Close to Threshold η' Production in Proton-Proton Scattering

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The $pp \longrightarrow pp\eta'$ (958) reaction has been measured at COSY using the internal beam and the COSY-11 facility. The total cross sections at the four different excess energies $Q = 1.5\ MeV,\ 1.7\ MeV,\ 2.9\ MeV,$ and $4.1\ MeV$ have been evaluated to be $\sigma = 2.5 \pm 0.5\ nb,\quad 2.9 \pm 1.1\ nb,\quad 12.7 \pm 3.2\ nb,$ and $25.2 \pm 3.6\ nb$, respectively.
In this region of excess energy the η' (958) cross sections are much lower compared to those of the π^0 and η production.

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The physics of the η' meson is related to one of the most intricate phenomena in particle physics. Historically, it was first stressed by S.L. Glashow [1] that in quark models there must exist a nearly massless flavour singlet partner η' to the well established octet of pseudoscalar (P) Goldstone bosons. However, with the advent of quantum chromo dynamics (QCD), the situation changed dramatically. It was suggested in ref. [2] that because of an anomalous divergence of the axial vector baryon current in QCD, which has become known as the U(1) anomaly, there is no necessity for a massless η'. The importance of the axial anomaly has been further quantified by Weinberg [3]. He showed that without the anomaly, the η' would be unacceptably light: $m^2_{\eta'} \leq 3m^2_{\pi}$. Consequently, t' Hooft [4] has stimulated an extensive dispute on how the U(1) anomaly and QCD instantons affect the mass spectrum of the $J^P = 0^-$ mesons [5, 6, 7, 8, 9]. The status of the flavour singlet 0^- state remained open until 1976 when it was well established that the $\eta'(958)$ is the heaviest member of the ground state pseudoscalar meson nonet with quantum numbers $I^G(J^{PC}) = 0^+(0^{-+})$. The first experimental evidence of the existence of the η' meson has been seen in the reaction channels $K^- + p \longrightarrow \Lambda^0 + neutrals$ performed in 1964 [10, 11]. The issues of i) η – η' mixing, ii) possible non-quarkonic component within the η' meson, and iii) coupling of the η' to gluons have attracted much attention in connection to the mass sum rules [12, 13, 14], two-photon decays $P \longrightarrow 2\gamma$ [15, 16, 17] and charmonium radiative decays $J/\Psi \longrightarrow P\ \gamma$ [17, 18, 19, 20]. The situation is far from being settled. Recently the CLEO [21] collaboration reported an anomalously large branching ratio for the inclusive decay of beauty particles $B \longrightarrow \eta' + X$, which can hardly be understood within the pure quarkonium picture of the η' and is vitally discussed as evidence for strong coupling of η' meson to gluonic components [22, 23, 24, 25, 26, 27].

There is no direct experimental information on the strength of the η' coupling to nucleons: $g_{\eta' NN}$. The relevance of this coupling strength to the spin crisis in polarized deep inelastic scattering has been emphasized [28, 29]. Generalizing the Goldberger-Treiman relation to the flavour singlet sector, Veneziano suggested a relation between the SU(3)-singlet axial charge of the nucleon and $g_{\eta' NN}$, known as the TGV relation. The smallness of the SU(3) singlet axial charge current extracted from deep inelastic scattering data suggests a small $\eta' NN$ coupling constant. On the other hand, the η' - nucleon coupling constant $g_{\eta' NN}$ can put constraints on the theoretical quark models [29, 30, 31]. Measurements of the cross sections for the $pp \longrightarrow pp\eta'$ reaction close to threshold give an opportunity to determine the value of $g_{\eta' NN}$.

Recently data were published concerning the $\eta'(958)$ meson production in the $pd \longrightarrow {}^3He\ X$ reaction performed at SATURNE using the SPES4 spectrometer [32]. Assuming a pure s-wave phase space distribution the measured differential cross section $d\sigma_{\eta'}/d\Omega^* = 13\ pb/sr$ results in a total cross section of $\sigma_{\eta'} \approx 0.16\ nb$ at a mean excess energy of $Q = 0.5\ MeV$. No data are published concerning the production of η' at threshold in proton-proton collisions. There are only preliminary results from measurements at SATURNE [33]. Thus, the η' is the last non-strange meson of the pseudoscalar nonet for which cross sections for the production in the elementary proton proton scattering are unknown close to threshold.

Measurements of the η' production in the pp interaction were performed at the cooler synchrotron COSY-Jülich [34] using an internal cluster target [35] in front of a regular C-shaped COSY dipole magnet acting as a magnetic spectrometer. The η' mesons were not identified directly but their four-momentum vectors were determined via the missing mass method. The two outgoing protons were registered in a set of two drift chamber stacks followed by a scintillator hodoscope arrangement and a large area scintillator wall placed nine meter downstream. Tracing the proton tracks back through the known three dimensional magnetic field into the target spot results in a definite momentum determination. With the measured time of flight a unique particle identification is possible and therefore the four momentum vector components are given. Details of the experimental apparatus are given elsewhere [36]. Measurements were performed at constant proton beam momenta as well as during a continuous beam momentum increase corresponding to excess energies from $Q = -3\ MeV$ to $Q = +5\ MeV$. The total cross sections for four different excess energies: $Q = 1.5\ MeV$, $1.7\ MeV$, $2.9\ MeV$, and $4.1\ MeV$ were evaluated. Figure 1a compares the experimental yield of the reaction $pp \longrightarrow ppX$ measured just below the η' production threshold (solid line) to a Monte Carlo (MC) calculation for the two and three pion production (dashed line). The broad structureless shape is well reproduced and thus explains the background. At the present value of the beam momentum up to seven pions could be produced in the pp scattering, however, due to the decreasing cross section with increasing number of pions these reactions do not contribute significantly.

Figure 1b shows the same experimental yield of the $pp \longrightarrow ppX$ measurement below the η' threshold (solid line) compared to the smoothed representation (dashed line) of these data which is used in the following to determine the reaction yield of the η' production above the unavoidable background. In Fig. 1c (similar as in Fig. 1a and Fig. 1b) the kinematical upper missing mass limit for the below threshold measurement is calibrated to the one above threshold. The clear η' peak is even more evident when subtracting both reaction yields from each other (above threshold minus below threshold) after normalization to the integrated luminosity, as seen in Fig. 1d. The small seemingly structure at missing mass values below the η' mass is not significant from statistical point of view and since it does not reproduce itself for measurements at the other beam momenta. The counting rates have been corrected by extensive MC calculations for the detector acceptance and reconstruction efficiency, where the geometrical detector acceptance drops from 100 % at threshold to 17 % at $Q = 4.1 \; MeV$. For the detector acceptance E_{ff} the p-p final state interaction and the Coulomb repulsion were taken into account as outlined in ref. [37].

Simultaneously to the reaction under investigation elastically scattered protons have been recorded on tape and analysed. The differential cross section in the angular range of $\cos \Theta_{CM} = 0.45$ to 0.75 was extracted and normalized to the EDDA data [38], in order to determine the luminosity which varied during the running periodes between $l = 4 \times 10^{29} cm^{-2} s^{-1}$ and $l = 8 \times 10^{29} cm^{-2} s^{-1}$. Denoting the integrated luminosity by L and the entries in the η' peak by N, the energy dependent total cross sections were evaluated according to: $\sigma(Q) = N/(L \times E_{ff}(Q))$.

The absolute beam momentum was calculated from the position of the η' peak in the missing mass spectrum. The inaccuracy of the missing mass evaluation originates besides from the beam momentum inaccuracy itself from the uncertainty in the computation of the four-momentum vectors of the registered two protons. That, in turn, can be caused by i) a misalignment of the angles of the drift chambers relative to the chosen coordinate system, ii) an uncertainty in the definition of the interaction point in both vertical and longitudinal directions, and iii) the inaccuracy of the knowledge of the dipole magnetic field. All these possible sources of miscalibration were carefully studied by means of the COSY-11 MC program. It was established [39] that these effects result in an error on the reconstructed missing mass of less than 0.4 MeV corresponding to an uncertainty in the absolute beam momentum of 1.2 MeV/c.

Figure 2 depicts the values of the total cross section. The vertical error bars denote the statistical errors only. The overall systematical error amounts to 15 %, where 10 % comes from the determination of the detection efficiency E_{ff} and 5 % from the luminosity calculation. The horizontal error bars result from the inaccuracy of the absolute beam momentum determination [39].

In Fig. 3 a comparison of the $pp \to pp\pi^0$, $pp \to pp\eta$, $and \; pp \to pp\eta'$ total cross sections is presented. Figure 3a depicts the production cross sections as a function of the respective excess energy, where we observe that the cross section ratio for the π^0/η' production scales approximately with the square of the mass ratio $(135/958)^2 \approx 0.02$, indicating a similar production process. Here the η production cross section is, however, much larger which can be attributed to a dominant contribution of the $S_{11}(1535)$ resonance. In fact, on this scale the two mesons η and π^0 are produced with rather similar cross sections, whereas the reaction yield for the η' is more than one order of magnitude smaller, see also ref. [40].

Representing the total cross sections as a function of the η variable, where the parameter η stands for the maximum center of mass meson momentum normalized to its mass, the $pp \to pp\eta'$ reaction yield is similar to the one of the $pp \to pp\pi^0$ data in contrast to the much larger η meson production rate, as is shown in Fig. 3b. This again suggests that the production mechanisms for π^0 and η' are similar.

The theory of η' production is in its formative stage. Whereas in the case of the η meson the production via the $S_{11}(1535)$ resonance is dominant[41, 42] there are no obvious candidates for baryon resonances decaying into $\eta'(958)$ and the nucleon, apart from the $D_{13}(2080)$ resonance [30] which, due to its spin s = 3/2, should have only a very suppressed influence on the reaction process at threshold. Therefore, as a first approximation, one can consider the effective Lagrangian approach with direct η'NN coupling (for a related discussion of photoproduction see ref. [30, 43]). Alongside with i) the pure phase space distribution (dotted line) and ii) the phase space distribution including the pp final state interaction [44] (solid line) (which is known to be important [45, 46], and calculated as outlined in ref [37]), the result of such a model evaluation is shown in Fig. 2 by the dashed line. The disagreement between the energy dependence obtained under these simple assumptions with the experimental data indicates that heavy meson exchange or other mechanisms may contribute significantly to the production of the η' meson in the $pp \to pp\eta'$ reaction.
With the assumption that the production of the η' meson is driven by the direct term only and that the production amplitude from the heavy meson exchange has the same sign as the amplitude of the direct term [47] the upper limit for the coupling constant can be estimated. By normalizing the theoretical result to the data point at $Q = 4.1\ MeV$ the pseudoscalar coupling constant $g_{\eta' pp}$ turns out to be smaller than 2.5, where quark model predictions for the value of $g_{\eta' pp}$ range from 1.9 to 7.5 [29, 30, 31].

In short, evidence has been given by the present studies of the $pp \longrightarrow pp\eta'$ reaction at threshold that i) there seems to be no indication that an S - wave $(N\eta')$ N^* resonance intermediate "doorway like" state governs the reaction mechanism and that ii) the η'coupling constant $g_{\eta' pp}$ extracted from a simple model analysis seems to be not in contradiction to the range expected by the quark model, barring an accidental cancellation between interferences of the amplitudes for the direct term and the heavy meson exchange.

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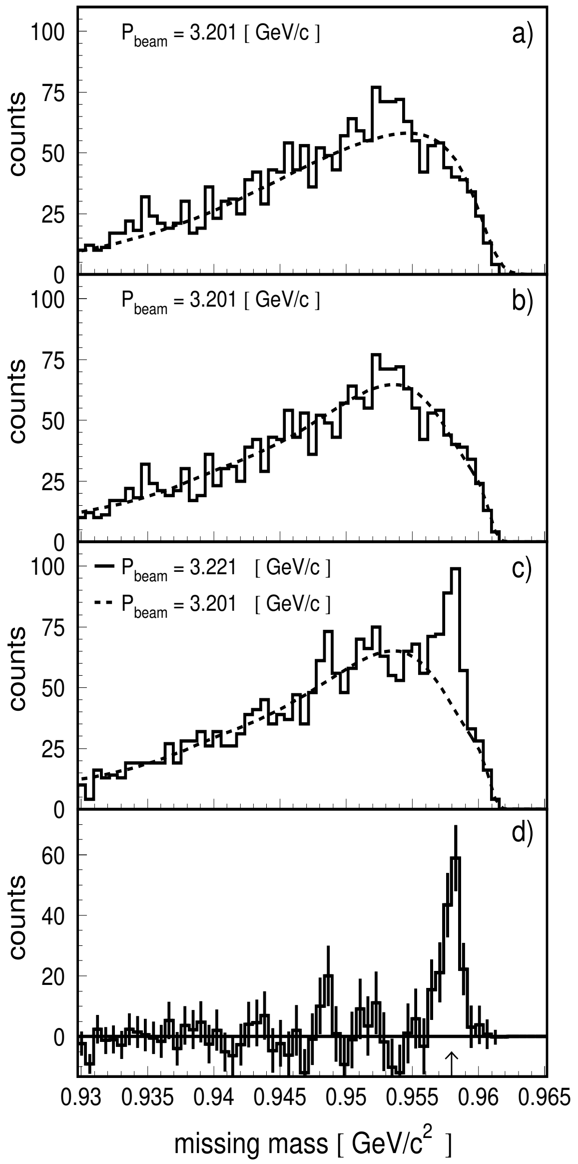

Figure 1: Missing mass spectra of the unobserved particle X in the reaction $pp \longrightarrow ppX$:

a) data at a beam momentum below threshold (solid line) and

MC calculations for the reactions $pp \longrightarrow pp\pi^+\pi^-$ and $pp \longrightarrow pp\pi^+\pi^-\pi^0$ (dashed line),

b) data (solid line), smooth fit function to the data (dashed line),

c) data at a beam momentum of 3.221 GeV/c for the η' production (solid line), scaled background from b) (dashed line)

d) difference between solid and dashed lines of c), the arrow indicates the η' mass.

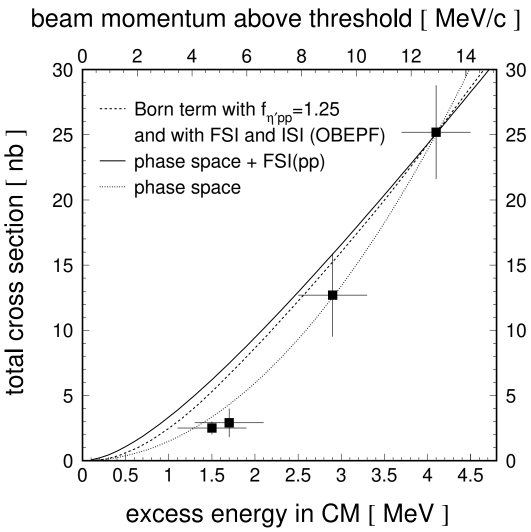

Figure 2: Total cross sections for the $pp \longrightarrow pp\eta'$ reaction as a function of the excess energy (bottom horizontal axis) and beam momentum above the threshold at 3.208 MeV/c (upper horizontal axis). The different lines show estimates for cross sections as described in the figure and outlined in the text, where the curves are normalized to the data point at 4.1 MeV.

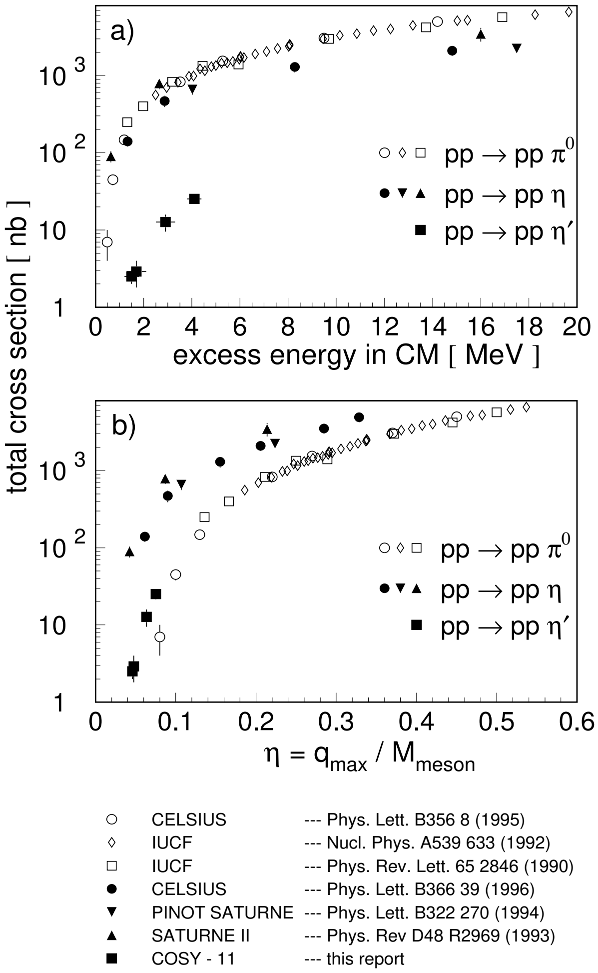

Figure 3: Total cross sections for the reactions: $pp \longrightarrow pp\pi^0$, $pp \longrightarrow pp\eta$, and $pp \longrightarrow pp\eta'$

a) as a function of the excess energy and

b) as a function of the maximum meson momentum normalized to the meson mass.