Comparison of $\eta$ and $\eta'$ production in the $pp \rightarrow pp\eta(\eta')$ reactions near threshold

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Abstract

The total cross section of the $pp \rightarrow pp\eta'$ reaction has been measured at two energies near threshold by detecting the final protons in a magnetic spectrometer. The values obtained are about a factor of 70 less than for the corresponding $\eta$ production, in good agreement with the predictions of a one-pion-exchange model.

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The production of \( \eta \) mesons in proton-proton collisions near threshold has been measured in recent years using three different techniques. By detecting both final protons in a magnetic spectrometer, the SPESIII group at Saturne \([1, 2]\) observed the \( \eta \) meson as a missing mass peak. The PINOT group \([3]\), also working at Saturne, instead identified the \( \eta \) directly through its decay into two photons. Up to at least the threshold for \( \eta \pi \) production this provides a clean measurement of the \( pp \rightarrow pp\eta \) total cross section. The CELSIUS group used a combination of the two techniques when measuring the \( \gamma \gamma \) decay in coincidence with the directions (but not the energies) of two final charged particles \([4]\). Each method has its own advantages but it is very reassuring that the total cross sections from the three groups, shown in fig. 1 in terms of the centre-of-mass excess energy \( Q \), present such a consistent picture. In the present letter we report on the first measurement of \( \eta' \) production in proton-proton collisions near threshold using the magnetic spectrometer technique, and compare the resulting cross sections with those obtained for the \( \eta \).

The experiment was carried out at the Laboratoire National SATURNE (LNS) using the SPESIII spectrometer under experimental conditions which were similar to those reported in ref. \([1]\) and so only essential features are reported here. SPESIII is a large acceptance magnetic spectrometer which is well suited to the study of meson production involving both two and three-body final states near threshold. The detection system consists of three multiwire drift chambers, the first situated on the focal plane, and four planes of scintillators, comprising in total 70 counters. Under its standard working conditions the spectrometer can analyse particles with momenta \( p/Z \) lying between 600 and 1400 MeV/c with a resolution \( \delta p/p \) in the range \((0.5 - 1.0) \times 10^{-3}\).

The maximum opening angles in both the horizontal and vertical directions are \( \pm 60 \) mr and the effective solid angle acceptance is \( \Delta \Omega \approx 10^{-2} \) sr. The momentum resolution can be improved by using one of a series of collimators, though at the expense of reducing the solid angle, and this was done for most of the \( \eta \) measurements reported in ref. \([1]\). In view of the smaller cross section expected for the \( \eta' \), the collimators were here withdrawn to obtain the maximum solid angle. In such conditions the spectrometer and its detection system covered about 85\% and 50\% of the total \( pp\eta' \) phase space at the two beam energies studied, which were nominally 2416 and 2430 MeV. The liquid hydrogen target had a thickness of 270 mg/cm\(^2\). The control of the beam intensity and measurement of the number of incident protons was carried out with the help of two scintillator telescopes viewing the target and an ionisation chamber placed in the beam downstream of the target. The absolute calibration of
these counters was carried out using the standard carbon activation technique [5]. The missing mass spectra of the $pp \rightarrow ppX$ reaction shown in figs. 2(a1) and (a2) correspond to measurements a little above the $\eta'$ threshold at $T_p = 2416$ and $2430$ MeV respectively. The clear rise near the end of these spectra contains $\eta'$ events but superimposed on a continuum of multipion production and this continuum must be subtracted in order to determine the numbers of $\eta'$ produced. This was carried out using analogous spectra recorded just below threshold at $T_p = 2400$ MeV. The measured momenta $p_1$ and $p_2$ for each event were increased by an amount $\Delta p$ and the missing mass was evaluated as if the beam energy were either 2416 or 2430 MeV. The values of $\Delta p$ were fixed by demanding that the range of proton momenta near the highest missing masses was the same above and below threshold. At the endpoint of the spectra, $\Delta p = m_p(\beta'\gamma' - \beta\gamma)$, where $\beta'$ and $\beta$ are the incident proton speeds above and below threshold. The predicted backgrounds shown in figs. 2(b1) and 2(b2) still manifest some enhancement near the ends of the spectra arising from the proton-proton final state interaction (FSI). The $\eta'$ peaks were obtained by subtracting these background spectra from those of the $pp \rightarrow ppX$ measured above the $\eta'$ production threshold. The shapes and widths of the $\eta'$ peaks in the resultant $pp \rightarrow pp\eta'$ spectra, shown in figs. 2(c1) and 2(c2), are in good agreement with the computer simulations discussed later.

In view of the rapid variations of the three-body cross section and the spectrometer acceptance near threshold, it is vital to determine the excess energy $Q$ in the centre-of-mass (cm) system with precision. Now the nominal beam energy calculated using the parameters of the SATURNE accelerator is in general slightly greater than the true value. Several previous detailed studies [2, 6, 7] show that the difference between the real and nominal energies does not depend upon the energy or particle type but rather on the tuning of the accelerator and on the beam extraction. From these measurements we determine an energy correction of $dT = 1.1 \pm 1.0$ MeV which changes a nominal beam energy of 2416 MeV to a ‘true’ value of $T_p = 2414.9$ MeV. Taken together with an $\eta'$ mass of $m_{\eta'} = (957.77 \pm 0.14)$ MeV/c$^2$ [8], this leads to a value of $Q = (3.5 \pm 0.4)$ MeV.

It is however possible to determine the value of $Q$ directly from the experimental data, as has been done previously at SPESIII for $\eta$ production [1, 6]. Near threshold the width of the proton momentum spectrum is a sensitive function of $Q$ which depends but weakly upon the final masses and the absolute calibrations of the beam and spectrometer. Fig. 3(a) shows such a spectrum for $\eta'$ production, obtained by selecting those events in figs. 2(a1) and 2(b1) in the range $956$ MeV/c$^2 \leq M_x \leq 962$ MeV/c$^2$. 
and performing a subtraction, to be compared with a simulation performed assuming that \( Q = 4.3 \) MeV. From the variation of \( \chi^2 \) for such fits shown in fig. 3(b), we deduce that \( Q = 4.3 \pm 0.9 \) MeV, corresponding to a value of \( m_{\eta'} = (957.0 \pm 0.9) \) MeV/c² for a beam energy of 2414.9 MeV. This is in good agreement with the World compilation of the \( \eta' \) mass [3]. The value of the mid-target value of \( Q \) quoted in Table 1 is the mean of the two types of determination. Adjustments in the Saturne beam energy of a few MeV can be accomplished with very high precision and the value of \( Q \) quoted for this in the table is based upon the change in nominal beam energy.

These values of \( Q \) were entered into a calculation of the acceptances which was carried out with a very refined simulation program taking into account all the details of the experimental set-up as well as the algorithms used for treating the data. This program, already used for the first determination of the \( pp \rightarrow pp\eta \) at SPESIII [1], has benefited from numerous upgrades, especially in regards of the effects of the proton-proton final state interaction. Thanks to such improvements the mass of the \( \eta \) determined at SPESIII, \( m_\eta = (547.65 \pm 0.18) \) MeV/c² [2], is in good agreement with the PDG average of \( m_\eta = (547.45 \pm 0.19) \) MeV/c² [8]. Updated values of the \( pp \rightarrow pp\eta \) total cross section of ref.[1] are given in table 1, along with the first measurements of the \( pp \rightarrow pp\eta' \) reaction, and also shown in fig. 1. The quoted errors take account of all the uncertainties both statistical and systematic, including an overall normalisation error of 10%. It should be noted that at \( Q = 3.7 \) MeV the acceptance is insensitive to small changes in the value of \( Q \) and this will also be true for the deduced value of \( \sigma_T \). On the other hand, a change of \( \pm 0.7 \) MeV at \( Q = 8.3 \) MeV would result in a variation of \( \pm 3.5 \) nb in the quoted cross section. Theoretical models are not currently sensitive to such small uncertainties.

In a one-pion-exchange model, a \( \pi^0 \) is emitted by one proton and converts to an \( \eta \) on the second, leaving the two final protons to be subject to the strong S-wave final state interaction [1]. If the initial \( pp \) distortion is neglected, it is straightforward to show in such a model that the S-wave contribution to the total \( pp \rightarrow pp\eta \) cross section near threshold should have the form

\[
\sigma_T(pp \rightarrow pp\eta) = A \frac{(m_p + m_\eta)^2}{(2m_p + m_\eta)^{5/2}} \frac{\sqrt{m_\eta}}{(m_p m_\eta + m_\pi^2)^2} |f(\pi^0 p \rightarrow p \eta)|^2 F(Q),
\]

with an analogous formula for \( \eta' \) production. Here \( m_p, m_\eta \) and \( m_\pi \) are respectively the \( p, \eta \) and \( \pi \) masses. Despite the dominance of the \( N^*(1535) \) resonance, the spin-average of the square of the \( \pi^0 p \rightarrow p \eta \) amplitude, \( |f|^2 \), varies slowly over the limited range of \( Q \) measured in this experiment. It is therefore sufficient to take its value at threshold.
In the short-range limit, which is valid for heavy-meson production, the effect of the proton-proton final state interaction can be modelled by the function \[ F(Q) = \epsilon \left( \frac{Q}{\epsilon} \right)^{2} \left( 1 + \sqrt{1 + Q/\epsilon} \right)^{-2}, \] (2)
where, including Coulomb distortion, \( \epsilon \approx 0.45 \text{ MeV} \). Such a function describes accurately the near-threshold energy dependence of the \( pp \rightarrow pp\pi^{0} \) total cross section down to \( Q \approx 1 \text{ MeV} \), when explicit Coulomb suppression becomes important \[10]\).

The overall factor \( A \) depends upon the \( \pi pp \) coupling constant and the proton mass etc., but is independent of parameters referring to the \( \eta \) meson, so that its value should be the same for both \( \eta \) and \( \eta' \) production.

The dashed curve in fig. 1 shows the prediction of eq.(1) when the value of \( A \) is adjusted to fit the lowest energy points of \( \eta \) production. The deviations from this curve of up to a factor of two at higher values of \( Q \) have been taken as evidence for an attractive \( \eta pp \) final state interaction \[4\]. By using the same value of \( A \), combined with experimental values for the threshold values of \( |f(\pi^{0}p \rightarrow p \eta)|^{2} = (365\pm30) \mu \text{b/sr} \) and \( |f(\pi^{0}p \rightarrow p \eta')|^{2} = (10\pm1) \mu \text{b/sr} \[11\], it is possible to make absolute predictions of the \( pp \rightarrow pp\eta' \) total cross section, and the resulting solid line shown in fig. 1, is only about 30\% below our two experimental points and in good agreement with the trend in the data. Though the predicted energy dependence is only weakly model dependent, more accurate estimates of the normalisation would require further information on the contributions of \( \rho \) and other heavy-meson exchange diagrams \[9\].

In summary, we have made a first measurement of the \( pp \rightarrow pp\eta' \) total cross section near threshold, determining the mass of the \( \eta' \) to better than 0.1\%. The relative production rates of the \( \eta' \) and \( \eta \) mesons are broadly consistent with expectations based on a meson exchange model. Since the preparation of this letter, we have been informed that measurements by the COSY-11 group closer to threshold have been submitted for publication \[12\]. It should be noted that there is satisfactory agreement in normalisation where the two experiments meet around \( Q = 4 \text{ MeV} \).
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Table 1: Total cross sections for $\eta$ and $\eta'$ production in proton-proton collisions near threshold measured with SPESIII. The excess energy $Q$ is the mean kinetic energy in the centre-of-mass system of the final state, taking into account the energy losses of the beam in the target. The inclusion of proton-proton final state interactions in the analysis led to a significant reduction of the $\eta$ cross section at 16 MeV, as compared to the value quoted in [1], and this might be reduced by up to a further 10% by a strong $\eta$-proton fsi.

| $Q$ (MeV) | $\sigma_T$ (nb) |
|-----------|-----------------|
| $pp \rightarrow pp\eta$ | 0.64 ± 0.25 80 ± 15 |
|          | 2.65 ± 0.25 730 ± 120 |
|          | 16.0 ± 0.6 2680 ± 540 |
| $pp \rightarrow pp\eta'$ | 3.7 ± 0.6 19.2 ± 2.7 |
|          | 8.3 ± 0.7 43.6 ± 6.5 |
Figure 1: Total cross sections for $pp \rightarrow pp\eta$ as a function of the mean mid-target kinetic energy $Q$ in the final state measured with SPESIII (filled squares) [1]. The CELSIUS points (circles) [4] and those of PINOT (triangles) [3] are subject to additional overall normalisation uncertainties of $\pm20\%$ and $\pm15\%$ respectively, whereas the $\pm10\%$ of the SPESIII points are included in the figure. The PINOT energies are slightly uncertain and the mean of their two solutions is shown, corrected for energy loss in the target. The points are compared to the predictions of eq.(1) (dashed curve), which reflects the proton-proton final state interaction folded with phase space. The arbitrary normalisation in eq.(1) for the $\eta$ case fixes the absolute scale for the $pp \rightarrow pp\eta'$ predictions shown as the solid curve. This is in reasonable agreement with our two measured $\eta'$ points (open squares).
Figure 2: Missing mass spectra of the $pp \rightarrow ppX$ reaction at nominal beam energies of (1) 2416 MeV, and (2) 2430 MeV. The observed spectra in (a1) and (a2) are to be compared with background spectra in (b1) and (b2) obtained by scaling the 2400 MeV data as described in the text. The shapes and widths of the $\eta'$ peaks, obtained by subtraction and shown in (c1) and (c2), are in good agreement with the Monte Carlo simulations.
Figure 3: (a) Proton momentum spectrum for events in the $\eta'$ peak in the 2416 MeV data of fig. 2 compared with a Monte Carlo simulation evaluated at an excess energy of $Q = 4.3$ MeV, where the fit leads to a value of $\chi^2 = 0.8$. The variation of $\chi^2$ with $Q$ shown in (b) allows us to estimate the energy to be $Q = (4.3 \pm 0.9)$ MeV.