Mechanism of Near-Threshold Production of the η Meson

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Measurements of the analyzing power for the $\vec{p}p \to pp\eta$ reaction have been performed at excess energies of $Q = 10$ and 36 MeV. The determined analyzing power is essentially consistent with zero, implying dominance of the s wave at both excess energies. The angular dependence of the analyzing power, combined with the isospin dependence of the total cross section for the η 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 π meson between the colliding nucleons.

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The strong interaction responsible for the existence of hadrons has been studied intensively for more than half 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 η 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 analyzing power for the $\vec{p}p \to pp\eta$ reaction. We also demonstrate that the confrontation of predictions based upon different scenarios, involving exchanges of various mesons, with the so far determined unpolarized observables and with results on the analyzing power, permits one to single out the dominant process and, hence, to understand details of the η meson production close to the kinematical threshold.

From precise measurements of the total cross sections of the η meson production in the $pp \to pp\eta$ reaction [2–9], it was concluded [10–17] 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 η meson (see Fig. 1). 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 [18–20]. Based only on the excitation function, it was, however, impossible to disentangle the contributions to the production process originating from the π, η, ω, or ρ meson exchange.

More constraints to theoretical models [10–17] have been deduced from the measurement of the isospin dependence of the total cross section by the WASA/PROMICE Collaboration [21,22]. The comparison of the η meson production in proton-proton and proton-neutron collisions inferred that the η meson is by a factor of 12 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 con-
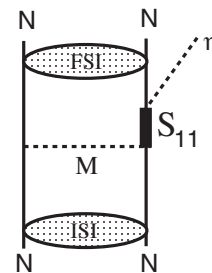

FIG. 1.   The mechanism of the η meson production in nucleon-nucleon collisions. M denotes an intermediate pseudoscalar or vector meson, e.g., π, η, ω, or ρ. ISI and FSI indicate initial and final state interaction between the nucleons.

ceivable as being responsible for such a strong isospin dependence. This result was already a large step forward, but still the relative contributions of the ρ and π mesons remained to be disentangled. The elucidation of this very detail in the production mechanism of the η meson constitutes the motivation for the measurements presented in this Letter. For this purpose, we have determined the analyzing 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 meson being exchanged in order to excite one of the colliding nucleons to the $S_{11}(1535)$ state.

For the measurement of the $\vec{p}p \rightarrow pp\eta$ reaction, the COSY-11 experimental setup [20,25–28] has been used, which is an internal beam facility at the cooler synchrotron COSY [29,30]. A vertically polarized proton beam [31] had been stored and accelerated in the COSY ring. The direction of the polarization 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 9 m 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 one to register only events scattered near the horizontal plane. In the analysis, the azimuthal angle ϕ was restricted to values of $\cos\phi$ ranging between 0.87 and 1.

For the determination of the analyzing power of the η meson at a given value of the polar angle θ_η and the azimuthal angle ϕ, it is required to measure a left-right asymmetry of yields of the η meson in the frame turned by the angle ϕ with respect to the laboratory coordinate system. This is often referred to as a Madison frame [32], which in our case has its y axis parallel to the $\vec{p}_{\text{beam}} \times \vec{p}_\eta$ vector, with $\vec{p}_{\text{beam}}$ and $\vec{p}_\eta$ denoting the momentum vectors of the proton beam and the η 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 η meson is produced to the left side with respect to the polarization 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 η meson production to the left side measured for the spin up and spin down modes of the beam polarization. For the quantitative evaluation, we define $N_+^\uparrow(\theta_\eta)$ and $N_-^\downarrow(\theta_\eta)$ as production yields of the η meson emitted to the left around the θ_η angle as measured with the up and down beam polarization, 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 η meson production for the unpolarized beam, $P^{\uparrow(\downarrow)}$ standing for the polarization degree corresponding to spin up and down modes, $E(\theta_\eta)$ being the efficiency of the COSY-11 facility for detecting the η meson emitted to the left side at the θ_η angle, and $L^{\uparrow(\downarrow)}$ denoting the luminosity during the beam polarization up and down. Signs in the brackets of Eqs. (1) and (2) follow the Madison convention. Assuming that $P^\uparrow \approx P^\downarrow$ [33], introducing the average beam polarization $P \approx (P^\uparrow + P^\downarrow)/2$ and the relative luminosity $L_{\text{rel}} = \int L^\uparrow dt / \int L^\downarrow dt$, and solving Eqs. (1) and (2) for $A_y(\theta_\eta)$, we obtain

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

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 analyzing power function, the range of the θ_η angle has been divided into four bins, at both excess energies. Figure 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 polarization. To separate the actual production rates from the background, both the reactions with multipion production as well as the events with the η meson production have been simulated using a program based on the GEANT3 [36] 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 [20,23]. 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.
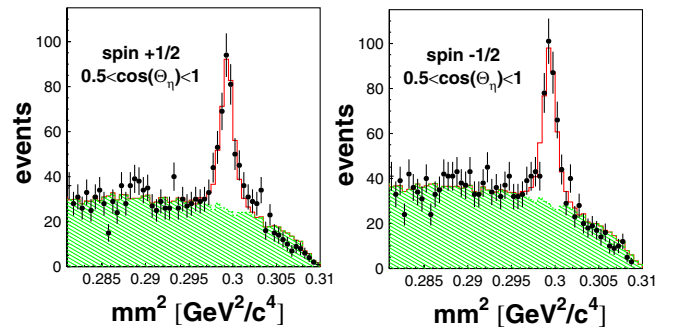

FIG. 2 (color online). Examples of missing mass spectra for $\cos\theta_\eta \in (0.5; 1)$ and opposite beam polarization states, as measured at the excess energy $Q = 10$ MeV. Solid circles correspond to the experimental values, which are shown with their statistical uncertainties. The solid line represents 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.

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 the coincidence rate in the polarization plane [37]. 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 $L_{\text{rel}}^{10} = 0.984\,68 \pm 0.000\,56 \pm 0.009\,85$ and $L_{\text{rel}}^{36} = 0.983\,01 \pm 0.000\,57 \pm 0.009\,85$ 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 polarization has been determined with the COSY-11 setup [37]. The principle of measurement was based on the determination of the asymmetry in the accelerator plane (perpendicular to the polarization vector) for the $\vec{p}p \rightarrow pp$ reaction. Although at a given beam polarization mode only protons elastically scattered to the right could be registered, it was possible to determine the polarization by flipping the spin and employing Eq. (3) with exchanged $A_y(\theta_\eta)$ and P. As a result, the value of the polarization degree $P = 0.680 \pm 0.007 \pm 0.055$ has been extracted. For the calculations, the values of analyzing powers for the elastic processes have been taken into account from the precise measurements performed by the EDDA Collaboration [34].

For the polarization monitoring during the run at $Q = 36$ MeV, we used the EDDA facility [34]. The obtained value of the averaged polarization equals $P = 0.663 \pm 0.003 \pm 0.008$.

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 [37]. 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 polarization plane. Assuming very conservatively a 4 mm shift and using the analyzing powers for the elastically scattered protons of Ref. [34], a value of 1% systematic uncertainty of the relative luminosity was established by means of Monte Carlo simula-

tions. The systematic uncertainty of 8% for the polarization measured with the COSY-11 polarimeter is determined by error propagation from Eq. (3) with the systematic uncertainties of the analyzing powers (1.2%), systematic error of the relative luminosity (1%), and the 1% systematic uncertainty of the number of elastically scattered yields [28]. During the measurement at the excess energy of $Q = 36$ MeV, the overall systematic error in the determination of the polarization value, when using the large acceptance EDDA detector, was 1.2% [34]. The analyzing powers calculated using Eq. (3) are summarized in Table I for both excess energies and are 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 ρ or π meson exchanges, a χ^2 test has been performed. The reduced value of the χ^2 for the pseudoscalar meson exchange model was determined to be $\chi_{\text{psc}}^2 = 0.54$, which corresponds to a significance level $\alpha_{\text{psc}} = 0.81$, whereas for the vector meson exchange model $\chi_{\text{vec}}^2 = 2.76$, resulting in a significance level of $\alpha_{\text{vec}} = 0.006$.

In the vector meson exchange dominance model [17], the angular distribution of the analyzing power is parametrized with the following equation:

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

where the amplitude $A_y^{\text{max,vec}}$ is a function of the excess energy Q, shown as a dotted line in the left panel in Fig. 4. We have estimated the values of $A_y^{\text{max,vec}}$, comparing the experimental data with the predicted shape utilizing a χ^2 test. The values of $A_y^{\text{max,vec}}$ for $Q = 10$ and 36 MeV have been determined to be $A_y^{\text{max,vec}}(Q = 10) = -0.071 \pm 0.058$ and $A_y^{\text{max,vec}}(Q = 36) = -0.081 \pm 0.091$, respectively.

TABLE I. The number of reconstructed η mesons and analyzing powers for the $\vec{p}p \rightarrow pp\eta$ reaction.

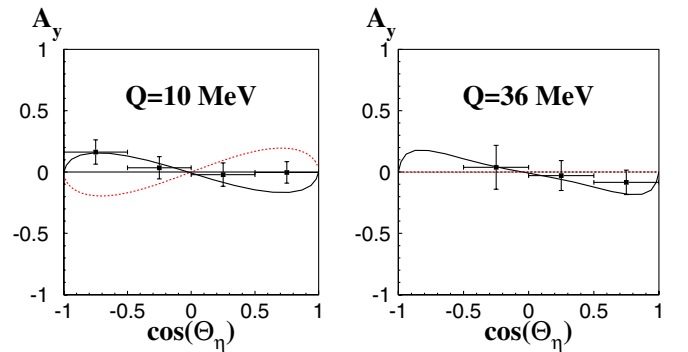| Q [MeV]	$\cos\theta_\eta$	$N_+^\uparrow$	$N_-^\downarrow$	A_y
10	$(-1; -0.5)$	306 ± 27	250 ± 26	$0.163 \pm 0.099 \pm 0.022$
	$(-0.5; 0)$	267 ± 22	260 ± 24	$0.035 \pm 0.091 \pm 0.012$
	$(0; 0.5)$	198 ± 18	208 ± 19	$-0.021 \pm 0.095 \pm 0.011$
	$(0.5; 1)$	279 ± 23	286 ± 25	$-0.003 \pm 0.088 \pm 0.009$
36	$(-0.5; 0)$	103 ± 16	100 ± 18	$0.039 \pm 0.179 \pm 0.012$
	$(0; 0.5)$	144 ± 16	153 ± 18	$-0.029 \pm 0.122 \pm 0.010$
	$(0.5; 1)$	259 ± 24	296 ± 28	$-0.084 \pm 0.100 \pm 0.011$

FIG. 3 (color online). Analyzing powers for the $\vec{p}p \rightarrow pp\eta$ reaction as functions of $\cos\theta_\eta$ for $Q = 10$ MeV (left panel) and $Q = 36$ MeV (right panel). Solid 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.
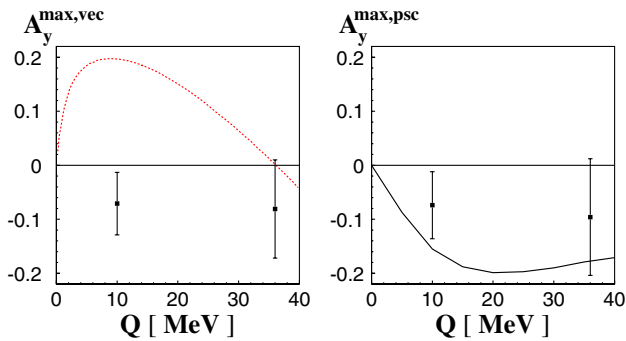
FIG. 4 (color online). Theoretical predictions for the amplitudes of the analyzing power's energy dependence confronted with the amplitudes determined in the experiments at $Q = 10$ and $Q = 36$ MeV for the vector (left panel) and pseudoscalar (right panel) meson exchange dominance model.

Similar calculations have been performed for the pseudoscalar meson exchange model [16], assuming that the shape of the analyzing 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 π meson dominance are fairly consistent with the data, whereas the calculations based on the dominance of the ρ meson exchange differ from the data by more than 4 standard deviations.

To summarize, the χ^2 analysis applied to the tested production models excludes the correctness of the assumption of a pure vector meson dominance (ρ exchange) with a significance level of 0.006, corresponding to a discrepancy between the model and the data larger than 4 standard deviations, and provides strong evidence for the supposition that the production of the η 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 mentioning that the analyzing powers of the $\vec{p}p \rightarrow pp\eta$ reaction for both excess energies studied are consistent with zero within 1 standard deviation. This may suggest that the η meson is predominantly produced in the s wave, an observation which is in agreement with the results of the analyzing power measurements performed by the DISTO Collaboration [38], where, interestingly, in the far-from-threshold energy region, the A_y were found to be also consistent with zero within 1 standard deviation.

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