η' Production in Proton-Proton Scattering Close to Threshold

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The $pp \rightarrow pp\eta'(958)$ reaction has been measured at the cooler synchrotron COSY at Jülich using the internal beam and the COSY-11 facility. The total cross sections at the four different excess energies $Q = 1.5$, 1.7, 2.9, and 4.1 MeV have been evaluated to be $\sigma = 2.5 \pm 0.5$, 2.9 ± 1.1, 12.7 ± 3.2, and 25.2 ± 3.6 nb, respectively. In this region of excess energy the $\eta'(958)$ cross sections are much lower compared to those of the π^0 and η production. [S0031-9007(98)05794-9]

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The first experimental evidence of the η' meson has been seen in the $K^- + p \rightarrow \Lambda^0 +$ neutrals reaction channels in 1964 [1,2]. Nowadays, the $\eta'(958)$ is well established as the heaviest member of the ground state pseudoscalar meson nonet with quantum numbers $I^G(J^{PC}) = 0^+(0^{-+})$. The physics of the η' meson is related to one of the most intricate phenomena in particle physics. In quark models [3] a nearly massless flavor singlet partner η' to the well established octet of pseudoscalar Goldstone bosons must exist. With the advent of quantum chromodynamics (QCD), however, the situation changed dramatically and there is no necessity [4] for a massless η'. Without this U(1) anomaly [5], the η' would be unacceptably light: $m_{\eta'}^2 \leq 3m_\pi^2$. Consequently, 't Hooft [6] has stimulated an extensive dispute on how the U(1) anomaly and QCD instantons effect the mass spectrum of the $J^P = 0^-$ mesons [7–11]. The issues of (i) η-η' mixing, (ii) possible nonquarkonic component within the η' meson, and (iii) coupling of the η' to gluons have attracted much attention, but the situation is far from being settled [12–14]. Recently the CLEO [15] Collaboration reported an anomalously large branching ratio for the inclusive decay of beauty particles $B \rightarrow \eta' + X$, which is vitally discussed as evidence for strong coupling of η' meson to gluonic components [16–21].

There is no direct experimental information on the strength of the η' coupling to nucleons: $g_{\eta' NN}$. The smallness of the SU(3) singlet axial charge current extracted from deep inelastic scattering data suggests a small $\eta' NN$ coupling constant [22]. On the other hand, the η'-nucleon coupling constant $g_{\eta' NN}$ can put constraints on the theoretical quark models [23,24]. Because there are no known "doorwaylike" $N\eta'$ resonances close to the production threshold, measurements of the cross sections for the $pp \rightarrow pp\eta'$ reaction at such energies give an opportunity to determine the value of $g_{\eta' NN}$. In the case of the η production, however, a reaction mechanism mediated by the intermediate resonance N^* $[S_{11}(1535)]$ is known to be important [25,26], making an extraction of the η-nucleon coupling constant $g_{\eta NN}$ very difficult.

Recently data were published concerning the $\eta'(958)$ meson production in the $pd \rightarrow {}^3\text{He} + X$ reaction performed at SATURNE using the SPES4 spectrometer [27]. 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 [28]. Thus, the η' is the last nonstrange 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 [29] using an internal cluster target [30] in front of a regular C-shaped COSY dipole magnet acting as a magnetic spectrometer. The η' mesons were not directly identified 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 9 m 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

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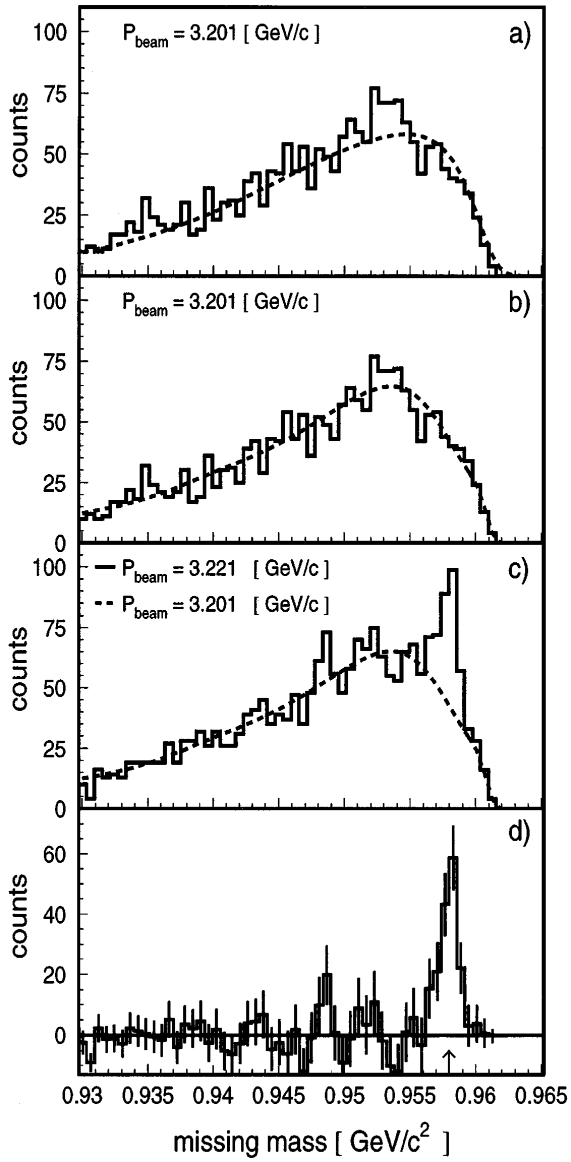

FIG. 1. Missing mass spectra of the unobserved particle X in the reaction $pp \rightarrow ppX$: (a) Data at a beam momentum below threshold (solid line), and MC calculations for the reactions $pp \rightarrow pp\pi^+\pi^-$ and $pp \rightarrow pp\pi^+\pi^-\pi^0$ (dashed line); (b) data (solid line), smooth 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.

are given. Details of the experimental apparatus are given elsewhere [31]. 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, $Q = 1.5$, 1.7, 2.9, and 4.1 MeV, were evaluated. Figure 1(a) compares the experimental yield of the reaction $pp \rightarrow ppX$ measured just below the η' production threshold (solid line) to a phase space 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 an increasing number of pions, these reactions do not contribute significantly.

Figure 1(b) shows the same experimental yield of the $pp \rightarrow ppX$ 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. A small difference in shape between the two determinations of the background—the MC calculations and the smoothed subthreshold measurement—is obvious. The η' yield evaluated by using the smoothed subthreshold measurement as the background is systematically $(7 \pm 2)\%$ larger than applying the MC method. For the further analysis the experimentally determined smoothed subthreshold background subtraction was used. In Fig. 1(c) [similar as in Figs. 1(a) and 1(b)] 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. 1(d). The seemingly small structure at missing mass values below the η' mass is not significant from a 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. [32].

Simultaneously to the reaction under investigation elastically scattered protons have been recorded on tape and analyzed. 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 [33], in order to determine the luminosity which varied during the running periods 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 spread in the beam momentum has been controlled by the sum signal of a beam position monitor from a longitudinal Schottky scan [29] to be $\Delta p = 1.1$ MeV$/c$. 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 [34] 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 [34].

In Fig. 3 a comparison of the $pp \rightarrow pp\pi^0$, $pp \rightarrow pp\eta$, and $pp \rightarrow pp\eta'$ total cross sections is presented. Figure 3(a) 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 1 order of magnitude smaller; see also Ref. [35].

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 $pp \rightarrow pp\eta'$ reaction yield is similar to the one of the $pp \rightarrow pp\pi^0$ data in contrast to the much larger η meson production rate, as is shown in Fig. 3(b). 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 [25,26], there are no obvious candidates for baryon resonances decaying into $\eta'(958)$ and the nucleon, apart from the $D_{13}(2080)$ resonance [23] which, due to its spin $s = \frac{3}{2}$, should have only a very suppressed influence on the reaction process at threshold. Therefore, as a first approximation, one can consider the effective Langrangian approach with direct $\eta' NN$ coupling (for a related discussion of photoproduction, see Refs. [23,36]). Alongside with (i) the pure phase space distribution (dotted line) and (ii) the phase space distribution including the pp final state interaction [37] (solid line) (which is known to be important [38,39] and

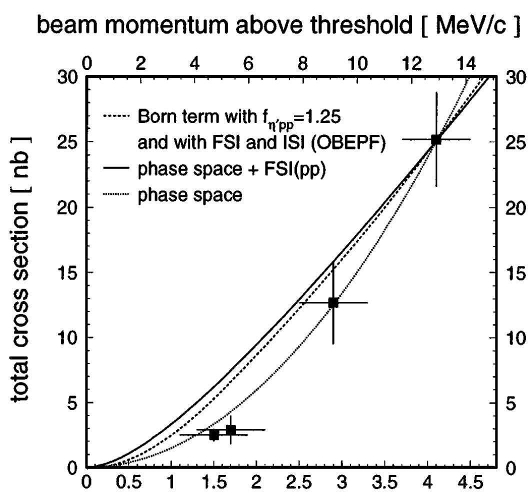

FIG. 2. Total cross sections for the $pp \rightarrow pp\eta'$ reaction as a function of the excess energy (bottom horizontal axis) and beam momentum above the threshold at 3.208 MeV$/c$ (upper horizontal axis). The different lines show estimates for cross sections as described in the figure and outlined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

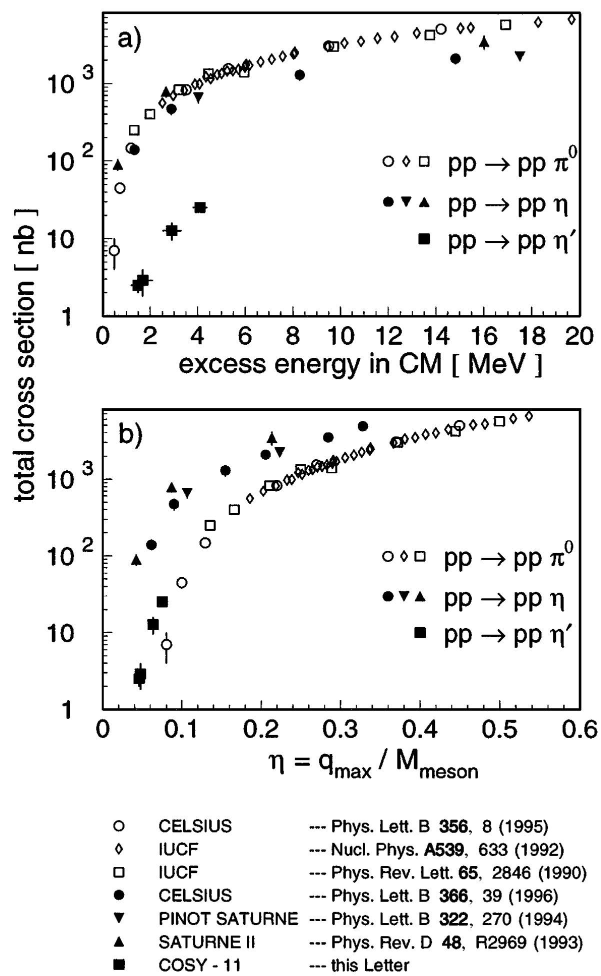

FIG. 3. Total cross sections for the reactions $pp \rightarrow pp\pi^0$, $pp \rightarrow pp\eta$, and $pp \rightarrow pp\eta'$; (a) as a function of the excess energy, and (b) as a function of the maximum meson momentum normalized to the meson mass.

calculated as outlined in Ref. [32]), 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 $pp \rightarrow pp\eta'$ 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 [40], 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 predictions [23,24,41] for $g_{\eta' pp}$ range from values 1.9 to 7.5, and the dispersion method [42] gives $g_{\eta' pp}$ values consistent with zero.

In short, evidence has been given by the present studies of the $pp \rightarrow pp\eta'$ reaction at threshold that (i) there seems to be no indication that an S-wave $(N\eta')$ N^* resonance intermediate doorwaylike state governs the reaction mechanism, and that (ii) the η' coupling constant $g_{\eta' pp}$ extracted from a simple model analysis appears to be consistent with 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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