshold total cross section for the $pp \rightarrow pp\eta'$ reaction assuming a dominance of these resonances and choosing an appropriate ratio of pseudoscalar to pseudovector coupling. However, the mesonic and nucleonic currents alone can describe the data as well [9].

The ambiguities in the description of the $pp \rightarrow pp\eta'$ reaction mechanisms, which are partly due to the poorly known coupling constants, indicate that the theory of the η' meson creation is still far from delivering a complete and univocal picture of the process and call for further theoretical and experimental effort. A possible gluonium admixture in the

η' meson makes the study even more complicated but certainly also more interesting. Albeit the quark content of η and η' mesons is very similar a fusion of gluons emitted from the exchanged quarks of the colliding protons [30] would contribute primarily to the creation of the η' meson which is predominantly a flavour singlet state due to the small pseudoscalar mixing angle ($\Theta_{ps} \approx -15^\circ$) [31].

Another complication in understanding the production mechanism is the unknown η' -proton interaction, which is of course in itself an interesting issue to be studied. One of the remarkable features of the published results on η and η' production is that the energy dependence of the total cross section appears not to follow the predictions based on the phase-space volume folded by the proton-proton final state interaction, which is the case in the π^0 meson production [32,33]. Moreover, for η and η' mesons the deviations from such predictions were qualitatively different: The close-to-threshold cross sections for the η meson are strongly enhanced compared to the model comprising only the proton-proton interaction [15], opposite to the observed suppression in case of the η' [5,6]. The energy dependence of the total cross section for the $pp \rightarrow pp\eta$ reaction can be described when the η -proton attractive interaction is taken into account [34,35]. Although the η -proton interaction is much weaker than the proton-proton one (compare the scattering length $a_{p\eta} = 0.751 \text{ fm} + i 0.274 \text{ fm}$ [36] with $a_{pp} = -7.83 \text{ fm}$ [37]) it becomes important through the interference terms between the various final pair interactions [35]. By analogy, the steep decrease of the total cross section when approaching the kinematical threshold for the $pp \rightarrow pp\eta'$ reaction could have been explained assuming a repulsive η' -proton interaction [5,6]. This interpretation, however, should rather be excluded now in view of the new COSY-11 data reported in this letter.

The experiment has been performed at the cooler synchrotron COSY-Jülich [2], using the COSY-11 facility [1] and the H_2 cluster target [3,4] installed in front of one of the regular COSY dipole magnets. The target, which is realized as a beam of H_2 molecules grouped to clusters of up to 10^6 atoms, crosses perpendicularly the beam of $\sim 2 \cdot 10^{10}$ protons circulating in the ring. The beam of accelerated protons is cooled stochastically during the measure-

Table 1

Total cross sections for the $pp \rightarrow pp\eta'$ reaction with respect to the excess energy in the center-of-mass system. Only statistical errors are quoted. In addition, there is an overall systematic uncertainty of 15% in the cross section and 0.44 MeV in energy

Excess energy [MeV]	Total cross section [nb]
1.53 ± 0.05	5.0 ± 0.68
2.11 ± 0.20	6.9 ± 1.4
5.80 ± 0.06	27.9 ± 3.3
7.57 ± 0.07	43.5 ± 4.3
9.42 ± 0.09	46.8 ± 5.6
10.98 ± 0.12	67.4 ± 8.2
14.21 ± 0.13	$82. \pm 13.$
23.64 ± 0.20	$140. \pm 19.$

ment cycle. Longitudinal and vertical cooling enables to keep the circulating beam practically without energy losses and without a spread of its dimensions when passing $1.6 \cdot 10^6$ times per second through the 10^{14} atoms/cm² thick target during a 60 minutes cycle. The beam dimensions are determined from the distribution of elastically scattered protons and are found to be 2 mm and 5 mm in the horizontal and vertical direction, respectively [38]. Quoted values denote standard deviations of an assumed Gaussian beam density distribution. The $pp \rightarrow pp\eta'$ reaction has been investigated at eight different energies of a proton beam corresponding to excess energies ranging from $Q = 1.53$ MeV to $Q = 23.64$ MeV as listed in Table 1. The total integrated luminosity obtained during two weeks of the experiment amounts to 1.4 pb^{-1} , and was monitored by the simultaneous measurement of elastically scattered protons. A comparison of the measured differential distributions with results from the literature [39] determines the absolute luminosity with the statistical accuracy of 2.5% for each excess energy.

If at the intersection point of the cluster beam with the COSY proton beam the collision of protons results in the production of a meson, then the ejected protons – having smaller momenta than the beam protons – are separated from the circulating beam by the magnetic field. Further they leave the vacuum chamber through a thin exit foil and are registered by the detection system consisting of drift chambers and scintillation counters [1,18]. The hardware trigger, based on signals from scintillation detectors, was

adjusted to register all events with at least two positively charged particles [40]. Tracing back trajectories from the drift chambers through the dipole magnetic field to the target point allowed for the determination of the particle momenta. From momentum and velocity, the latter measured using scintillation detectors, it is possible to identify the mass of the particle. Fig. 1 shows the squared mass of two simultaneously detected particles. A clear separation is seen into groups of events with two protons, two pions, proton and pion and also deuteron and pion. This spectrum enables to select events with two registered protons. The knowledge of the momenta of both protons before and after the reaction allows to calculate the mass of an unobserved particle or system of particles created in the reaction. Fig. 2a depicts the missing mass spectrum obtained for the $pp \rightarrow ppX$ reaction at an excess energy of $Q = 5.8$ MeV above the η' meson production threshold. Most of the entries in this spectrum originate from the multi-pion production [8,40], forming a continuous background to the well distinguished peaks accounting for the creation of ω and η' mesons, which can be seen at mass values of $782 \text{ MeV}/c^2$ and $958 \text{ MeV}/c^2$, respectively. The signal of the $pp \rightarrow pp\eta'$

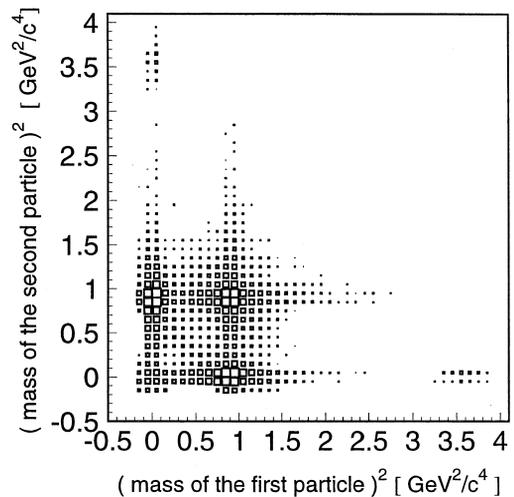


Fig. 1. Squared masses of two positively charged particles measured in coincidence. Pronounced peaks are to be recognized when two protons, proton and pion, two pions, or pion and deuteron were registered. Note that the number of events is shown in logarithmic scale.

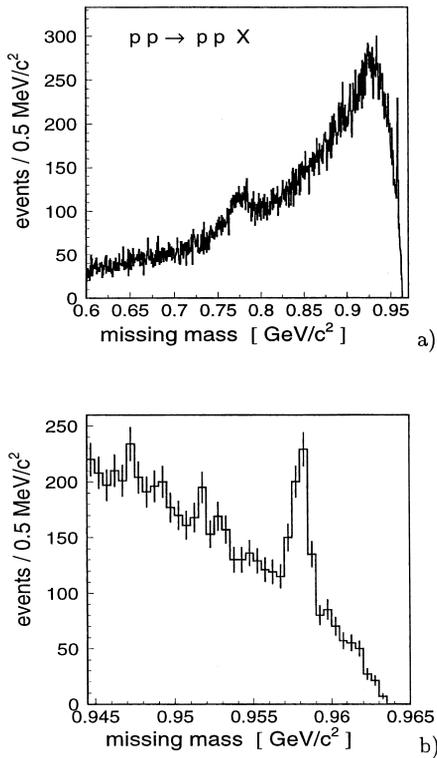


Fig. 2. Mass spectrum of the unobserved particle or system of particles in the $pp \rightarrow ppX$ reaction determined at $Q = 5.8$ MeV above the η' production threshold.

reaction is better to be seen in Fig. 2b, where the missing mass distribution in the vicinity of its kinematical limit is presented. Fig. 3a shows the missing mass spectrum for the measurement at $Q = 7.57$ MeV together with the multi-pion background (dotted line) as combined from the measurements at different excess energies [38]. Subtraction of the background leads to the spectrum with a clear signal at the mass of the η' meson as shown by the solid line in Fig. 3b. The dashed histogram in this figure corresponds to Monte Carlo simulations where the beam and target conditions were deduced from the measurements of elastically scattered protons [38]. The magnitude of the simulated distribution was fitted to the data, but the consistency of the widths is a measure of understanding of the detection system and the target-beam conditions. Histograms from a measurement at $Q = 1.53$ MeV shown in Fig. 3c,d demonstrate the achieved missing-mass resolution at

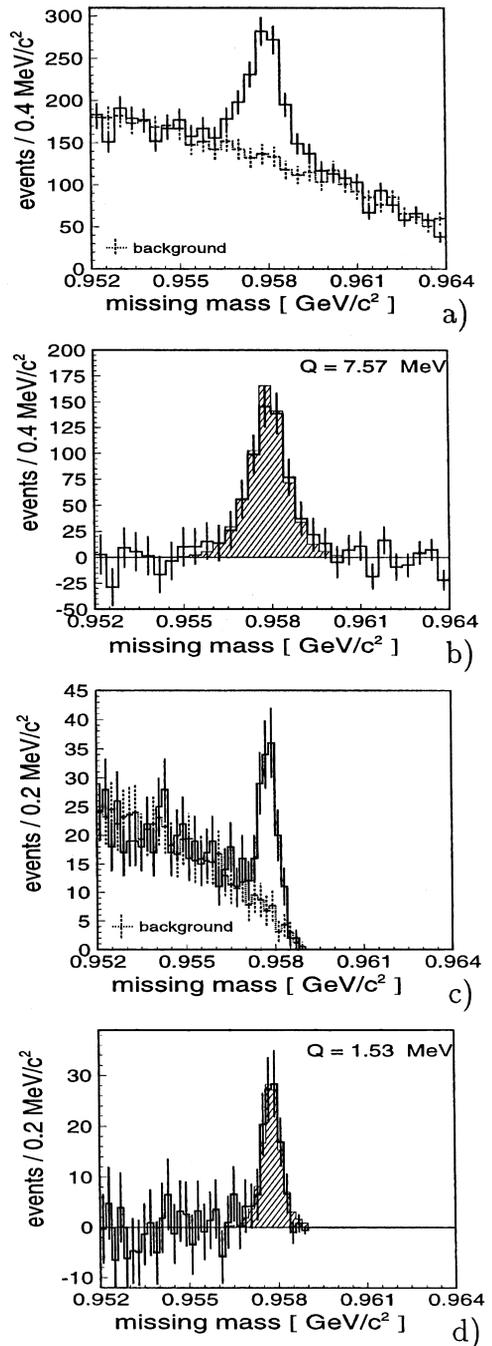


Fig. 3. Missing mass distribution with respect to the proton-proton system: (a),(b) measurements at $Q = 7.57$ MeV and (c),(d) at $Q = 1.53$ MeV. Background shown as dotted lines is combined from the measurements at different energies shifted to the appropriate kinematical limits and normalized to the solid-line histogram. Dashed histograms are obtained by means of Monte Carlo simulations.

the COSY-11 detection system, when using a stochastically cooled proton beam. The width of the missing mass distribution (Fig. 3d), which is now close to the natural width of the η' meson ($\Gamma_{\eta'} = 0.203$ MeV [41]), is again well reproduced by the Monte Carlo simulations. The broadening of the width of the η' signal with increasing excess energy (compare Fig. 3b and 3d) is a kinematical effect discussed in more detail in Ref. [18]. The decreasing signal-to-background ratio with growing excess energy is due to the broadening of the η' peak and the increasing background (see Fig. 2b) when moving away from the kinematical limit. At the same time, the shape of the background, determined by the convolution of the detector acceptance and the distribution of the two- and three-pion production [40], remains unchanged within the studied range of beam momenta from 3.213 GeV/c to 3.283 GeV/c. The signal-to-background ratio changes from 1.8 at $Q = 1.53$ MeV to 0.17 at $Q = 23.64$ MeV. The geometrical acceptance, being defined by the gap of the dipole magnet and the scintillation detector most distant from the target [1,18], decreases from 50% to 4% within this range of excess energies. However, in the horizontal plane the range of polar scattering angles is still unlimited. The calculated acceptance depends on the angular distribution of the reaction products, which was assumed to be defined by the three body phase-space and the interaction of the outgoing protons. Calculating acceptance, the proton-proton FSI was taken into account by weighting phase-space generated events by the square of the proton-proton 1S_0 -wave amplitude, $|A|^2$. The enhancement, $|A|^2$, from the proton-proton FSI was estimated as an inverse of the squared Jost function, with Coulomb interaction being taken into account [42]. Generally, the attractive proton-proton FSI lowers the angle between outgoing protons, increasing the acceptance. However, at the same time the efficiency for the reconstruction of both proton trajectories decreases. For the first five measurements denoted in Table 1 both effects are in the order of 3% and cancel each other. An increase of the overall efficiency is crucial only for the last two points listed in Table 1 and amounts to 9% and 25% for $Q = 14.21$ MeV and $Q = 23.64$ MeV, respectively. In order to estimate a systematical error due to the inaccuracy of the pp-FSI, we calculated the acceptance using an-

other prescription for $|A|^2$, which was obtained from the phase-shifts [43] calculated according to the modified Cini-Fubini-Stanghellini formula with the Wong-Noyes Coulomb correction [37,44,45]. Now the obtained efficiency was 13% and 34% larger as compared to the pure phase-space calculations for $Q = 14.21$ MeV and $Q = 23.64$ MeV, respectively. Thus, for the highest energy there is a 9% difference depending on the applied prescription. The second main source of the systematical error is the inaccuracy of the determination of the two-track reconstruction efficiency. This was established to be 9% at $Q = 1.53$ MeV [40] and close to zero at $Q = 23.64$ MeV. This uncertainty decreases with increasing Q , since at higher excess energy the probability that the tracks of the protons will be too close to be unresolved by the drift chambers is reduced. In addition to the discussed sources of the systematical error, which add up to 9% inaccuracy independent of energy, there are further systematical uncertainties with respect to i) the geometry of the detection system (2%), ii) the estimated losses due to the multiple scattering or nuclear reactions (1%) and iii) the luminosity determination (3%) [40]. Hence, the overall systematical error of the cross section values, including the normalization uncertainty, amounts to 15%.

Fig. 4 shows the compilation of total cross sections for the η' meson production. The data reported here are shown as filled circles. The absolute value of the excess energy was determined from the position of the η' peak in the missing mass spectrum, which should correspond to the mass of the meson η' . The systematical error of the excess energy established by this method equals to 0.44 MeV and constitutes of 0.14 MeV due to the uncertainty of the η' meson mass [41] and of 0.3 MeV due to the inaccuracy of the detection system geometry [46], with the largest effect originating from the inexactness of relative settings of target, dipole and drift chambers.

The solid line depicts calculations of the total cross section assuming that the primary production amplitude is constant and that only a proton-proton interaction significantly influences the exit channel. The magnitude was fitted to the data and the obtained χ^2 value per degree of freedom amounts to 1.6. An inclusion of the η' -proton interaction in the

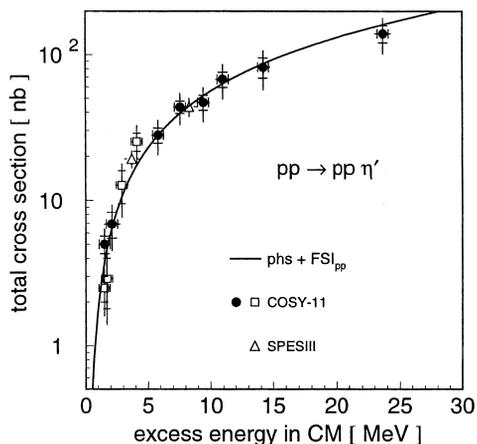


Fig. 4. Total cross sections for the $pp \rightarrow pp\eta'$ reaction as a function of the center-of-mass excess energy. Open squares and triangles are from Refs. [8] and [7], respectively. Filled circles indicate the results of the COSY-11 measurements reported in this letter. Corresponding numerical values are given in Table 1. Statistical and systematic errors are separated by dashes. The solid line shows the phase-space distribution with the inclusion of proton-proton strong and Coulomb interactions.

scattering length approximation, by factorizing p-p and η' -p FSI, resulted in a rather modest estimation of the real part of the η' -proton scattering length: $|Re a_{\eta'p}| < 0.8$ fm. The proton-proton scattering amplitude was computed according to the formulas from Ref. [42]. The obtained energy dependence (solid line in Fig. 4) agrees within a few line thicknesses with the model developed by Fäldt and Wilkin [47].

The present data show that the phase-space volume weighted by the proton-proton FSI describes the near-threshold energy dependence of the total cross section for the $pp \rightarrow pp\eta'$ reaction quite well. The influence of the η' -proton FSI on the energy dependence of the total cross section is too weak to be seen within the up-to-date experimental accuracy. Based on the energy dependence of the total cross section only, it is impossible to decouple effects from η' -proton FSI and primary production amplitude. As shown by Nakayama et al. [9] the variation of the energy dependence of the total cross section, due to the production mechanism in the discussed energy range, can be in the order of 10%. To learn more about the η' -proton interaction a determination of differential cross sections is required.

It is interesting to note that in proton-proton collisions at much higher momenta (450 GeV/c) the η and η' mesons seem to have a similar production mechanism which differs from that of the π^0 one [48]. However, close to threshold the data show similarities between η' and π^0 mesons rather than between the η and η' .

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