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Abstract

The pp→ppη cross section has been measured at six energies close to threshold, from 1258 MeV to 1352 MeV, using an internal cluster gas jet target in the CELSIUS storage ring. The η is detected through its decay photons, in an array of CsI detectors, and the forward-going protons are detected in a plastic scintillator spectrometer. A complete event reconstruction is obtained at the higher energies in the measured interval. The new data, together with earlier data, give an accurate determination of the energy dependence close to threshold. The influence of the η-proton FSI is seen in the total cross section data as well as in a Dalitz plot of the η-p invariant mass distributions.

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Meson production in nucleon-nucleon collisions near the energy threshold provides valuable information on reaction mechanisms as well as on nucleon-nucleon and meson-nucleon interactions. Pion production in the $pp \to pp\pi^0$ reaction close to the threshold has been shown to probe short range physics[1], and it might also be sensitive to off-shell effects in the πN amplitude[2]. The pion-nucleon interaction in the $pp \to pp\pi^0$ reaction close to threshold is weak since the reaction is dominated by a $^3P_0 \to {}^1S_0 s$ transition. Thus s-wave pions dominate and the Δ is unimportant. In the case of near threshold η production the situation is very different, since the $pp \to pp\eta$ reaction will be dominated by the formation of the S-wave N*(1535) resonance. The η-nucleon interaction might therefore have a significant influence on the near-threshold production cross section.

Values of the total $pp \to pp\eta$ cross-section have recently been published at three different energies close to threshold ($T_p \leq 1.3$ GeV)[3,4]. The measurement was carried out with the SPES3 magnetic spectrometer at Saturne by detecting the two outgoing protons. Four additional data points in the energy region up to $T_p = 1.5$ GeV were measured with the PINOT spectrometer at Saturne[5], where the η was detected through its decay into two photons.

The available data can be compared to a meson exchange model where the η is produced *via* the decay of an N* resonance. Since large momentum transfers are involved, the reaction is also sensitive to mesons heavier than the pion. Theoretical calculations have been carried out within the framework of such a model, but with slightly different approximations. Germond and Wilkin[6], who included only the N*(1535) S-wave resonance, found that ρ–exchange plays a dominant role. This was confirmed in the calculation by Laget, Wellers and Lecolley[7], who included amplitudes up to F-wave. Vetter, Engel, Biró and Mosel[8] found, however, that the π, ρ, and ω give approximately equal contributions to the cross section owing to their choice of a smaller coupling constant $g_{\rho NN^*}$ in the calculation.

Close to threshold, the observed energy variation is much stronger than predicted by these calculations which do not include η-proton final state interaction (FSI). This suggests that, in addition to the proton-proton FSI, the η-proton FSI must be included, as shown qualitatively in ref. 9. The importance of the η-proton FSI has been independently investigated by Moalem *et al* [10], in a more formal treatment. They also confirmed that the energy variation of the cross section is independent of the relative phase of the π, ρ and the η-exchange amplitudes, while there is a large dependence in the magnitude of the cross section on the relative phase[6,7].

In the present work, data on the total cross section of the $pp \to pp\eta$ reaction are presented at six lab-energies from 1258 MeV close to the threshold (1254.6 MeV) up to 1352 MeV. The experiment was performed at the The Svedberg Laboratory, Uppsala, using a cluster gas jet target in the CELSIUS storage ring. A typical luminosity of 5×10^{30} cm^{-2}s^{-1} was achieved. The detector set-up, shown in fig. 1, consists of a two-arm spectrometer for detecting decay photons from neutral mesons and a forward scintillator spectrometer for charged particles. The construction and performance of the whole detector system is described in detail in refs. 9 and 11. Each arm of the photon spectrometer contains 56 tapered CsI(Na) crystals with photomultiplier readout, stacked in a 7×8 array, which covers scattering angles from 30° to 90° and about ±25° in azimuthal angles. The mesons are identified by the invariant mass calculated from the angles and energies of the decay photons. The photon spectrometer is placed with one arm on either side of the cluster-jet target, and is preceded by veto counters in order to reject charged particles. A scintillation detector system downstream of the target detects charged particles recoiling in the forward direction at polar angles between 3° and 22°. The front part of this detector system is a hodoscope[12] consisting of three layers, each of 0.5 cm thick plastic scintillators, with spiral- and sector-shaped elements arranged in a configuration to provide positions information from the hit pattern of charged particles. Following this hodoscope, a calorimeter comprising four thick layers, each of 11 cm plastic scintillators, measures the energy deposition of charged particles.

With this set-up it is possible to observe all final state particles in meson producing pp collisions near threshold. Our method of detecting the decay photons provides a clean trigger and makes it possible to measure total cross sections down to threshold without any losses in acceptance. All final state particles in the $pp \to pp\eta$ reaction can be detected at beam energies above 1275 MeV, and a reconstruction of the total event kinematics can be performed, providing additional information on the reaction process. A complete event reconstruction also allows for an accurate determination of the beam energy. A detailed Monte Carlo simulation of the detector system using GEANT was performed to obtain the overall acceptance for η detection. The invariant mass resolution of the η, given purely by the photon detection, is 44 MeV (FWHM).

The use of an internal gas-jet target in a storage ring does not allow for the luminosity to be determined sufficiently accurate from known values of target thickness and beam current. An independent calibration of the luminosity using known cross sections of other reactions is therefore needed. We have measured the total π^0 production cross section in pp collisions simultaneously with the η production. The advantage of this normalization method is that the π^0 is measured in the same way as the η, thereby minimizing systematic errors due to detection inefficiencies. The details of this normalization procedure is described in ref. 9. The resulting absolute cross section for the η production at 1352 MeV is 4.9 ± 0.7 μb. An independent check based on detecting elastic pp scattering yielded 4.3 ± 0.9 μb .

The absolute beam energy was determined by a kinematical fit to the measured variables of the final states particles, *i e* the energies and scattering angles of the decay photons from the η, and the scattering angles of the two outgoing protons. This procedure, described in ref. 9, was applied at different energies, and an average value of the circumference of the circulating beam could be obtained (81.754±0.008 m). The error in the circumference, together with an uncertainty in the relative beam momentum of about $\Delta p/p = 4\times10^{-4}$, correspond to an uncertainty in the beam energy of 1.3 MeV (standard deviation). This value corresponds to an error in the kinetic energy of the final state in the CM-system (excess energy) of 0.5 MeV in the measured energy interval.

Our data on the total cross section are presented in table 1 and in fig. 2. The figure also includes previous data in the relevant energy region. The data are compared with the theoretical predictions from refs. 7, 8, and 10. As pointed out above, the calculation including the η-proton FSI gives better agreement with the data than those neglecting that contribution.

The importance on the η-proton FSI can be further elucidated by investigating correlations between the final state particles, appearing in *e.g.* η-p invariant-mass distributions. Such distributions have been calculated with respect to both protons, and the Dalitz plot obtained at 1352 MeV is shown in fig. 3. Since the two final protons are identical, we have to label them by some convention. We choose to plot the high-mass η-p pair along the x-axis and the low-mass pair along the y-axis, *i.e.* the symmetric Dalitz plot is folded along the symmetry axis. The bin-size corresponds to one standard deviation in the invariant mass resolution. The experimental data have been divided by Monte Carlo data generated according to phase space and experimental acceptances, so that any deviation from phase space will show up as a structure in the plot. Two regions of enhancement can be discerned, one in the upper right corner and one in the lower part of the plot. These enhancements are best seen at the highest energy (1352 MeV), where the range in invariant mass is the largest. The region in the upper right corner of the Dalitz plot corresponds for both η-p pairs to maximum invariant mass, which occurs when the two protons are emitted together and the η recoils with equal and opposite momentum. Hence, the relative p-p momentum is minimal. This is the region where the effect of p-p FSI is expected, and indeed a Monte Carlo model including the p-p FSI gives an enhancement[9]. We point out that in a corresponding Dalitz plot for the $pp\rightarrow pp\pi^0$ reaction, our experimental data[13] show evidence for p-p FSI, but no enhancement indicating π-p FSI. Low energy η's are much more strongly interacting than π's, and this fact suggests that the enhancement in the lower part of the η-p Dalitz plot in fig. 3 is due to the η-p interaction.

Deviations from a phase space behavior in the $pp\rightarrow pp\eta$ reaction are expected due to the influence of the N*(1535) resonance. However, the width of this resonance (≈150 MeV) makes it difficult to discern its influence on the Dalitz plot, where the range of masses covered is less than 40 MeV.

Another indication of the importance of the η−proton FSI comes from comparing the energy dependence of the η and π^0 cross sections. In Fig. 4 the ratio of these two cross sections is plotted as a function of the excess energy. By forming this ratio the influences of phase space and p-p FSI are effectively removed, so that a deviation from a constant would reflect an η–proton FSI. The figure shows indeed an enhancement of the η cross section relative to the π^0 cross section very close to threshold. This is in accordance with what one would expect from a strong η-proton FSI, since close to threshold the interaction between the η and the final state protons is most pronounced.

In summary, our data on the $pp \to pp\eta$ reaction together with previous data determine accurately the energy variation close to threshold. The shape of the energy variation is determined by phase space and FSI in the p-p and η–p systems. In particular, the importance of the η–p FSI interaction is clearly demonstrated by its presence both in the Dalitz plot of the η–p invariant mass and in the energy dependence of the ratio between the η and π^0 cross sections.

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Beam energy (MeV)	Excess energy (MeV)	σ_{tot} (μb)
1258	1.462	0.14 ± 0.02
1262	3.009	0.47 ± 0.08
1276	8.416	1.29 ± 0.19
1293	14.96	2.11 ± 0.32
1328	28.39	3.50 ± 0.52
1352	37.56	4.92 ± 0.74

Table 1. Total cross section from the pp→ppη reaction.

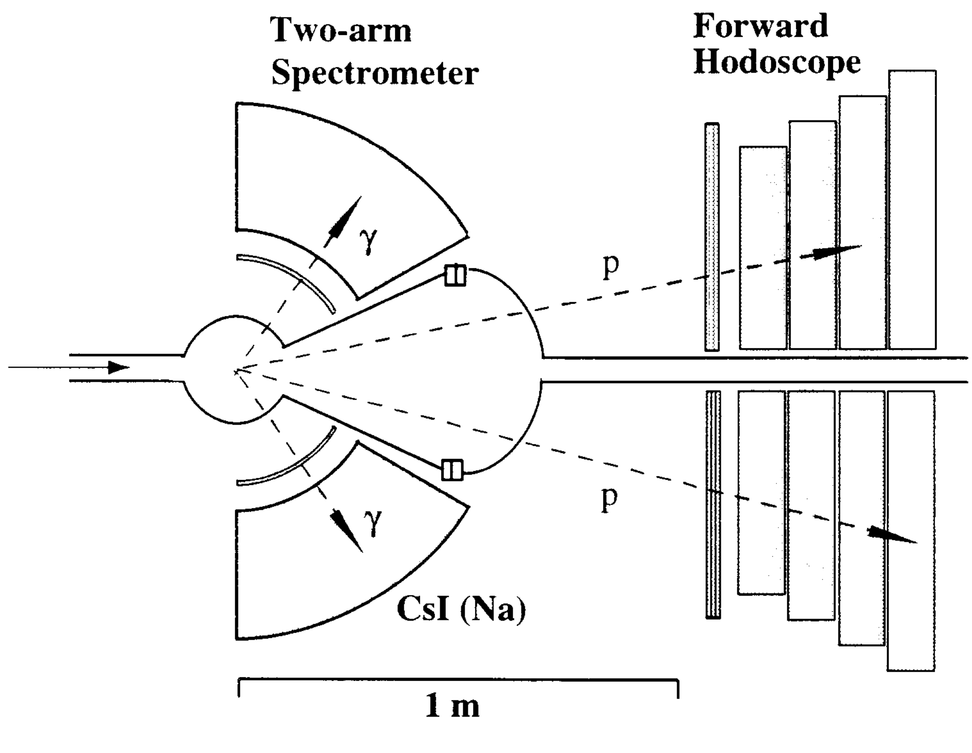

Fig. 1. A schematic view of the detector set-up showing the CsI detector for the photons and the scintillator hodoscope and calorimeter for the forward going charged particles.

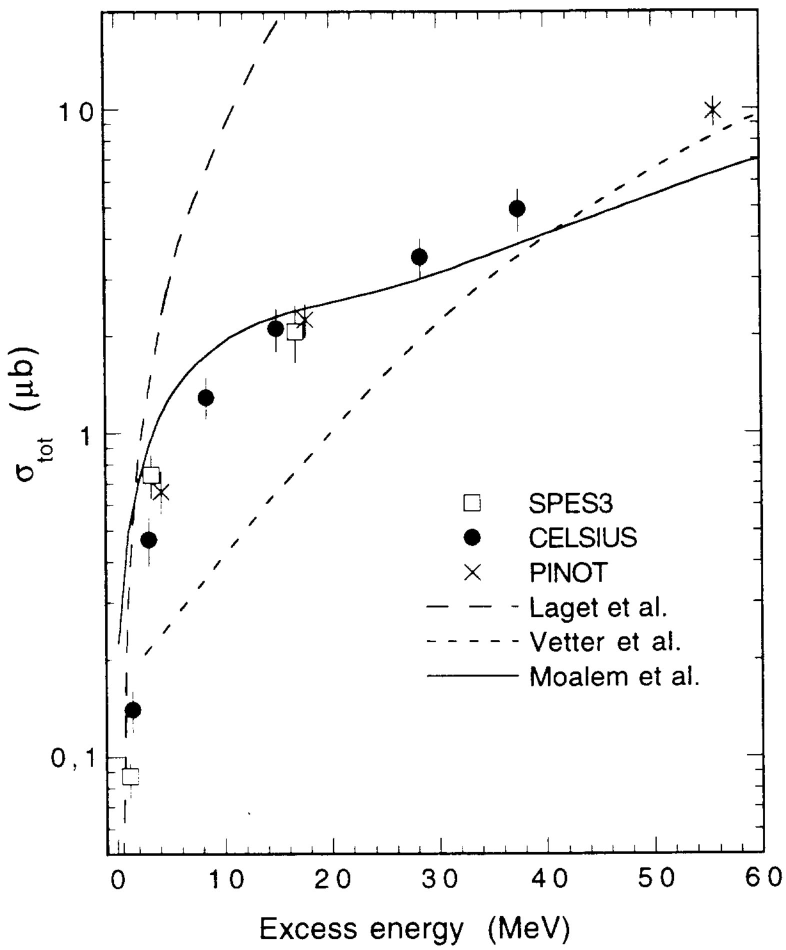

Fig. 2. Total cross section data on the pp→ppη reaction together with theoretical predictions (see text). Only the prediction by Moalem includes η-proton FSI. The SPES3 data are the reanalyzed set of ref. 4.

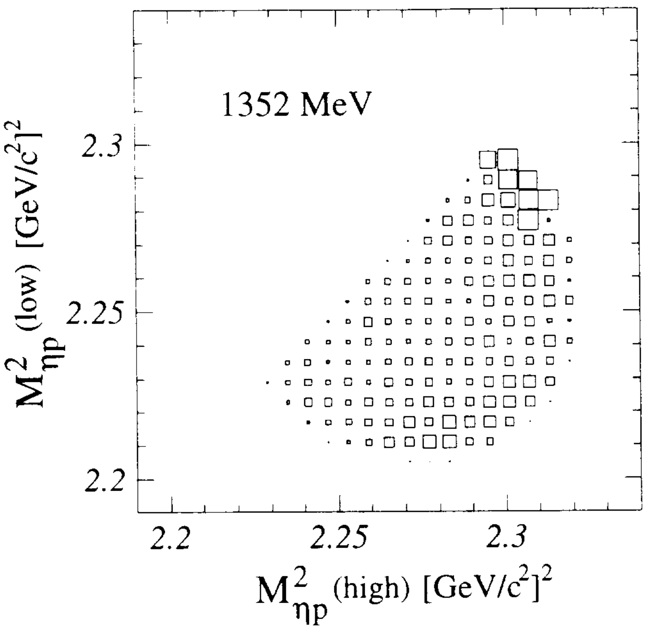

Fig. 3. Dalitz plot of the η–p invariant mass obtained at 1352 MeV.

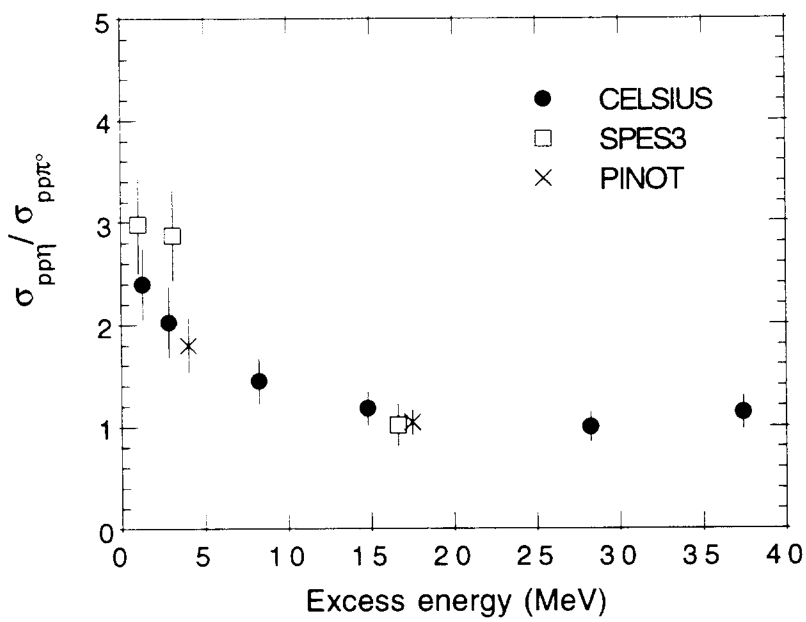

Fig. 4. The ratio (arbitrarily normalized) between the η and π^0 production near the threshold energies, respectively, plotted as a function of excess energy.