Heavy Meson Production at COSY - 11

P. Moskal[a], H. -H. Adam[b], J. T. Balewski[c,d,e], A. Budzanowski[c], C. Goodman[e], D. Grzonka[d], L. Jarczyk[a], M. Jochmann[f], A. Khoukaz[b], K. Kilian[d], P. Kowina[g], M. Köhler[f], T. Lister[b], W. Oelert[d], C. Quentmeier[b], R. Santo[b], G. Schepers[b,d], U. Seddik[h], T. Sefzick[d], S. Sewerin[d], J. Smyrski[a], A. Strzałkowski[a], M. Wolke[d], P. Wüstner[f]

[a] *Institute of Physics, Jagellonian University, PL–30059 Cracow, Poland*
[b] *IKP, Westf. Wilhelms-Universität, Wilhelm-Klemm-Straße 9, D–48149 Münster, Germany*
[c] *Institute of Nuclear Physics, ul. Radzikowskiego 152, PL-31-342 Cracow, Poland*
[d] *Institut für Kernphysik, Forschungszentrum Jülich, D–52425 Jülich, Germany*
[e] *IUCF, Milo B. Samson Lane, Bloomington, IN 47405, USA*
[f] *ZEL, Forschungszentrum Jülich, D–52425 Jülich, Germany*
[g] *Institute of Physics, Silesian University, PL-40-007 Katowice, Poland*
[h] *Egyptian Atomic Energy Authority, 101 Sharia Kaser El-Aini, 13759 Cairo, Egypt*

Abstract. The COSY-11 collaboration has measured the total cross section for the $pp \to pp\eta'$ and $pp \to pp\eta$ reactions in the excess energy range from Q = 1.5 MeV to Q = 23.6 MeV and from Q = 0.5 MeV to Q = 5.4 MeV, respectively. Measurements have been performed with the total luminosity of 73 nb^{-1} for the $pp \to pp\eta$ reaction and 1360 nb^{-1} for the $pp \to pp\eta'$ one. Recent results are presented and discussed.

INTRODUCTION

The word heavy used in the title requires a short explanation. The reason is rather historical, and it seems now that heavy are all mesons but not pions. The talk will concern the production of the η and η' mesons, and since η' is even heavier than η the discussion concerning this meson will constitute the major part of the presentation.

Last year, for the first time total cross sections for the production of the η' meson in the collision of protons close to the reaction threshold have been published [1,2]. Two independent experiments performed at the accelerators SATURNE and COSY have delivered consistent results.

The first remarkable inference derived from these experiments was that the total cross sections for the $pp \to pp\eta'$ reaction are by about a factor of fifty smaller than the cross sections for the $pp \to pp\eta$ reaction at the corresponding values of the excess energy. Trying to explain this large difference Hibou et al. [1] showed that the one-pion-exchange model with the parameters adjusted to fit the total cross section for the $pp \to pp\eta$ reaction underestimate the η' data by about a factor of two. This discrepancy suggests that short-range production mechanisms as for example heavy meson exchange, mesonic currents [3], or more exotic processes like the production via a fusion of gluons [4] may contribute significantly in the creation of η and η' mesons [5]. Especially that the momentum transfer required to create these mesons is much larger compared to the pion production, and already in case of pions a significant contribution from the short-range heavy meson exchange is necessary in order to obtain agreement with the experiments [6,7].

The second interesting observation was that the energy dependence of the total cross section for the $pp \to pp\eta$ and $pp \to pp\eta'$ reactions does not follow the predictions based on the phase space volume and the proton-proton final state interaction, which is the case in the π^0 meson production [8,9]. Moreover, for η and η' mesons the deviation from this prediction were qualitatively different. Namely, the close to threshold cross sections for the η meson are strongly enhanced compared to the model comprising only the proton-proton interaction [10] in contrary to the observed suppression in the case of the meson η'. The energy dependence of the total cross section for the $pp \to pp\eta$ reaction can be, however, explained when the η-proton attractive interaction is taken into account [11,12]. Albeit η-proton interaction is much weaker than the proton-proton one (compare scattering length $a_{p\eta} = 0.751$ fm + i 0.274 fm [13] with $a_{pp} = -7.83$ fm [14]) it becomes important through the interference terms between the various final pair interactions [12]. By analogy, the steep decrease of the total cross section when approaching a kinematical threshold for the $pp \to pp\eta'$ reaction could have been explained assuming a repulsive η'-proton interaction [15,16]. This interpretation, however, should rather be excluded now in view of the new COSY-11 data which will be presented in the next chapters.

POSSIBLE PRODUCTION MECHANISMS

The theoretical studies of the mechanisms accounting for the π^0 and η mesons creation in the close to threshold $pp \to pp\pi^0(\eta)$ reactions have shown that the short-range component of the N-N force and the off-shell pion rescattering dominate the production process of the π^0 meson [6,7,17], whereas the η meson is predominantly produced through the excitation of the intermediate baryonic resonance [18–21,10]. However, the comparison of the experimentally determined η and η' total cross section ratio with the predictions based on the one-pion-exchange model indicates that we are still far from the full understanding of the dynamics of the discussed processes. In particular, at present there is not much known about the relative contribution of the possible reaction mechanisms to the production of the meson η'. It is expected that similarly as in the case of pions the η' meson can be produced as depicted in Figures 1a,b,c,d. However, because of the much larger four-momentum transfer, short-range mechanisms, like heavy meson exchange (Figure 1c) or depicted in Figure 1e production via a mesonic current, where the η' is created in a fusion of exchanged virtual ω, ρ, or σ mesons shell contribute even more significantly. Recently Nakayama et al. [3], studied contributions from the *nucleonic* (Fig. 1b), *nucleon resonance* (Fig. 1d), and *mesonic* (Fig. 1e) currents and found that each one separately could describe the absolute values and energy dependence of the close to threshold η' data points [1,2] after an appropriate adjustment of the ratio of the pseudoscalar to the pseudovector coupling. This rather pessimistic conclusion means that it is not possible to judge about the mechanisms responsible for the η' meson production from the total cross section alone.

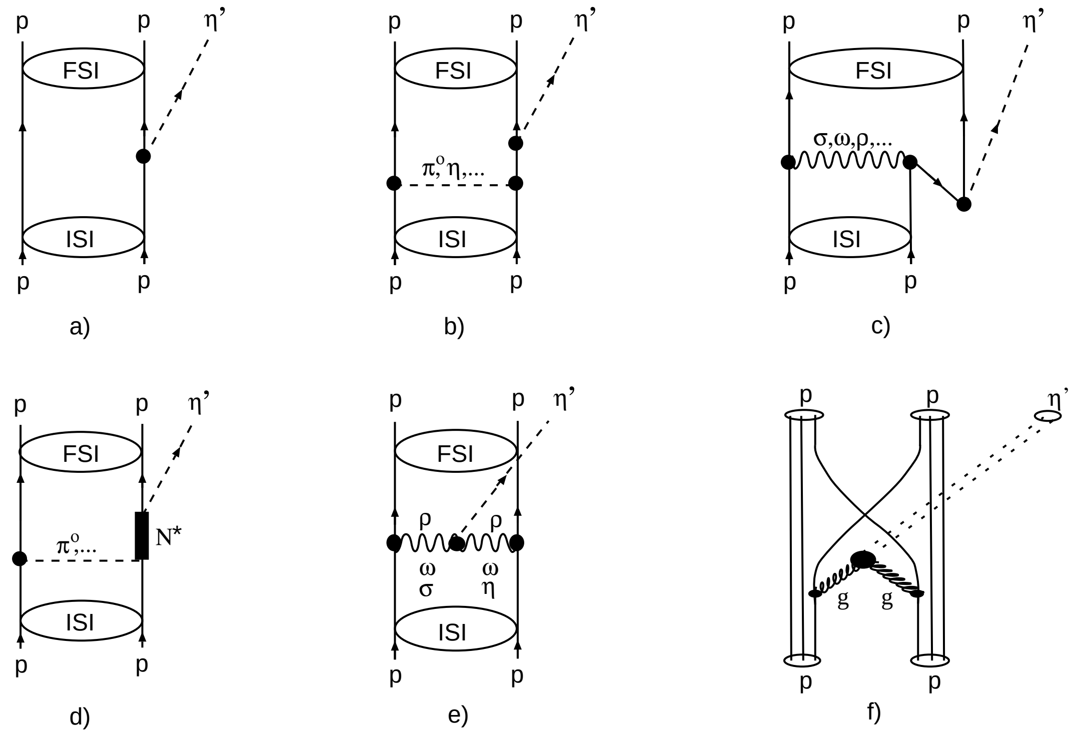

FIGURE 1. Diagrams for the $pp \to pp\eta'$ reaction near-threshold: (a)— η'-bremsstrahlung (nucleonic current) (b)— "rescattering" term (nucleonic current) (c)— production through the heavy meson exchange (d)— excitation of an intermediate resonance (nucleon resonance current) (e)— emission from the virtual meson (mesonic current) (f)— production via a fusion of gluons (gluonic current).

Moreover, the possible gluonium admixture in the meson η' makes the study even more complicated but certainly also more interesting. Figure 1f depicts appropriate short-range mechanism which may lead to the creation of the flavour singlet state via a fusion of gluons emitted from the exchanged quarks of the colliding protons [22]. Albeit the quark content of η and η' mesons is very similar, this manner of the production should contribute primarily in the creation of the meson η'. This is due to the small pseudoscalar mixing angle ($\Theta_{PS} \approx -15^o$) [23] which implies that the η' meson is predominantly a flavour singlet state and is expected to contain a significant admixture of gluons. Further, it is almost two times heavier than η and hence its creation requires much larger momentum transfer which is more probable to be realized in the short-range interactions. Unfortunately, at present there are no theoretical calculations concerning this mechanism. Now, since the effective coupling constant describing the η'-proton-proton vertex is not known, it is even not possible to determine the contribution from the simplest possible production mechanism where the η' is supposed to be emitted as a bremsstrahlung radiation from one of the colliding protons as it is shown in Figure 1a. Therefore, investigations of the η' production have to deal with a few problems at the same time. Namely: unknown reaction mechanism, unknown coupling constant, and unknown proton-η' interaction. In the next section the present status of the knowledge about the effective NNη' coupling constant will be given.

$NN\eta'$ coupling constant

In the effective Lagrangian approach [24,25] the strength of the nucleon-η' coupling is driven by the the $NN\eta'$ coupling constant $g_{NN\eta'}$, which comprises the information about the structure of the η' meson and the nucleon. The knowledge of the coupling constant is necessary in the calculation of the production cross section if one considers the Feynman diagrams as illustrated in Figure 1.

The main difficulty in the determination of this quantity is due to the fact that usually the direct production on the nucleon is either associated with the production through baryonic resonances, as in the case of the $\gamma p \to \eta' p$ reaction [26], or with the exchange of other mesons. Therefore, if the direct production mechanism is not dominant it is not possible to extract the $NN\eta'$ coupling without the clear understanding of the other mechanisms. However, it would be very interesting to determine the $g_{NN\eta'}$ coupling constant and to compare it with the calculations performed on the quark level assuming the η' meson structure. First theoretical considerations concerning this issue have been published last year [27].

Assuming that the η and η' mesons are mixtures of the SU(3) singlet and octet states, one can relate the $NN\eta$ and $NN\eta'$ coupling constants by the following equation [24,28]:

$$g_{NN\eta'} = \frac{sin\Theta + \sqrt{2}cos\Theta}{cos\Theta - \sqrt{2}sin\Theta} \cdot g_{NN\eta} \xlongequal{\Theta=-15.5^{\circ}} 0.82 \cdot g_{NN\eta}. \qquad (1)$$

The measurements of the $\gamma p \to p\eta$ [29,30] reaction have yielded that: $0.2 \leq g_{NN\eta} \leq 6.2$, whereas the comparison of the $\pi^- p \to \eta n$ and $\pi^- p \to \pi^0 n$ reaction cross sections implies [29]: $5.7 \leq g_{NN\eta} \leq 9.0$. The above inequalities and equation 1 lead to the following range for the $g_{NN\eta'}$ value: $\mathbf{4.7} \leq \mathbf{g_{NN\eta'}} \leq \mathbf{5.1}$, which is to be compared to the η' coupling determined from the fits to low energy nucleon-nucleon scattering in the one-boson-exchange models amounting to $g_{NN\eta'} = 7.3$ [31].

On the other hand, the $g_{NN\eta'}$ coupling constant determined via dispersion methods [32] turns out to be smaller than 1, $g_{NN\eta'} < 1$, which is in contradiction to the above estimations.

The $g_{NN\eta'}$ coupling constant is also related to the issue of the total quark contribution to the proton spin ($\Delta\Sigma$). The approximate equation derived in reference [33] reads: $\Delta\Sigma = \Delta u + \Delta d + \Delta s = \frac{\sqrt{3} f_{\eta'}}{2M} g_{NN\eta'}$, where, $f_{\eta'} \approx 166\ MeV$ [33] denotes the η' decay constant and M the proton mass. Δu, Δd and Δs are the contributions from up, down and strange quarks, respectively [1]. The total contribution of the quarks to the proton spin amounts to $\Delta\Sigma = 0.38^{+0.09}_{-0.10}$ [34]. Applying this value in the above equation one obtains $g_{NN\eta'} = 2.48^{+0.59}_{-0.65}$, which is consistent with the upper limit ($g_{NN\eta'} \leq 2.5$) set from the comparison of the measured total cross section values for the $pp \to pp\eta'$ reaction with the calculations based on the effective Lagrangian approach, where only a direct production has been considered [2].

The present estimations for $g_{NN\eta'}$ inferred from different experiments are widely spread from 0.2 to 7.3 and are not consistent with each others. Therefore more effort is needed on experimental as well as theoretical side to fix this important parameter.

THE COSY - 11 EXPERIMENT

The experiments were performed at the cooler synchrotron COSY-Jülich [42] which accelerates protons up to a momentum of 3500 MeV/c. The threshold momenta for the $pp \to pp\eta$ and $pp \to pp\eta'$ reactions are equal to **1981.6 MeV/c** and **3208.3 MeV/c**, respectively. About $2 \cdot 10^{10}$ accelerated protons circulate in the ring passing $1.6 \cdot 10^{6}$ times per second through the H_2 cluster target [43,44] installed in front of one of the dipole magnets, as depicted schematically in Figure 2. The target is realized as a beam of H_2 molecules grouped inside clusters of up to 10^5 atoms.

At the intersection point of the cluster beam with the COSY proton beam the collision of protons may result for example in the production of the η' meson. The ejected protons of the $pp \to pp\eta(\eta')$ reaction, 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 as depicted in Figure 2.

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1) Contribution of quarks heavier than the *strange* quark are usually not considered, but I. Halperin and A. Zhitnitsky suggested [41] that the intrinsic charm component of proton may also carry a significant amount of the proton spin. The quark and gluon contributions to the proton spin are widely discussed in the literature [33–40] based on measurements of the spin asymmetries in deep-inealstic scattering of polarised muons on polarised protons.

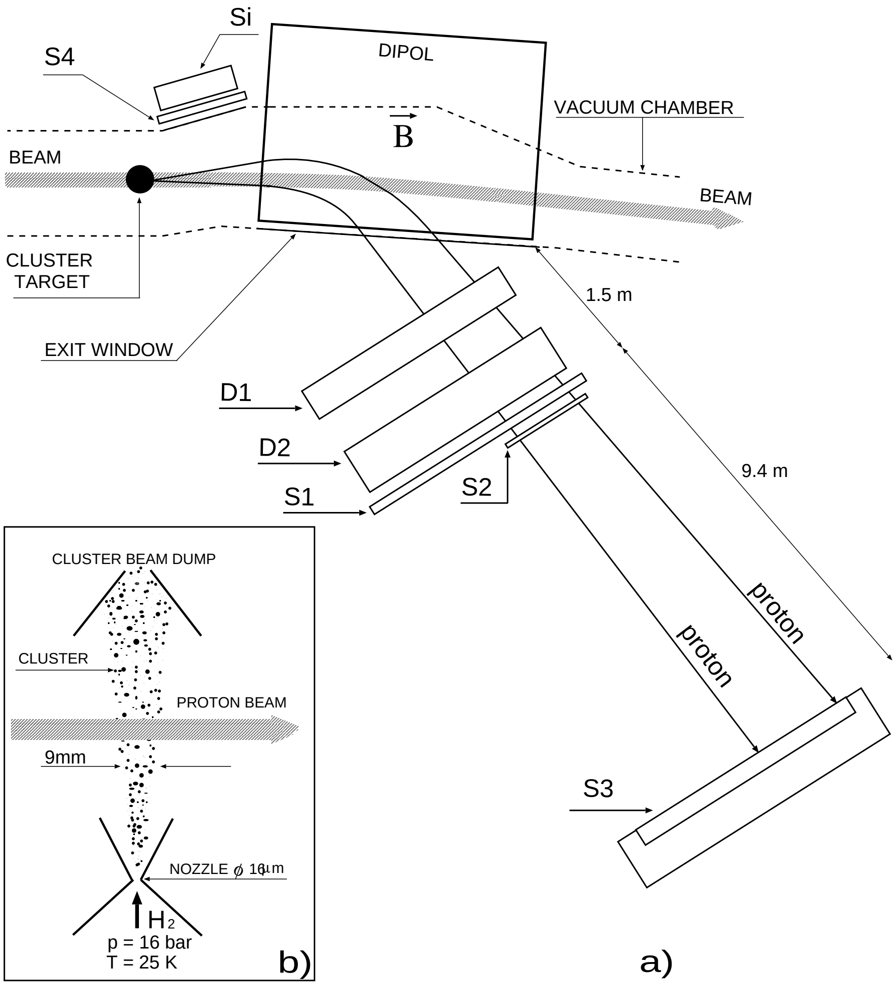

FIGURE 2. a) Schematic view of the COSY-11 detection setup [45]. Only detectors used for the measurements of the $pp \rightarrow pp\eta(\eta')$ reactions are shown.
The cluster target is located in front of the accelerator dipole magnet. Protons from the $pp \rightarrow pp\eta(\eta')$ reaction are bent by the magnetic field of the dipole magnet, whereas the beam particles keep circulating in the COSY ring. The decay products of the η or η' mesons are not shown, since the analysis is based on the measurement of the four-momenta of the outgoing protons, which leave the vacuum chamber through the thin exit foil and are detected: i) in two drift chamber stacks D1, D2, ii) in the scintillator hodoscopes S1, S2, iii) and in the scintillator wall S3. For the measurement of the elastically scattered protons, additionally, scintillation detector S4 and silicon pad detector Si are used in coincidence with the S1, D1 and D2 detectors.
b) Schematic view of the cluster target.

The measurement of the track direction by means of the drift chambers, and the knowledge of both the dipol magnetic field and the target position allow to reconstruct the momentum vector for each registered particle. The time of flight measured between the S1 (S2) - and the S3 scintillators gives the particle velocity.

Having momentum and velocity for each particle one can calculate its mass, and hence identify it.

In the first step of the data analysis events with two tracks in drift chambers were preselected, and the mass of each particle was evaluated. Figure 3 shows the squared mass of two simultaneously detected particles. A clear separations is seen into groups of events with two protons, two pions, proton and pion and also deuteron and pion. Thus, this spectrum allowed for a software selection of events with two registered protons.

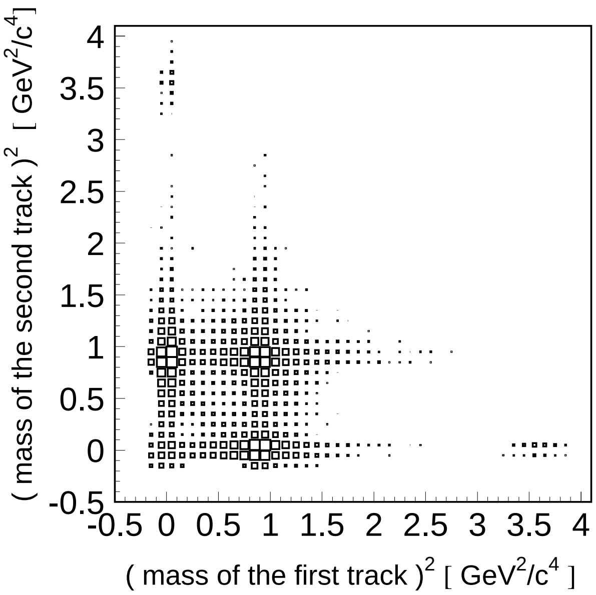

FIGURE 3. Squared masses of two positively charged particles measured in coincidence. Pronounced peaks are to be recognized when two protons, proton and pion, two pions, or pion and deuteron were registered. Note that the number of events is shown in logarithmic scale.

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. Figure 4a depicts the missing mass spectrum obtained for the $pp \rightarrow ppX$ reaction at the excess energy value of Q = 5.8 MeV above the η' meson production threshold. Most of the entries in this spectrum originate in the multi-pion production, forming a continuous background to the well distinguishable peaks accounting for the ω and η' mesons production, which can be seen at mass values of 782 MeV/c^2 and 958 MeV/c^2, respectively. The signal of the $pp \rightarrow pp\eta'$ reaction is better to be seen in the Figure 4b, where the missing mass distribution only in the vicinity of the kinematical limit is presented. Figure 4c shows the missing mass spectrum for the measurement at Q = 7.6 MeV together with the multi-pion background as combined from the measurements at different excess energies [46]. Subtraction of the background leads to the spectrum with a clear peak at the mass of the meson η' as shown by the solid line in Figure 4d. The dashed histogram in this figure corresponds to the Monte-Carlo simulations where the beam and target conditions were deduced from the measurements of the elastically scattered protons [46].

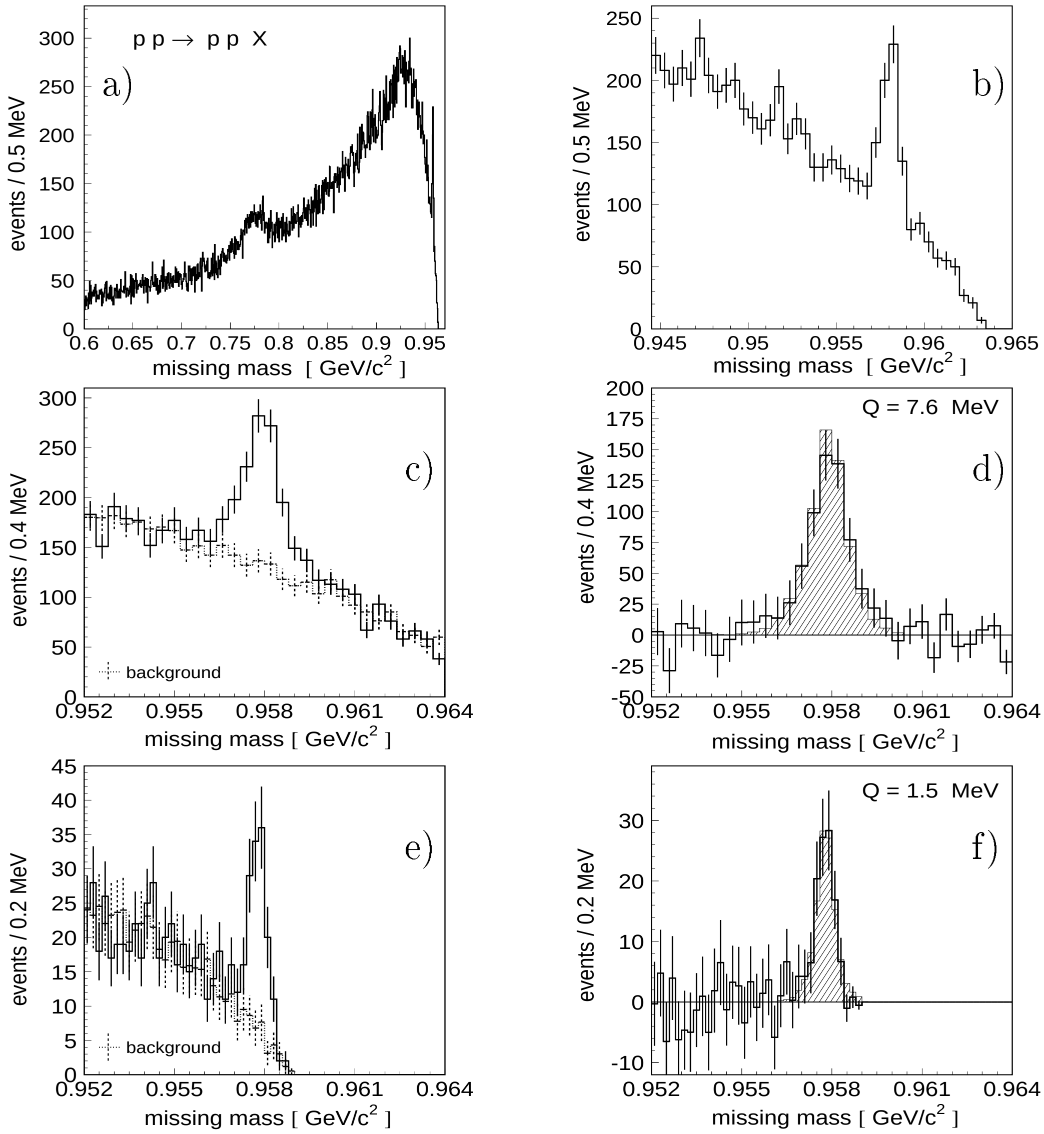

FIGURE 4. Missing mass of the unobserved particle or system of particles; **upper row:** measurements at Q = 5.8 MeV above the η' production threshold; **middle row:** at Q = 7.6 MeV; and **lower row:** at Q = 1.5 MeV. Background shown as dotted lines is combined from the measurements at different energies shifted to the appropriate kinematical limits and normalized to the solid-line histogram.

The scale of the simulated distribution was adjusted to fit 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 = 1.5 MeV shown in Figures 4e,f demonstrate the achieved accuracy at the COSY-11 detection system. The width of the missing mass distribution (Fig. 4f), which is now close to the natural width of the η' meson ($\Gamma_{\eta'} = 0.203$ MeV [47]), is again well reproduced by the Monte-Carlo simulations.

RESULTS

Total cross section

Determination of (a) number of the produced η' events from the presented above missing mass distributions, (b) luminosity from the simultaneous measurements of the elastically scattered protons, and (c) detection system acceptance by means of the Monte-Carlo simulations allows for the calculations of the total cross section for the $pp \to pp\eta'$ reaction. The total cross section for the $pp \to pp\eta$ reaction was determined by the same method, however, with a much bigger signal to background ratio (40/1) due to the larger total cross section values [48].

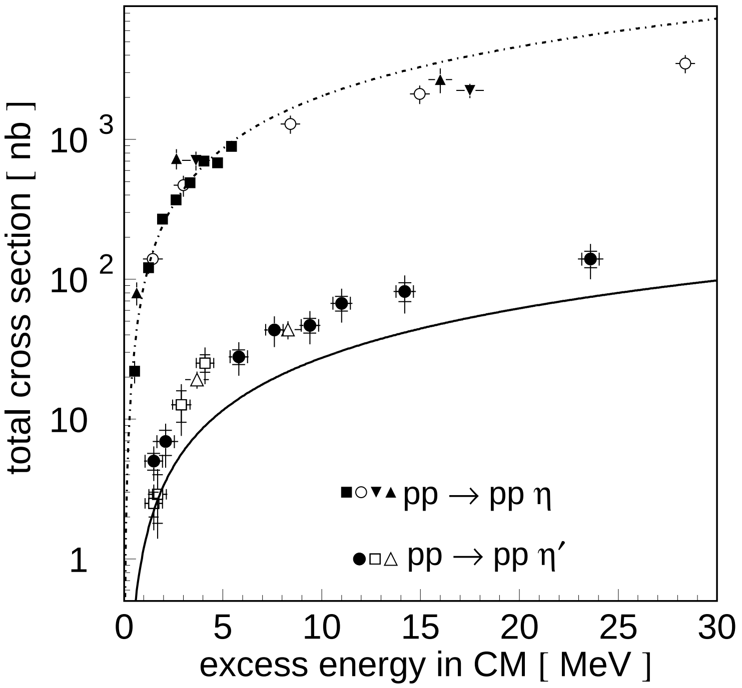

FIGURE 5. Total cross section for the reactions $pp \to pp\eta$ (upper points) and $pp \to pp\eta'$ (lower points). Solid squares and solid circles corresponds to the yet unpublished COSY - 11 results. Triangles indicate measurements performed at SATURNE [1,49], open circles at CELSIUS [10], and open squares at COSY [2]. The curves are explained in the text.

Figure 5 shows the compilation of the total cross sections for the η and η' meson production together with the new COSY-11 data shown as filled squares (η) and filled circles (η'). The COSY-11 data on the η production were taken changing continously during the measurement cycle a momentum of the uncooled proton beam. This technique allowed for the precise determination of the total cross section energy dependence near the kinematical threshold. The obtained result confirmed the enhancement of the close to threshold total cross section values compared to the predictions based on the phase space factors and the proton-proton FSI which was earlier observed by the PINOT [49], WASA [10], and SPES III [1,50] collaborations.

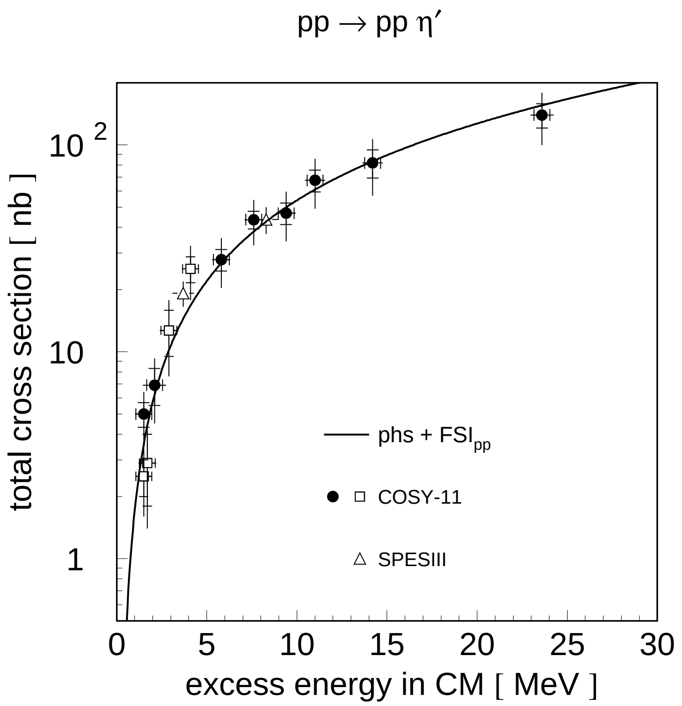

FIGURE 6. Total cross section for the $pp \to pp\eta'$ reaction as a function of the center of mass excess energy. Open squares and triangles are from references [2] and [1], respectively. Filled circles indicate the results of the analysis of the COSY - 11 measurements performed in February 1998. The solid line depicts calculations of the total cross section under assumption that the primary production amplitude is constant and that only a proton-proton interaction take place in the exit channel. The proton-proton scattering amplitude was computed according to the formulas from reference [53]. The obtained energy dependence agrees within a few line thickness with the Fäldt and Wilkin model [52] presented in Figure 5 as a solid line.

New COSY - 11 data concerning η' meson production are shown in Figure 5 as filled circles. These measurements on the $pp \to pp\eta'$ reaction were performed with the stochastically cooled proton beam and the integrated luminosity of 1360 nb^{-1}. Statistical and systematical errors are separated by dashes. The systematical error of the energy equals to 0.44 MeV constitutes of the 0.3 MeV due to the uncertainty in the detection system [51] and 0.14 MeV due to the uncertainty in the η' meson mass [47]. The systematical error of the cross section values, including the overall normalization uncertainty, amounts to 15 % [2,28]. It is worth to stress again, that

SPES III and COSY - 11 results obtained at different laboratories are in a perfect agreement.

The dashed-dotted line in Figure 5 shows the energy dependence predicted by Fäldt and Wilkin [52] normalized now to the COSY-11 data points, and the solid line corresponds to the predictions based on a one-pion-exchange model adjusted to fit the close to threshold $pp \to pp\eta$ data (dashed line) [1]. The factor two discrepancy suggests that the short-range mechanisms may play a prominent role in the production of these mesons [5,4]. However, recent calculations performed by Nakayama et al. [3] indicate that the determination of the total cross section close to threshold is surely not sufficient to establish the contributions from different mechanisms to the overall production amplitude. Specifically, the primary production amplitude for processes studied by these authors (Fig. 1b,d,e) does not change significantly within the present experimental accuracy for the excess energies below Q = 30 MeV. Therefore, the energy dependence of the total cross section for Q $\leq$ 30 MeV should be quite well described by the integral of the phase space volume weighted by the squared amplitude of the final state interaction among the outgoing particles. And indeed, as shown in Figure 6, the data are in a good agreement with this model even without considering the η'-proton interaction. This leads to the conclusion that the η'-proton interaction is too weak to influence considerably, within the experimental error bars, the total cross section energy-dependence.

Primary production amplitudes

The cross section for the reaction $pp \to ppX$ can be expressed as:

$$\sigma_{pp\to ppX} = \frac{\int phase\ space \cdot |M_{pp\to ppX}|^2}{flux\ factor}, \tag{2}$$

where, $M_{pp\to ppX}$ denotes the transition matrix element for the $pp \to ppX$ reaction, and X stands for π^0, η or η' mesons. In analogy with the *Watson-Migdal* approximation [54] for two body processes, it can be assumed that the complete transition amplitude of a production process $M_{pp\to ppX}$ factorizes approximately as [12]:

$$M_{pp\to ppX} \approx M_0 \cdot M_{FSI} \tag{3}$$

where, M_0 accounts for all possible production processes, and M_{FSI} describes the elastic interaction of protons and X meson in the exit channel. Making further assumptions that only the proton-proton interaction is present in the exit channel ($M_{FSI} = M_{pp\to pp}$) and that the primary production amplitude does not change with the excess energy, it is possible to calculate $|M_0|$. The enhancement from the proton-proton interaction, $|M_{pp\to pp}|^2$, was estimated as an inverse of the squared Jost function, with Coulomb interaction being taken into account [53]. The

$|M_{pp\to pp}|^2$ is a dimensionless factor which turns to zero with vanishing relative protons momentum k, peaks sharply at k≈25 MeV/c and approaches asymptotically unity for large proton-proton relative momenta.

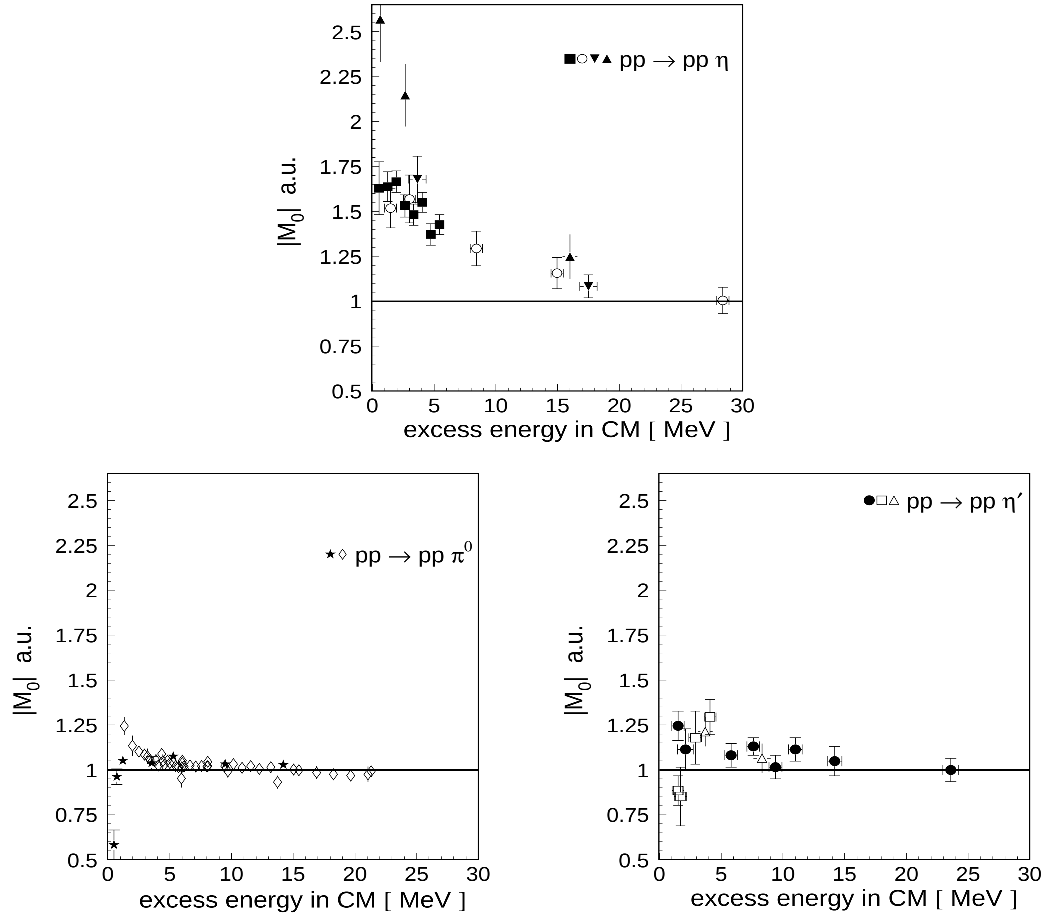

FIGURE 7. Quantity $|M_0|$ extracted from the experimental data for the reactions $pp \to pp\eta$ — upper picture; $pp \to pp\pi^0$ — left picture; $pp \to pp\eta'$ — right picture;

Figure 7 compares the extracted absolute values for the modulus of the primary production amplitude for the near-threshold production of the η, π^0 and η' mesons. The quantity $|M_0|$ is normalized to unity at the point of highest excess energy, for each meson separately. If the performed assumptions in the derivation of $|M_0|$ were fulfilled the obtained values would be equal to one as depicted by the solid line. It can be seen, however, that in the case of the η meson, $|M_0|$ grows with decreasing excess energy reflecting attractive η-proton interaction. In the data for the π^0 production, apart from the two closest-to-threshold points[2], one can notice a tiny grow of $|M_0|$ when the excess energy decreases from Q = 20 MeV to Q = 2 MeV.

[2] Due to the steep falling of the total cross section near-threshold already a small change of the energy (0.2 MeV) lifts the points significantly up. Moreover, for the very low energies nuclear

This may be cause by the small π-proton interaction. The deviation from the constant is much smaller than in the η meson case since, the S-wave π-proton interaction is much weaker than the η-proton one.

Similarly, neglecting the two lowest points for the η' meson, one observes about 20 % increase of $|M_0|$ when approaching the threshold. This may indicate a small attractive η'-proton interaction. Anyhow, with the new COSY - 11 data points the possible η'-proton repulsive interaction must be excluded.

Instead of conclusion the article of Bernard et al. [56] is recommended where the threshold matrix-elements for the $pp \to pp\pi^0(\eta, \eta')$ reactions were evaluated in a fully relativistic Feynman diagrammatic approach as reported by N. Kaiser at this conference.

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and Coulomb scattering are expected to compete. The limit is approximately at 0.8 MeV of the proton energy in the rest system of the other proton, where the Coulomb penetration factor C^2 is equal to 0.5 [55]. Thus, one should be careful, at small excess energies, where the approximately treated Coulomb interaction dominates.

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