

# Mechanism of the close-to-threshold production of the $\eta$ meson

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(Dated: February 6, 2008)

Measurements of the analysing power for the  $\bar{p}p \rightarrow pp\eta$  reaction have been performed in the close-to-threshold energy region at beam momenta of  $p_{beam} = 2.010$  and  $2.085$  GeV/c, corresponding to excess energies of  $Q = 10$  and  $36$  MeV, respectively. The determined analysing power is essentially consistent with zero implying that the  $\eta$  meson is produced predominantly in the  $s$ -wave at both excess energies. The angular dependence of the analysing power, combined with the hitherto determined isospin dependence of the total cross section for the  $\eta$  meson production in nucleon-nucleon collisions, reveal a statistically significant indication that the excitation of the nucleon to the  $S_{11}(1535)$  resonance, the process which intermediates the production of the  $\eta$  meson, is predominantly due to the exchange of the  $\pi$  meson between the colliding nucleons.

In the low energy region investigations of the production and decay of hadrons deliver information needed to deepen our knowledge about the strong interaction in the domain where the perturbative approach is not possible.

In this letter we focus on the hadronic production mechanism of the  $\eta$  meson and interpret the empirical observations in the framework of meson exchange models. We report on the determination of the angular dependence of the beam analysing power for the  $\bar{p}p \rightarrow pp\eta$  reaction. We also demonstrate that the confrontation of predictions based upon different scenarios, involving exchanges of various mesons, with the so far determined unpolarised observables and with results on the analysing power, permits to single out the dominant process and hence to understand details of the  $\eta$  meson production close to the kinematical threshold.

From precise measurements of the total cross sections of the  $\eta$  meson production in the  $pp \rightarrow pp\eta$  reaction [?] it was concluded [?] that this process proceeds through the excitation of one of the protons to the  $S_{11}(1535)$  state which subsequently deexcites via the emission of the  $\eta$  meson (see Fig. 1).

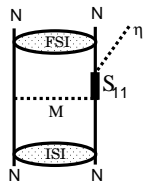


FIG. 1: The mechanism of the  $\eta$  meson production in nucleon-nucleon collisions: excitation of a nucleon to the  $S_{11}(1535)$  resonance state via meson exchange, and its subsequent decay into the proton- $\eta$  system. M denotes an intermediate pseudoscalar or vector meson, e.g.  $\pi$ ,  $\eta$ ,  $\omega$ ,  $\rho$ . ISI and FSI indicate initial and final state interaction between the nucleons.

The crucial observations were a large value of the absolute cross section and an isotropic distributions of the emission angle of the  $\eta$  meson in the reaction center-of-

mass system. In practice, within the meson exchange picture, the excitation of the intermediate resonance can be induced by exchange of any of the pseudoscalar or vector ground state mesons between the nucleons. Based only on the excitation function it was, however, impossible to disentangle the contributions to the production process originating from the  $\pi$ ,  $\eta$ ,  $\omega$  or  $\rho$  meson exchange. In fact, due to the negligible variation of the production amplitude in the range of a few tens of MeV, the only information available from the excitation function is reduced to a single number [? ? ? ? ?].

More constraints to theoretical models [? ? ? ? ? ? ? ? ?] have been deduced from the measurement of the isospin dependence of the total cross section by the WASA/PROMICE collaboration [?] [1] The comparison of the  $\eta$  meson production in proton-proton and proton-neutron collisions inferred that the  $\eta$  meson is by a factor of twelve more copiously produced when the total isospin of the nucleons is zero with respect to the case when it is one. As a consequence only an isovector meson exchange is conceivable as being responsible for such a strong isospin dependence. This result was already a large step forward but still the relative contributions of the  $\rho$  and  $\pi$  mesons remained to be disentangled. The elucidation of this very detail in the production mechanism of the  $\eta$  meson constitutes the motivation for the measurements presented in this letter. For this purpose we have determined the analysing power for the  $\bar{p}p \rightarrow pp\eta$  reaction since its theoretical value [? ?] is sensitive to the assumption on the type of the meson being exchanged in order to excite one of the colliding nucleons to the  $S_{11}(1535)$  state.

For the measurement of the  $\bar{p}p \rightarrow pp\eta$  reaction the COSY-11 experimental setup [?] has been used, which is an internal beam facility at the cooler synchrotron COSY [? ?]. This facility has been described in various publications, therefore herein we only briefly report the main idea of the measurement referring the interested reader to the articles [? ?] for the description of the instrumentation system and to [? ? ?] for the particle identification and monitoring of the beam and target parameters.

A vertically polarised proton beam [?], had been stored and accelerated in the COSY ring. The direction of the polarisation was being flipped from cycle to cycle. The target is installed in front of a machine dipole magnet acting as a momentum separator for the charged reaction products. The positively charged ejectiles were registered in drift chambers and scintillator hodoscopes. For each particle its trajectory and time of flight on a nine meter distance was measured. Tracking back these trajectories through the known magnetic field inside the dipole magnet to the reaction vertex allows for the momentum reconstruction with a precision of about 4 MeV/c [? ?] in the center-of-mass frame. The acceptance of the COSY-11 facility allows to register only events scattered near the horizontal plane. In the analysis the azimuthal angle  $\phi$  was restricted to values of  $\cos\phi$  ranging between 0.87 and 1.

For the determination of the analysing power of the  $\eta$  meson at a given value of the polar angle  $\theta_\eta$  and the azimuthal angle  $\phi$  it is required to measure a left-right asymmetry of yields of the  $\eta$  meson in the frame turned by the angle  $\phi$  with respect to the laboratory coordinate system. This is often referred to as a Madison frame [2] which in our case has its  $y$  axis parallel to the  $\vec{p}_{beam} \times \vec{p}_\eta$  vector, with  $\vec{p}_{beam}$  and  $\vec{p}_\eta$  denoting the momentum vectors of the proton beam and the  $\eta$  meson in the center-of-mass system, respectively.

In the case of the  $pp \rightarrow pp\eta$  reaction, the COSY-11 detector setup, has much larger acceptance for events where the  $\eta$  meson is produced to the left side with respect to the polarisation plane as compared to those for which it is emitted to the right. Therefore, the left-right asymmetries are determined from numbers of events with the  $\eta$  meson production to the left side measured for the spin up and spin down mode of the beam polarisation. For

TABLE I: Number of reconstructed  $\eta$  mesons and analysing powers for the  $\bar{p}p \rightarrow pp\eta$  reaction.

| Q [MeV] | $\cos\theta_\eta$ | $N_+^\uparrow$ | $N_-^\downarrow$ | $A_y$                  |
|---------|-------------------|----------------|------------------|------------------------|
| 10      | (-1; -0.5)        | 306±27         | 250±26           | <b>.163±.099±.022</b>  |
|         | (-0.5; 0)         | 267±22         | 260±24           | <b>.035±.091±.012</b>  |
|         | (0; 0.5)          | 198±18         | 208±19           | <b>-.021±.095±.011</b> |
|         | (0.5; 1)          | 279±23         | 286±25           | <b>-.003±.088±.009</b> |
| 36      | (-0.5; 0)         | 103±16         | 100±18           | <b>.039±.179±.012</b>  |
|         | (0; 0.5)          | 144±16         | 153±18           | <b>-.029±.122±.010</b> |
|         | (0.5; 1)          | 259±24         | 296±28           | <b>-.084±.100±.011</b> |

the quantitative evaluation we define  $N_+^\uparrow(\theta_\eta)$  and  $N_-^\downarrow(\theta_\eta)$  as production yields of the  $\eta$  meson emitted to the left around the  $\theta_\eta$  angle as measured with the up and down beam polarisation, respectively, i.e.

$$N_+^\uparrow(\theta_\eta) = \sigma_0(\theta_\eta) (1 + P^\uparrow A_y(\theta_\eta)) E(\theta_\eta) \int L^\uparrow dt, \quad (1)$$

$$N_-^\downarrow(\theta_\eta) = \sigma_0(\theta_\eta) (1 - P^\downarrow A_y(\theta_\eta)) E(\theta_\eta) \int L^\downarrow dt, \quad (2)$$

with  $\sigma_0(\theta_\eta)$  denoting the cross section for the  $\eta$  meson production for unpolarised beam,  $P^{\uparrow(\downarrow)}$  standing for the polarisation degree corresponding to spin up and down modes,  $E(\theta_\eta)$  being the efficiency of the COSY-11 facility for detecting the  $\eta$  meson emitted to the left side at the  $\theta_\eta$  angle and  $L^{\uparrow(\downarrow)}$  denoting the luminosity during the beam polarisation up and down. Signs in the brackets of Eqs. 1 and 2 follow the Madison convention. Assuming

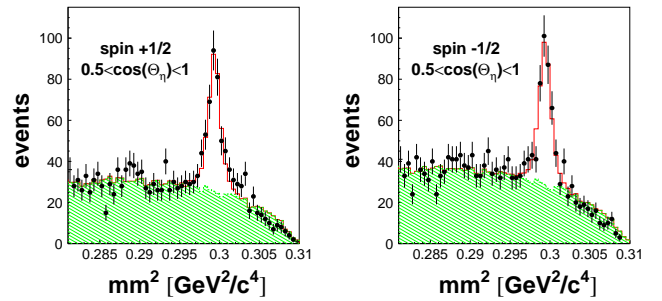


FIG. 2: Examples of missing mass spectra for  $\cos\theta_\eta \in (0.5; 1)$  and opposite beam polarisation states, as measured at the excess energy  $Q = 10$  MeV. Full points correspond to the experimental values which are shown with their statistical uncertainties. The solid line represents the sum of the  $pp\eta$  and multipion background production channels determined by Monte-Carlo simulations. The shaded parts of the histograms show the simulated contributions from the multipion background.

that  $P^\uparrow \approx P^\downarrow$  [3] and introducing the average beam polarisation  $P \approx \frac{P^\uparrow + P^\downarrow}{2}$ , the relative luminosity  $L_{rel} = \frac{\int L^\uparrow dt}{\int L^\downarrow dt}$  and solving Eqs. 1 and 2 for  $A_y(\theta_\eta)$  we obtain:

$$A_y(\theta_\eta) = \frac{1}{P} \frac{N_+^\uparrow(\theta_\eta) - L_{rel} N_-^\downarrow(\theta_\eta)}{N_+^\uparrow(\theta_\eta) + L_{rel} N_-^\downarrow(\theta_\eta)}. \quad (3)$$

The production yields  $N_+^\uparrow(\theta_\eta)$  and  $N_-^\downarrow(\theta_\eta)$  have been extracted from the missing mass spectra. Optimizing the statistics and the expected shape of the analysing power function, the range of the  $\theta_\eta$  angle has been divided into four bins, at both excess energies. Fig. 2 presents missing mass spectra obtained for the measurements at  $Q = 10$  MeV for  $\cos\theta_\eta \in (0.5; 1)$  corresponding to different states of the beam polarisation. To separate the actual production rates from the background both the reactions with multipion production as well as the events with the  $\eta$  meson production have been simulated using a program based on the GEANT3 [?] code. Since we consider here only the very edge of the phase space distributions, i.e. where the protons are emitted predominantly

in the S-wave, the shape of the background can be reproduced assuming that the homogenous phase space distribution is modified only by the interaction between protons [? ?]. A fit of the simulated missing mass spectra to the corresponding experimental histograms has been performed with the amplitudes of the simulated spectra treated as free parameters. The extracted  $N_+^\perp(\theta_\eta)$  and  $N_-^\perp(\theta_\eta)$  values, are quoted in Table I along with their statistical uncertainties.

The relative luminosity for both excess energies has been determined by means of the measurement of coincidence rate in the polarisation plane [?]. Due to the parity invariance, in the polarisation plane the differential cross section for any nuclear reaction caused by the strong interaction is independent of the beam polarisation and therefore a ratio of the numbers of events during spin up and down modes can be used as a measure of the relative luminosity. Values of  $L_{rel}^{10} = 0.98468 \pm 0.00056 \pm 0.00985$  and  $L_{rel}^{36} = 0.98301 \pm 0.00057 \pm 0.00985$  have been obtained at the excess energies of  $Q = 10$  and  $36$  MeV, respectively.

During the run at the excess energy of  $Q = 10$  MeV the beam polarisation has been determined with the COSY-11 setup [?]. The principle of measurement was based on the determination of the asymmetry in the accelerator plane (perpendicular to the polarization vector) for the  $\bar{p}p \rightarrow pp$  reaction. Although at a given beam polarisation mode only protons elastically scattered to the right could be registered it was possible to determine the polarisation by flipping the spin and employing Eq. 3 with exchanged  $A_y(\theta_\eta)$  and  $P$ . As a result the value of the polarisation degree  $P = 0.680 \pm 0.007 \pm 0.055$  has been extracted. For the calculations the values of analysing powers for the elastic processes have been taken into account from the precise measurements performed by the EDDA collaboration [?].

For the polarisation monitoring during the run at  $Q = 36$  MeV we used the EDDA facility [?]. The determination of the polarisation degree with this setup is based on the asymmetry measurement for the  $\bar{p}p \rightarrow pp$  process. The obtained value of the averaged polarisation equals to  $P = 0.663 \pm 0.003 \pm 0.008$ .

The main source of the systematic uncertainties in the determination of the production yields originates from a background misidentification. In order to estimate the systematic error, an alternative method (with respect to the method presented above) of background subtraction has been applied which is based on a polynomial background cut [?]. Differences in the production yields obtained by this independent method were less than 1.5%. The main contribution to the systematic uncertainty of the relative luminosity might be due to a slight shift of the center of detectors outside the polarisation plane. Assuming very conservatively a 4 mm shift and using the analysing powers for the elastically scattered protons of Ref. [?] a value of 1% systematic uncertainty of the

relative luminosity was established by means of Monte-Carlo simulations. The systematic uncertainty of 8% for the polarisation measured with the COSY-11 polarimeter is determined by error propagation from Eq. 3 with the systematic uncertainties of the analysing powers (1.2%), systematic error of the relative luminosity (1%) and the 1% systematic uncertainty of the number of elastically scattered yields [?]. During the measurement at the excess energy of  $Q = 36$  MeV the overall systematic error in the determination of the polarisation value, when using the large acceptance EDDA detector, was 1.2% [?].

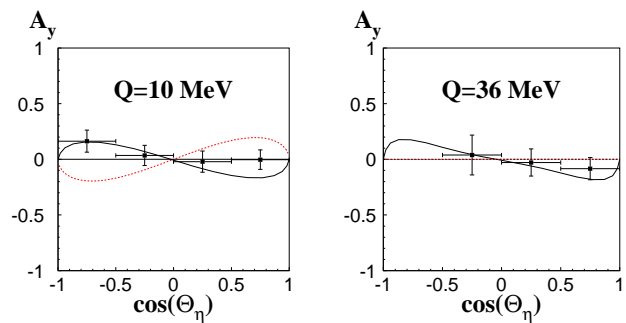


FIG. 3: Analysing powers for the  $\bar{p}p \rightarrow pp\eta$  reaction as functions of  $\cos\theta_\eta$  for  $Q = 10$  MeV (left panel) and  $Q = 36$  MeV (right panel). Full lines are the predictions based on the pseudoscalar meson exchange model [?] whereas the dotted lines represent the calculations based on the vector meson exchange [?]. In the right panel the dotted line is consistent with zero. Shown are the statistical uncertainties solely.

The analysing powers calculated using Eq. 3 are summarized in Table I for both excess energies and presented in Fig. 3. At the excess energy of  $Q = 36$  MeV insufficient statistics for the  $\cos\theta_\eta \in (-1; -0.5)$  range resulted in an error larger than the allowed range and hence this point was omitted.

In order to verify the correctness of the models based on the dominance of the  $\rho$  or  $\pi$  meson exchanges, a  $\chi^2$  test has been performed. The reduced value of the  $\chi^2$  for the pseudoscalar meson exchange model was determined to be  $\chi_{psc}^2 = 0.54$ , which corresponds to a significance level  $\alpha_{psc} = 0.81$ , whereas for the vector meson exchange model  $\chi_{vec}^2 = 2.76$ , resulting in a significance level of  $\alpha_{vec} = 0.006$ .

In the vector meson exchange dominance model [?] the angular distribution of the analysing power is parameterized with the following equation:

$$A_y(\theta_\eta) = A_y^{max,vec} \sin 2\theta_\eta, \quad (4)$$

where the amplitude  $A_y^{max,vec}$  is a function of the excess energy  $Q$ , shown as a dotted line in the left panel of Fig. 4.

We have estimated the values of  $A_y^{max,vec}$  comparing the experimental data with predicted shape utilizing a  $\chi^2$  test. The values of  $A_y^{max,vec}$  for  $Q = 10$  and  $36$  MeV have been deter-

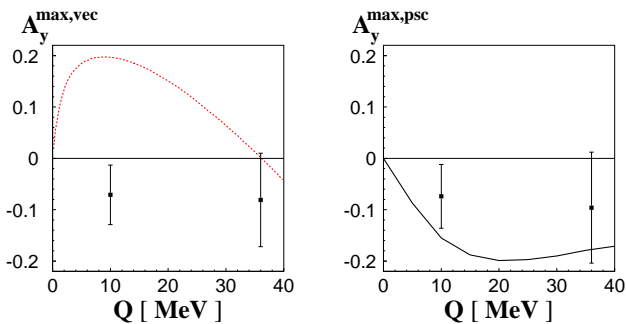


FIG. 4: Theoretical predictions for the amplitudes of the analysing power's energy dependence confronted with the amplitudes determined in the experiments at  $Q = 10$  and  $Q = 36$  MeV for the vector (left panel) and pseudoscalar (right panel) meson exchange dominance model.

mined to be  $A_y^{max,vec}(Q = 10) = -0.071 \pm 0.058$  and  $A_y^{max,vec}(Q = 36) = -0.081 \pm 0.091$ , respectively.

Similar calculations have been performed for the pseudoscalar meson exchange model [? ], assuming that the shape of the analysing power as a function of the  $\cos\theta_\eta$  does not depend on the excess energy, which is correct within about 5% accuracy. It has been found that  $A_y^{max,psc}(Q = 10) = -0.074 \pm 0.062$ , and  $A_y^{max,psc}(Q = 36) = -0.096 \pm 0.108$ . These results are presented in Fig. 4. The figure shows that the predictions of the model based on the  $\pi$  mesons dominance are fairly consistent with the data, whereas the calculations based on the dominance of the  $\rho$  meson exchange differ from the data by more than four standard deviations.

Summarizing, the  $\chi^2$  analysis applied to the tested production models excludes the correctness of the assumption of a pure vector meson dominance ( $\rho$  exchange) with a significance level of 0.006 corresponding to discrepancy between the model and the data larger than four standard deviations, and provides strong evidence for the supposition that the production of the  $\eta$  mesons in nucleon-nucleon collision is dominated by the pion exchange. This result confirms empirically the scenario which could have been derived intuitively from the examination of the branching fractions of the  $S_{11}(1535)$

resonance intermediating the production of the  $\eta$  meson. In the review of particles properties [? ] it is quoted that  $S_{11}(1535)$  decays in about 45% to the  $N\pi$  channel whereas the  $\rho N$  branching fraction is estimated to be lower than 4%.

One should, however, keep in mind that the interference in the exchange of both types of mesons are not excluded and should be studied theoretically and experimentally by the measurement of further spin observables.

It is also worth to mention that the analysing powers of the  $\bar{p}p \rightarrow pp\eta$  reaction for both excess energies studied are consistent with zero within one standard deviation. This may suggest that the  $\eta$  meson is predominantly produced in the  $s$ -wave, an observation which is in agreement with the results of the analysing power measurements performed by the DISTO collaboration [? ] where, interestingly, in the far-from-threshold energy region the  $A_y$  were found to be also consistent with zero within one standard deviation.

The authors would like to thank K. Nakayama, K. S. Man, and C. Wilkin for providing the predictions for  $A_y$  and A. Kupść and S. Bass for reading the early version of the manuscript. We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 programme (Hadron Physics, N4:EtaMesonNet, RII3-CT-2004-506078) and the support of the Polish State Committee for Scientific Research (grant No. PB1060/P03/2004/26).

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- [1] The measurement of the isospin dependence is being extended by the COSY-11 collaboration [? ] to the  $\eta'$  production which may also be sensitive to gluonic production mechanism [? ].
  - [2] Madison Convention, *Polarisation Phenomena in Nuclear Reactions*, University of Wisconsin Press, Madison, pp. XXV (1971)
  - [3] Which is valid within  $\pm 2\%$  accuracy, as has been studied with the EDDA [? ] and COSY [? ] polarimeters.

# Mechanism of the close-to-threshold production of the $\eta$ meson

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Measurements of the analysing power for the  $\vec{p}p \rightarrow pp\eta$  reaction have been performed at excess energies of  $Q = 10$  and  $36$  MeV. The determined analysing power is essentially consistent with zero implying dominance of the  $s$ -wave at both excess energies. The angular dependence of the analysing power, combined with the isospin dependence of the total cross section for the  $\eta$  meson production in nucleon-nucleon collisions, reveal that the excitation of the nucleon to the  $S_{11}(1535)$  resonance, is predominantly due to the exchange of the  $\pi$  meson between the colliding nucleons.

The strong interaction, responsible for the existence of hadrons, has been studied intensively since more than half of a century. At high energies it is well described by QCD in a perturbative approach with quarks and gluons as the relevant degrees of freedom. However, in the low energy regime where the interaction between quarks and gluons cannot be treated perturbatively, there exists no clear understanding of the processes governed by the strong forces. The phenomena in this regime are not calculable using the particles and fields of the Standard Model. Here hadrons become the relevant degrees of freedom and the interaction between hadrons may be described by meson exchange processes. Therefore, in order to understand the behavior of the strong interaction in systems such as nucleons which make up most of the matter surrounding us, it is essential to perform measurements involving the production and decay of hadrons and interpret them in the framework of the effective theories [1].

In this letter we focus on the hadronic production mechanism of the  $\eta$  meson and interpret the empirical observations in the framework of meson exchange models. We report on the determination of the angular dependence of the beam analysing power for the  $\vec{p}p \rightarrow pp\eta$  reaction. We also demonstrate that the confrontation of predictions based upon different scenarios, involving exchanges of various mesons, with the so far determined unpolarised observables and with results on the analysing power, permits to single out the dominant process and hence to understand details of the  $\eta$  meson production close to the kinematical threshold.

From precise measurements of the total cross sections of the  $\eta$  meson production in the  $pp \rightarrow pp\eta$  reaction [2, 3, 4, 5, 6, 7, 8, 9] it was concluded [10, 11, 12, 13, 14, 15, 16, 17] that this process proceeds through the excitation of one

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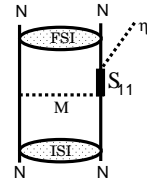


FIG. 1: The mechanism of the  $\eta$  meson production in nucleon-nucleon collisions. M denotes an intermediate pseudoscalar or vector meson, e.g.  $\pi$ ,  $\eta$ ,  $\omega$ ,  $\rho$ . ISI and FSI indicate initial and final state interaction between the nucleons.

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More constraints to theoretical models [10, 11, 12, 13, 14, 15, 16, 17] have been deduced from the measurement of the isospin dependence of the total cross section by the WASA/PROMICE collaboration [21] [37]. The comparison of the  $\eta$  meson production in proton-proton and proton-neutron collisions inferred that the  $\eta$  meson is by a factor of twelve more copiously produced when the total isospin of the nucleons is zero with respect to the case when it is one. As a consequence only an isovector meson exchange is conceivable as being responsible for such a strong isospin dependence. This result was already a large step forward but still the relative contributions of the  $\rho$  and  $\pi$  mesons remained to be disentangled. The elucidation of this very detail in the production mechanism of the  $\eta$  meson constitutes the motivation for the measurements presented in this letter. For this purpose we have determined the analysing power for the  $\vec{p}p \rightarrow pp\eta$  reaction since its theoretical value [16, 17] is sensitive

to the assumption on the type of the meson being exchanged in order to excite one of the colliding nucleons to the  $S_{11}(1535)$  state.

For the measurement of the  $\bar{p}p \rightarrow pp\eta$  reaction the COSY-11 experimental setup [20, 22, 23, 24, 25] has been used, which is an internal beam facility at the cooler synchrotron COSY [26, 27].

A vertically polarised proton beam [28], had been stored and accelerated in the COSY ring. The direction of the polarisation was being flipped from cycle to cycle. The target is installed in front of a machine dipole magnet acting as a momentum separator for the charged reaction products. The positively charged ejectiles were registered in drift chambers and scintillator hodoscopes. For each particle its trajectory and time of flight on a nine meter distance was measured. Tracking back these trajectories through the known magnetic field inside the dipole magnet to the reaction vertex allows for the momentum reconstruction with a precision of about 4 MeV/c [8, 20] in the center-of-mass frame. The acceptance of the COSY-11 facility allows to register only events scattered near the horizontal plane. In the analysis the azimuthal angle  $\phi$  was restricted to values of  $\cos\phi$  ranging between 0.87 and 1.

For the determination of the analysing power of the  $\eta$  meson at a given value of the polar angle  $\theta_\eta$  and the azimuthal angle  $\phi$  it is required to measure a left-right asymmetry of yields of the  $\eta$  meson in the frame turned by the angle  $\phi$  with respect to the laboratory coordinate system. This is often referred to as a Madison frame [38] which in our case has its  $y$  axis parallel to the  $\vec{p}_{beam} \times \vec{p}_\eta$  vector, with  $\vec{p}_{beam}$  and  $\vec{p}_\eta$  denoting the momentum vectors of the proton beam and the  $\eta$  meson in the center-of-mass system, respectively.

In the case of the  $pp \rightarrow pp\eta$  reaction, the COSY-11 detector setup, has much larger acceptance for events where the  $\eta$  meson is produced to the left side with respect to the polarisation plane as compared to those for which it is emitted to the right. Therefore, the left-right asymmetries are determined from numbers of events with the  $\eta$  meson production to the left side measured for the spin up and spin down mode of the beam polarisation. For

the quantitative evaluation we define  $N_+^\uparrow(\theta_\eta)$  and  $N_-^\downarrow(\theta_\eta)$  as production yields of the  $\eta$  meson emitted to the left around the  $\theta_\eta$  angle as measured with the up and down beam polarisation, respectively, i.e.

$$N_+^\uparrow(\theta_\eta) = \sigma_0(\theta_\eta) (1 + P^\uparrow A_y(\theta_\eta)) E(\theta_\eta) \int L^\uparrow dt, \quad (1)$$

$$N_-^\downarrow(\theta_\eta) = \sigma_0(\theta_\eta) (1 - P^\downarrow A_y(\theta_\eta)) E(\theta_\eta) \int L^\downarrow dt, \quad (2)$$

with  $\sigma_0(\theta_\eta)$  denoting the cross section for the  $\eta$  meson production for unpolarised beam,  $P^{\uparrow(\downarrow)}$  standing for the polarisation degree corresponding to spin up and down modes,  $E(\theta_\eta)$  being the efficiency of the COSY-11 facility for detecting the  $\eta$  meson emitted to the left side at the  $\theta_\eta$  angle and  $L^{\uparrow(\downarrow)}$  denoting the luminosity during the beam polarisation up and down. Signs in the brackets of Eqs. 1 and 2 follow the Madison convention. Assuming

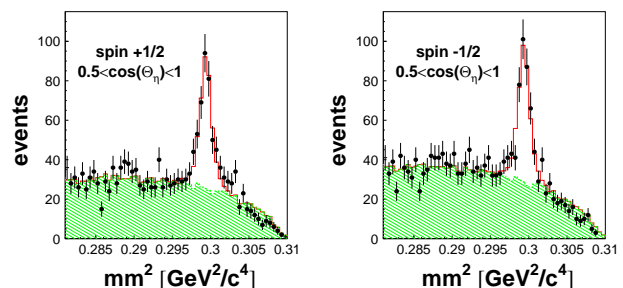


FIG. 2: Examples of missing mass spectra for  $\cos\theta_\eta \in (0.5; 1)$  and opposite beam polarisation states, as measured at the excess energy  $Q = 10$  MeV. Full points correspond to the experimental values which are shown with their statistical uncertainties. The solid line represents the sum of the  $pp\eta$  and multipion background production channels determined by Monte-Carlo simulations. The shaded parts of the histograms show the simulated contributions from the multipion background.

that  $P^\uparrow \approx P^\downarrow$  [39] and introducing the average beam polarisation  $P \approx \frac{P^\uparrow + P^\downarrow}{2}$ , the relative luminosity  $L_{rel} = \frac{\int L^\uparrow dt}{\int L^\downarrow dt}$  and solving Eqs. 1 and 2 for  $A_y(\theta_\eta)$  we obtain:

$$A_y(\theta_\eta) = \frac{1}{P} \frac{N_+^\uparrow(\theta_\eta) - L_{rel} N_-^\downarrow(\theta_\eta)}{N_+^\uparrow(\theta_\eta) + L_{rel} N_-^\downarrow(\theta_\eta)}. \quad (3)$$

The production yields  $N_+^\uparrow(\theta_\eta)$  and  $N_-^\downarrow(\theta_\eta)$  have been extracted from the missing mass spectra. Optimizing the statistics and the expected shape of the analysing power function, the range of the  $\theta_\eta$  angle has been divided into four bins, at both excess energies. Fig. 2 presents missing mass spectra obtained for the measurements at  $Q = 10$  MeV for  $\cos\theta_\eta \in (0.5; 1)$  corresponding to different states of the beam polarisation. To separate the actual production rates from the background both the

TABLE I: Number of reconstructed  $\eta$  mesons and analysing powers for the  $\bar{p}p \rightarrow pp\eta$  reaction.

| Q [MeV] | $\cos\theta_\eta$ | $N_+^\uparrow$ | $N_-^\downarrow$ | $A_y$                  |
|---------|-------------------|----------------|------------------|------------------------|
| 10      | (-1; -0.5)        | 306±27         | 250±26           | <b>.163±.099±.022</b>  |
|         | (-0.5; 0)         | 267±22         | 260±24           | <b>.035±.091±.012</b>  |
|         | (0; 0.5)          | 198±18         | 208±19           | <b>-.021±.095±.011</b> |
|         | (0.5; 1)          | 279±23         | 286±25           | <b>-.003±.088±.009</b> |
| 36      | (-0.5; 0)         | 103±16         | 100±18           | <b>.039±.179±.012</b>  |
|         | (0; 0.5)          | 144±16         | 153±18           | <b>-.029±.122±.010</b> |
|         | (0.5; 1)          | 259±24         | 296±28           | <b>-.084±.100±.011</b> |

reactions with multipion production as well as the events with the  $\eta$  meson production have been simulated using a program based on the GEANT3 [29] code. Since we consider here only the very edge of the phase space distributions, i.e. where the protons are emitted predominantly in the S-wave, the shape of the background can be reproduced assuming that the homogenous phase space distribution is modified only by the interaction between protons [20, 30]. A fit of the simulated missing mass spectra to the corresponding experimental histograms has been performed with the amplitudes of the simulated spectra treated as free parameters. The extracted  $N_{+}^{\uparrow}(\theta_{\eta})$  and  $N_{-}^{\downarrow}(\theta_{\eta})$  values, are quoted in Table I along with their statistical uncertainties.

The relative luminosity for both excess energies has been determined by means of the measurement of coincidence rate in the polarisation plane [31]. Due to the parity invariance, in the polarisation plane the differential cross section for any nuclear reaction caused by the strong interaction is independent of the beam polarisation and therefore a ratio of the numbers of events during spin up and down modes can be used as a measure of the relative luminosity. Values of  $L_{rel}^{10} = 0.98468 \pm 0.00056 \pm 0.00985$  and  $L_{rel}^{36} = 0.98301 \pm 0.00057 \pm 0.00985$  have been obtained at the excess energies of  $Q = 10$  and  $36$  MeV, respectively.

During the run at the excess energy of  $Q = 10$  MeV the beam polarisation has been determined with the COSY-11 setup [32]. The principle of measurement was based on the determination of the asymmetry in the accelerator plane (perpendicular to the polarization vector) for the  $\bar{p}p \rightarrow pp$  reaction. Although at a given beam polarisation mode only protons elastically scattered to the right could be registered it was possible to determine the polarisation by flipping the spin and employing Eq. 3 with exchanged  $A_y(\theta_{\eta})$  and  $P$ . As a result the value of the polarisation degree  $P = 0.680 \pm 0.007 \pm 0.055$  has been extracted. For the calculations the values of analysing powers for the elastic processes have been taken into account from the precise measurements performed by the EDDA collaboration [33].

For the polarisation monitoring during the run at  $Q = 36$  MeV we used the EDDA facility [33]. The determination of the polarisation degree with this setup is based on the asymmetry measurement for the  $\bar{p}p \rightarrow pp$  process. The obtained value of the averaged polarisation equals to  $P = 0.663 \pm 0.003 \pm 0.008$ .

The main source of the systematic uncertainties in the determination of the production yields originates from a background misidentification. In order to estimate the systematic error, an alternative method (with respect to the method presented above) of background subtraction has been applied which is based on a polynomial background cut [31]. Differences in the production yields obtained by this independent method were less than 1.5%. The main contribution to the systematic uncertainty of

the relative luminosity might be due to a slight shift of the center of detectors outside the polarisation plane. Assuming very conservatively a 4 mm shift and using the analysing powers for the elastically scattered protons of Ref. [33] a value of 1% systematic uncertainty of the relative luminosity was established by means of Monte-Carlo simulations. The systematic uncertainty of 8% for the polarisation measured with the COSY-11 polarimeter is determined by error propagation from Eq. 3 with the systematic uncertainties of the analysing powers (1.2%), systematic error of the relative luminosity (1%) and the 1% systematic uncertainty of the number of elastically scattered yields [25]. During the measurement at the excess energy of  $Q = 36$  MeV the overall systematic error in the determination of the polarisation value, when using the large acceptance EDDA detector, was 1.2% [33]. The analysing powers calculated using Eq. 3 are summa-

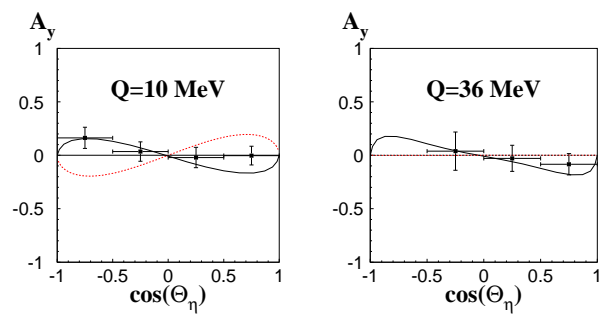


FIG. 3: Analysing powers for the  $\bar{p}p \rightarrow pp\eta$  reaction as functions of  $\cos\theta_{\eta}$  for  $Q = 10$  MeV (left panel) and  $Q = 36$  MeV (right panel). Full lines are the predictions based on the pseudoscalar meson exchange model [16] whereas the dotted lines represent the calculations based on the vector meson exchange [17]. In the right panel the dotted line is consistent with zero. Shown are the statistical uncertainties solely.

ized in Table I for both excess energies and presented in Fig. 3. At the excess energy of  $Q = 36$  MeV insufficient statistics for the  $\cos\theta_{\eta} \in (-1; -0.5)$  range resulted in an error larger than the allowed range and hence this point was omitted.

In order to verify the correctness of the models based on the dominance of the  $\rho$  or  $\pi$  meson exchanges, a  $\chi^2$  test has been performed. The reduced value of the  $\chi^2$  for the pseudoscalar meson exchange model was determined to be  $\chi_{psc}^2 = 0.54$ , which corresponds to a significance level  $\alpha_{psc} = 0.81$ , whereas for the vector meson exchange model  $\chi_{vec}^2 = 2.76$ , resulting in a significance level of  $\alpha_{vec} = 0.006$ .

In the vector meson exchange dominance model [17] the angular distribution of the analysing power is parameterized with the following equation:

$$A_y(\theta_{\eta}) = A_y^{max,vec} \sin 2\theta_{\eta}, \quad (4)$$

where the amplitude  $A_y^{max,vec}$  is a function of the excess energy  $Q$ , shown as a dotted line in the left

panel of Fig. 4. We have estimated the values of

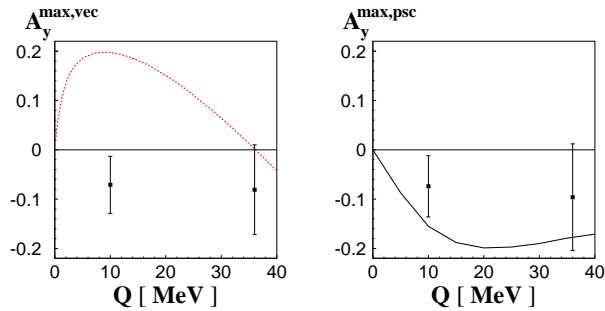


FIG. 4: Theoretical predictions for the amplitudes of the analysing power's energy dependence confronted with the amplitudes determined in the experiments at  $Q = 10$  and  $Q = 36$  MeV for the vector (left panel) and pseudoscalar (right panel) meson exchange dominance model.

$A_y^{max,vec}$  comparing the experimental data with predicted shape utilizing a  $\chi^2$  test. The values of  $A_y^{max,vec}$  for  $Q = 10$  and  $36$  MeV have been determined to be  $A_y^{max,vec}(Q = 10) = -0.071 \pm 0.058$  and  $A_y^{max,vec}(Q = 36) = -0.081 \pm 0.091$ , respectively. Similar calculations have been performed for the pseudoscalar meson exchange model [16], assuming that the shape of the analysing power as a function of the  $\cos\theta_\eta$  does not depend on the excess energy, which is correct within about 5% accuracy. It has been found that  $A_y^{max,psc}(Q = 10) = -0.074 \pm 0.062$ , and  $A_y^{max,psc}(Q = 36) = -0.096 \pm 0.108$ . These results are shown in Fig. 4. The figure shows that the predictions of the model based on the  $\pi$  mesons dominance are fairly consistent with the data, whereas the calculations based on the dominance of the  $\rho$  meson exchange differ from the data by more than four standard deviations.

Summarizing, the  $\chi^2$  analysis applied to the tested production models excludes the correctness of the assumption of a pure vector meson dominance ( $\rho$  exchange) with a significance level of 0.006 corresponding to discrepancy between the model and the data larger than four standard deviations, and provides strong evidence for the supposition that the production of the  $\eta$  mesons in nucleon-nucleon collision is dominated by the pion exchange.

One should, however, keep in mind that the interference in the exchange of both types of mesons are not excluded and should be studied theoretically and experimentally by the measurement of further spin observables.

It is also worth to mention that the analysing powers of the  $\bar{p}p \rightarrow pp\eta$  reaction for both excess energies studied are consistent with zero within one standard deviation. This may suggest that the  $\eta$  meson is predominantly produced in the  $s$ -wave, an observation which is in agreement with the results of the analysing power measurements performed by the DISTO collaboration [34] where, interestingly, in the far-from-threshold energy region the  $A_y$

were found to be also consistent with zero within one standard deviation.

The authors would like to thank K. Nakayama, K. S. Man, and C. Wilkin for providing the predictions for  $A_y$  and A. Kupść and S. Bass for reading the early version of the manuscript. We acknowledge the support of the European Community-Research Infrastructure Activity under the FP6 programme (Hadron Physics, N4:EtaMesonNet, RII3-CT-2004-506078) and the support of the Polish State Committee for Scientific Research (grant No. PB1060/P03/2004/26).

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- [1] C. Hanhart, Phys. Rept. **397**, 155 (2004).
  - [2] F. Hibou et al., Phys. Lett. **B 438**, 41 (1998).
  - [3] J. Smyrski et al., Phys. Lett. **B 474**, 182 (2000).
  - [4] A. M. Bergdolt et al., Phys. Rev. **D 48**, 2969 (1993).
  - [5] E. Chiavassa et al., Phys. Lett. **B 322**, 270 (1994).
  - [6] H. Calén et al., Phys. Lett. **B 366**, 39 (1996).
  - [7] H. Calén et al., Phys. Rev. Lett. **79**, 2642 (1997).
  - [8] P. Moskal et al., Phys. Rev. **C 69**, 025203 (2004).
  - [9] M. Abdel-Bary et al., Eur. Phys. J. **A 16**, 127 (2003).
  - [10] A. Moalem et al., Nucl. Phys. **A 600**, 445 (1996).
  - [11] M. Batinić et al., Phys. Scripta **56**, 321 (1997).
  - [12] J. F. Germond et al., Nucl. Phys. **A 518**, 308 (1990).
  - [13] J. M. Laget et al., Phys. Lett. **B 257**, 254 (1991).
  - [14] T. Vetter et al., Phys. Lett. **B 263**, 153 (1991).
  - [15] B. L. Alvaredo et al., Phys. Lett. **B 324**, 125 (1994).
  - [16] K. Nakayama et al., Phys. Rev. **C 65**, 045210 (2002).
  - [17] G. Fäldt and C. Wilkin, Phys. Scripta **64**, 427 (2001).
  - [18] V. Bernard et al., Eur. Phys. J. **A 4**, 259 (1999).
  - [19] P. Moskal et al., Prog. Part. Nucl. Phys. **49**, 1 (2002).
  - [20] P. Moskal, ArXiv:hep-ph/0408162 (2004).
  - [21] H. Calén et al., Phys. Rev. **C 58**, 2667 (1998).
  - [22] S. Brauksiepe et al., Nucl. Instr. Meth. **A 376**, 397 (1996).
  - [23] J. Smyrski et al., Nucl. Instr. Meth. **A 541**, 574 (2005).
  - [24] P. Klaja et al., AIP Conf. Proc. **796**, 160 (2005).
  - [25] P. Moskal et al., Nucl. Instr. Meth. **A 466**, 448 (2001).
  - [26] R. Maier et al., Nucl. Instr. Meth. **A 390**, 1 (1997).
  - [27] D. Prasuhn et al., Nucl. Instr. Meth. **A 441**, 167 (2000).
  - [28] H. Stockhorst (2004), hep-ph/0411148.
  - [29] GEANT (1994), CERN Prog. Lib. Writ. W5013.
  - [30] P. Moskal et al., J. Phys. **G 32**, 629 (2006).
  - [31] R. Czyżykiewicz, ArXiv:nucl-ex/0702010 (2007).
  - [32] R. Czyżykiewicz, Schriften FZ-Juelich **21**, 122 (2004).
  - [33] M. Altmeier et al., Phys. Rev. Lett. **85**, 1819 (2000).
  - [34] F. Balestra et al., Phys. Rev. **C 69**, 064003 (2004).
  - [35] S. D. Bass, Phys. Lett. **B 463**, 286 (1999).
  - [36] F. Bauer et al., Nucl. Instr. Meth. **A 431**, 385 (1999).
  - [37] The measurement of the isospin dependence is being extended by the COSY-11 collaboration [30] to the  $\eta'$  production which may also be sensitive to gluonic production mechanism [35].
  - [38] Madison Convention, *Polarisation Phenomena in Nuclear Reactions*, University of Wisconsin Press, Madison, pp. XXV (1971)
  - [39] Which is valid within  $\pm 2\%$  accuracy, as has been studied with the EDDA [33] and COSY [36] polarimeters.