

STUDY OF THE η' MESON STRUCTURE, WIDTH AND INTERACTIONS WITH NUCLEONS AT COSY-11*

E. CZERWIŃSKI^{a,b,c}, J. KLAJA^b, P. KLAJA^b, P. MOSKAL^{a,b}

^aInstitute of Physics, Jagellonian University, 30-059 Kraków, Poland

^bInstitute for Nuclear Physics and Juelich Center for Hadron Physics
Research Center Jülich, 52425 Jülich, Germany

^cINFN, Laboratori Nazionali di Frascati, 00044 Frascati, Italy

(Received August 9, 2010)

We present results on the isospin dependence of the η' production cross-section in nucleon–nucleon collisions, as well as the results of comparative analysis of the invariant mass distributions for the $pp \rightarrow pp\eta'$ and $pp \rightarrow p\eta\eta'$ reactions in the context of the proton– η and proton– η' interaction. Additionally, the value of the total width of the η' is reported as derived directly from the measurement of the mass distribution and an explanation of the experimental technique used in order to achieve a precision about an order of magnitude better than former experiments is included.

PACS numbers: 13.60.Le, 13.75.Cs, 14.40.Be, 14.70.Dj

1. Experimental setup

The reported experiments have been performed in the Research Centre Jülich at the cooler synchrotron COSY [1] by means of the COSY–11 detector system [2] presented in Fig. 1. The collision of a proton from the COSY beam with a proton or deuteron cluster target may cause an η' meson creation. In that case all outgoing nucleons have been registered by the COSY–11 detectors, whereas for the η' meson identification the missing mass technique was applied.

2. Production of the η' meson in the $pn \rightarrow pn\eta'$ reaction

The main goal of this experiment was the determination of the excitation function for the quasi-free $pn \rightarrow pn\eta'$ reaction near the kinematical threshold. The motivation was the comparison of the $pp \rightarrow pp\eta'$ and $pn \rightarrow pn\eta'$

* Presented at the Workshop “Excited QCD 2010”, Tatranská Lomnica/Stará Lesná, Tatra National Park, Slovakia, January 31–February 6, 2010.

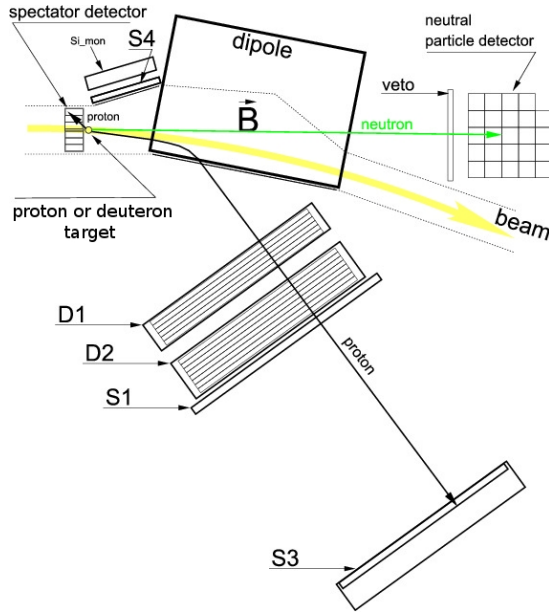


Fig. 1. Schematic view of the COSY-11 detector setup (top view). S1, S3, S4 denote scintillator detectors, D1, D2 indicate drift chambers and Si stands for the silicon-pad detector. An array of silicon pad detectors (spectator detector) is used for the registration of the spectator protons. Neutrons are registered in the neutral particle detector. Detectors S4 and Si were used for the measurement of elastically scattered protons needed for monitoring purposes [3–6]. Example of $pd \rightarrow pnp_{\text{spectator}}X$ reaction is presented.

total cross-sections in order to learn about the production mechanism of the η' meson in the channels of isospin 1 and 0, and to investigate aspects of the gluonium component of the η' meson.

The ratio $R_{\eta'} = \sigma(pn \rightarrow pn\eta')/\sigma(pp \rightarrow pp\eta')$ has not been measured so far, and the existing predictions differ drastically depending on the model. Cao and Lee [7] assumed, by analogy to the production of the η meson, that the production of the η' meson proceeds dominantly via the $S_{11}(1535)$ resonance. As a consequence, they predicted within an effective Lagrangian approach a $R_{\eta'}$ value equal to the experimentally established $R_{\eta} = \sigma(pn \rightarrow pn\eta)/\sigma(pp \rightarrow pp\eta)$ value. In contrast, Kaptari and Kämpfer [8] predicted a value of $R_{\eta'}$ close to ~ 1.5 in the kinematic range of the COSY-11 experiment with the dominant contribution coming from the meson conversion currents. In the extreme scenario of glue-induced production saturating the η' production cross-section, the ratio $R_{\eta'}$ would approach unity after correcting for the final state interaction between the two outgoing nucleons.

Detailed description of measurement and data analysis is presented in [5, 9]. The result is shown in Fig. 2. The horizontal bars represents the intervals of the excess energy, for which the upper limit of the total cross-section was calculated. The total cross-section for the $pp \rightarrow pp\eta'$ reaction

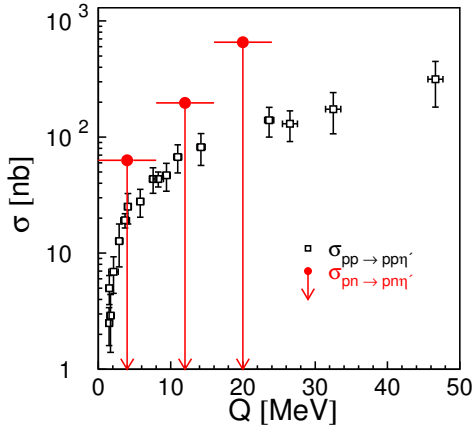


Fig. 2. Total cross-sections for the $pp \rightarrow pp\eta'$ reaction as a function of the excess energy (open squares). Upper limit for the total cross-section for the $pn \rightarrow pn\eta'$ reaction as a function of the excess energy (dots).

was measured in previous experiments [10–14]. It reveals a strong excess energy dependence, especially very close to threshold. This dependence must be taken into account when comparing to the results for the $pn \rightarrow pn\eta'$ reaction which were established for 8 MeV excess energy intervals. Therefore, for a given interval of excess energy, we have determined the mean value of the total cross-section for $pp \rightarrow pp\eta'$ reaction using the parametrisation of Fäldt and Wilkin [15, 16] fitted to the experimental data [17]. For the η' meson the upper limit of the ratio for the excess energy range [0, 8] MeV is nearly equal to values of the ratio obtained for the η meson, whereas for larger excess energy ranges [8, 16] MeV and [16, 24] MeV the upper limits of the ratio are lower by about one standard deviation each. The value of R_η is ≈ 6.5 at excess energies larger than ~ 16 MeV [18] suggests the dominance of isovector meson exchange in the production mechanism. The decrease of R_η close to the threshold [19] may be explained by the different energy dependence of the proton–proton and proton–neutron final state interactions [20]. A smaller $R_{\eta'}$ than R_η is consistent with a possible greater role for singlet currents in η' production than η production. If there are important new dynamics in the η' production process relative to eta production, a key issue is the relative phase [21] of possible additional exchanges compared to the isovector currents which dominate the η production. The observed limit

thus constrains modelling of the production processes. To confirm these interesting observations and to go further, new experimental investigations with improved statistics are required.

3. Interactions of the η' meson

In principle, studies of $pp \rightarrow pp \text{ meson}$ reactions permit information about the proton–meson interaction to be gained not only from the shape of the excitation function but also from differential distributions of proton–proton and proton–meson invariant masses. Therefore, in order to investigate the proton– η interaction the COSY-11 Collaboration performed a measurement [22] of the proton– η and proton–proton invariant mass distributions close to the threshold at $Q = 15.5$ MeV, where the outgoing particles possess small relative velocities. Indeed a large enhancement in the region of small proton– η and large proton–proton relative momenta was observed¹. However, the observed effect cannot be univocally assigned to the influence of the proton– η interaction in the final state [24, 25], since it can also be explained by the admixture of higher partial waves in the proton–proton system [26], or by the energy dependence of the production amplitude [27, 28].

The endeavor to explain the origin of the observed enhancement motivated the measurement of the proton–proton and proton– η' invariant mass distributions for the $pp \rightarrow pp\eta'$ reaction presented in this article. Detailed description of measurement and data analysis resulted in invariant mass distributions for the $pp \rightarrow pp\eta'$ reaction is presented in [6, 29]. The absolute values of the cross-section for the $pp \rightarrow pp\eta'$ reaction determined as a function of s_{pp} and $s_{p\eta'}$ are shown in Fig. 3.

Within the statistical and systematic error bars both model of Deloff [27] and of Nakayama *et al.* [26] describe the data well although they differ slightly in the predicted shapes. This indicates that perhaps, not only higher partial waves but also the energy dependence of the production amplitude should be taken into account. Also, the inclusion of the proton–proton final state interaction is not sufficient to explain the enhancement seen in the range of large s_{pp} values.

Within the achieved uncertainties, the shape of the proton–proton and proton–meson invariant mass distributions determined for the η' meson is essentially the same to that established previously for the η meson. Since the enhancement is similar in both cases, and the strength of proton– η and proton– η' interaction is different [6, 30], one can conclude that the observed enhancement is not caused by a proton–meson interaction. Therefore, on

¹ The same enhancement was also seen in independent measurements by the COSY-TOF Group [23].

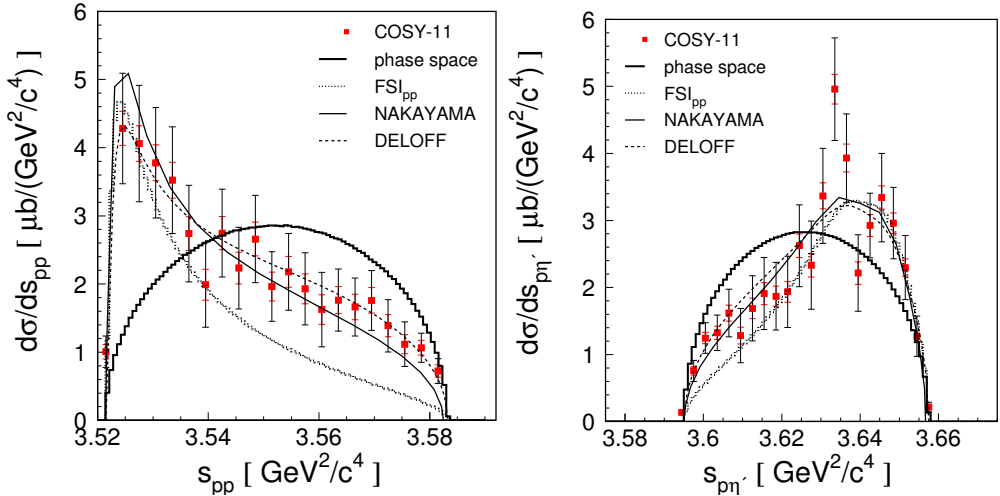


Fig. 3. Distributions of the squared proton–proton (s_{pp}) and proton– η' ($s_{p\eta'}$) invariant masses, for the $pp \rightarrow pp\eta'$ reaction at the excess energy of $Q = 16.4$ MeV. The experimental data (closed squares) are compared to the expectation under the assumption of a homogeneously populated phase space (thick solid lines) and the integrals of the phase space weighted by the proton–proton scattering amplitude — FSI_{pp} (dotted histograms). The solid and dashed lines correspond to calculations when taking into account contributions from higher partial waves and allowing for a linear energy dependence of the ${}^3P_0 \rightarrow {}^1S_0$ partial wave amplitude, respectively.

the basis of the presented invariant mass distributions, it is not possible to disentangle univocally which of the discussed models is more appropriate. As pointed out in [26], future measurements of the spin correlation coefficients should help disentangle these two model results in a model independent way.

4. Total width of the η' meson ($\Gamma_{\eta'}$)

In the latest review by the Particle Data Group (PDG) [31], two values for the total width of the η' meson are given. One of these values, (0.30 ± 0.09) MeV/ c^2 , results from the average of two measurements [32,33], though only in one of these experiments was $\Gamma_{\eta'}$ extracted directly based on the mass distribution [33]. The second value (0.205 ± 0.015) MeV/ c^2 , recommended by the PDG, is determined by fit to altogether 51 measurements of partial widths, branching ratios, and combinations of particle widths obtained from integrated cross-sections [31]. The result of the fit is strongly correlated with the value of the partial width $\Gamma(\eta' \rightarrow \gamma\gamma)$, which causes serious difficulties when the total and the partial width have to be used at the same time, like *e.g.* in studies of the gluonium content of the η' meson [34–36].

The value of the total width of the η' meson was established directly from its mass distribution independently of other properties of this meson, like *e.g.* partial widths or production cross-sections. The η' meson was produced in proton–proton collisions via the $pp \rightarrow pp\eta'$ reaction and its mass was reconstructed based on the momentum vectors of protons taking part in the reaction. The reader interested in the description of the detectors and analysis procedures can find detailed informations in Ref. [4, 37]. The momentum of the COSY beam and the dedicated zero degree COSY-11 facility enabled the measurement at an excess energy of only a fraction of an MeV above the kinematic threshold for the η' meson production. This was the most decisive factor in minimizing uncertainties of the missing mass determination, since at threshold the partial derivative of the missing mass with respect to the outgoing proton momentum tends to zero. In addition, close to threshold the signal-to-background ratio increases due to the more rapid reduction of the phase space for multimeson production than for the η' .

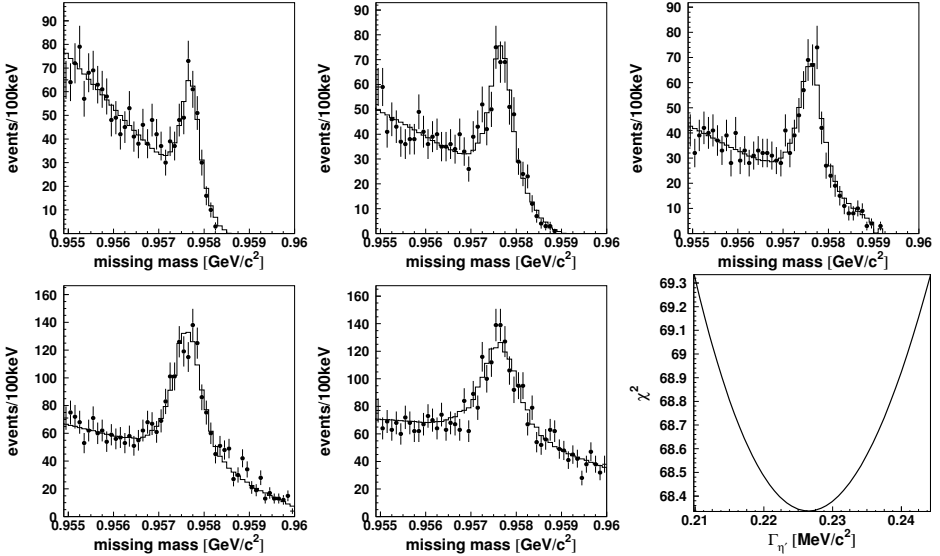


Fig. 4. The missing mass spectra for the $pp \rightarrow ppX$ reaction for excess energies in the CM system equal to 0.8, 1.4, 1.7, 2.8, and 4.8 MeV (from left to right, top to bottom). The η' meson signal is clearly visible. The experimental data are presented as black points, while in each plot the solid line corresponds to the sum of the Monte Carlo generated signal for an η' with $\Gamma_{\eta'} = 0.226$ MeV and the shifted and normalised second order polynomial obtained from a fit to the signal-free background region for another energy. The last plot (bottom right) presents χ^2 as a function of the $\Gamma_{\eta'}$. The minimum value corresponds to $\Gamma_{\eta'} = 0.226$ MeV, and the range where $\chi^2 = \chi_{\min}^2 + 1$, corresponding to the value of the statistical error, is equal to $\pm 0.017(\text{stat.})$.

The systematic error was estimated by studying the sensitivity of the result to the variation of parameters describing the experimental conditions in the analysis and in the simulation [4]. Finally, the total systematic error was estimated as the quadratic sum of independent contributions and is $0.014 \text{ MeV}/c^2$. The final missing mass spectra are presented in Fig. 4. The total width of the η' meson was extracted from the missing-mass spectra and amounts to $\Gamma_{\eta'} = 0.226 \pm 0.017(\text{stat.}) \pm 0.014(\text{syst.}) \text{ MeV}/c^2$. The result does not depend on knowing any of the branching ratios or partial decay widths. The extracted $\Gamma_{\eta'}$ value is in agreement with both previous direct determinations of this value [32,33], and the achieved accuracy is similar to that obtained by the PDG [31].

The work was partially supported by the European Commission under the 7th Framework Programme through the *Research Infrastructures* action of the *Capacities* Programme. Call: FP7-INFRASTRUCTURES-2008-1, Grant Agreement No. 227431, by the PrimeNet, by the Polish Ministry of Science and Higher Education through grants No. 1202/DFG/2007/03, 0082/B/H03/2008/34, 0084/B/H03/2008/34 and 1253/B/H03/2009/36, by the German Research Foundation (DFG), by the FFE grants from the Research Center Jülich, and by the virtual institute *Spin and Strong QCD* (VH-VP-231).

REFERENCES

- [1] R. Maier *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A390**, 1 (1997).
- [2] S. Brauksiepe *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A376**, 397 (1996).
- [3] P. Moskal *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A466**, 448 (2001).
- [4] E. Czerwinski, PhD thesis, [arXiv:0909.2781](https://arxiv.org/abs/0909.2781) [nucl-ex].
- [5] J. Klaja, PhD thesis, [arXiv:0909.4399](https://arxiv.org/abs/0909.4399) [nucl-ex].
- [6] P. Klaja, PhD thesis, [arXiv:0907.1491](https://arxiv.org/abs/0907.1491) [nucl-ex].
- [7] Xu Cao, Xi-Guo Lee, *Phys. Rev.* **C78**, 035207 (2008).
- [8] L.P. Kaptari, B. Kämpfer, *Eur. Phys. J.* **A37**, 69 (2008).
- [9] J. Klaja *et al.*, *Phys. Rev.* **C81**, 035209 (2010).
- [10] P. Moskal *et al.*, *Phys. Lett.* **B474**, 416 (2000).
- [11] A. Khoukaz *et al.*, *Eur. Phys. J.* **A20**, 345 (2004).
- [12] F. Balestra *et al.*, *Phys. Lett.* **B491**, 29 (2000).
- [13] P. Moskal *et al.*, *Phys. Rev. Lett.* **80**, 3202 (1998).
- [14] F. Hibou *et al.*, *Phys. Lett.* **B438**, 41 (1998).
- [15] G. Fäldt, C. Wilkin, *Phys. Lett.* **B382**, 209 (1996).

- [16] G. Fäldt, C. Wilkin, *Phys. Rev.* **C56**, 2067 (1997).
- [17] P. Moskal *et al.*, *Int. J. Mod. Phys.* **A22**, 305 (2007).
- [18] H. Calén *et al.*, *Phys. Rev.* **C58**, 2667 (1998).
- [19] P. Moskal *et al.*, *Phys. Rev.* **C79**, 015208 (2009).
- [20] C. Wilkin, private communication (2008).
- [21] G. Fäldt, C. Wilkin, *Phys. Scr.* **64**, 427 (2001).
- [22] P. Moskal *et al.*, *Phys. Rev.* **C69**, 025203 (2004).
- [23] M. Abdel-Bary *et al.*, *Eur. Phys. J.* **A16**, 127 (2003).
- [24] A. Fix, H. Arenhövel, *Phys. Rev.* **C69**, 014001 (2004).
- [25] A. Fix, H. Arenhövel, *Nucl. Instrum. Methods Phys. Res.* **A697**, 277 (2002).
- [26] K. Nakayama *et al.*, *Phys. Rev.* **C68**, 045201 (2003).
- [27] A. Deloff, *Phys. Rev.* **C69**, 035206 (2004).
- [28] S. Ceci, A. Švarc, B. Zauner, *Acta Phys. Pol. B Proc. Supp.* **2**, 157 (2009).
- [29] P. Klaja *et al.*, *Phys. Lett.* **B684**, 11 (2010).
- [30] P. Moskal *et al.*, *Phys. Lett.* **B482**, 356 (2000).
- [31] C. Amsler *et al.*, *Phys. Lett.* **667**, 1 (2008).
- [32] R. Wurzinger *et al.*, *Phys. Lett.* **B374**, 283 (1996).
- [33] D.M. Binnie *et al.*, *Phys. Lett.* **B83**, 41 (1979).
- [34] B. Di Micco, *Acta Phys. Pol. B Proc. Supp.* **2**, 63 (2009).
- [35] F. Ambrosino *et al.*, *J. High Energy Phys.* **07**, 105 (2009).
- [36] B. Di Micco, *Eur. Phys. J.* **A38**, 129 (2008).
- [37] E. Czerwinski *et al.*, *Phys. Rev. Lett.* **105**, 122001 (2010).