Spin dependence of η meson production in proton-proton collisions close to threshold

P. Adlarson,[1,*] W. Augustyniak,[2] W. Bardan,[3] M. Bashkanov,[4] S. D. Bass,[3] F.S. Bergmann,[5] M. Berłowski,[6] A. Bondar,[7,8] M. Büscher,[9,†] H. Calén,[1] I. Ciepał,[10] H. Clement,[11,12] E. Czerwiński,[3] K. Demmich,[5] R. Engels,[9] A. Erven,[13] W. Erven,[13] W. Eyrich,[14] P. Fedorets,[9,15] K. Föhl,[16] K. Fransson,[1] F. Goldenbaum,[9] A. Goswami,[17,9] K. Grigoryev,[9] K. Grigoryev,[9,18] C.–O. Gullström,[1] L. Heijkenskjöld,[1,*] V. Hejny,[9] N. Hüsken,[5] L. Jarczyk,[3] T. Johansson,[1] B. Kamys,[3] G. Kemmerling,[13,‡] G. Khatri,[3,§] A. Khoukaz,[5] O. Khreptak,[3] D.A. Kirillov,[19] S. Kistryn,[3] H. Kleines,[13,‡] B. Kłos,[20] W. Krzemień,[3] P. Kulessa,[10] A. Kupść,[1,6] A. Kuzmin,[7,8] K. Lalwani,[21] D. Lersch,[9] B. Lorentz,[9] A. Magiera,[3] R. Maier,[9,22] P. Marciniewski,[1] B. Mariański,[2] H.–P. Morsch,[2] P. Moskal,[3] H. Ohm,[9] W. Parol,[10] E. Perez del Rio,[11,12,¶] N.M. Piskunov,[19] D. Prasuhn,[9] D. Pszczel,[1,6] K. Pysz,[10] A. Pyszniak,[1,3] J. Ritman,[9,22,23] A. Roy,[17] Z. Rudy,[3] O. Rundel,[3] S. Sawant,[24] S. Schadmand,[9] I. Schätti–Ozerianska,[3] T. Sefzick,[9] V. Serdyuk,[9] B. Shwartz,[7,8] K. Sitterberg,[5] T. Skorodko,[11,12,25] M. Skurzok,[3] J. Smyrski,[3] V. Sopov,[15] R. Stassen,[9] J. Stepaniak,[6] E. Stephan,[20] G. Sterzenbach,[9] H. Stockhorst,[9] H. Ströher,[9,22] A. Szczurek,[10] A. Trzciński,[2] M. Wolke,[1] A. Wrońska,[3] P. Wüstner,[13] A. Yamamoto,[26] J. Zabierowski,[27] M.J. Zieliński,[3] J. Złomańczuk,[1] P. Żuprański,[2] and M. Żurek[9]

(WASA-at-COSY Collaboration)

[1] *Division of Nuclear Physics, Department of Physics and Astronomy, Uppsala University, Box 516, 75120 Uppsala, Sweden*
[2] *Department of Nuclear Physics, National Centre for Nuclear Research, ul. Hoza 69, 00-681, Warsaw, Poland*
[3] *Institute of Physics, Jagiellonian University, prof. Stanisława Łojasiewicza 11, 30-348 Kraków, Poland*
[4] *School of Physics and Astronomy, University of Edinburgh, James Clerk Maxwell Building, Peter Guthrie Tait Road, Edinburgh EH9 3FD, Great Britain*
[5] *Institut für Kernphysik, Westfälische Wilhelms–Universität Münster, Wilhelm–Klemm–Str. 9, 48149 Münster, Germany*
[6] *High Energy Physics Department, National Centre for Nuclear Research, ul. Hoza 69, 00-681, Warsaw, Poland*
[7] *Budker Institute of Nuclear Physics of SB RAS, 11 akademika Lavrentieva prospect, Novosibirsk, 630090, Russia*
[8] *Novosibirsk State University, 2 Pirogova Str., Novosibirsk, 630090, Russia*
[9] *Institut für Kernphysik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[10] *The Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences, 152 Radzikowskiego St, 31-342 Kraków, Poland*
[11] *Physikalisches Institut, Eberhard–Karls–Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany*
[12] *Kepler Center für Astro– und Teilchenphysik, Physikalisches Institut der Universität Tübingen, Auf der Morgenstelle 14, 72076 Tübingen, Germany*
[13] *Zentralinstitut für Engineering, Elektronik und Analytik, Forschungszentrum Jülich, 52425 Jülich, Germany*
[14] *Physikalisches Institut, Friedrich–Alexander–Universität Erlangen–Nürnberg, Erwin–Rommel-Str. 1, 91058 Erlangen, Germany*
[15] *Institute for Theoretical and Experimental Physics named by A.I. Alikhanov of National Research Centre "Kurchatov Institute", 25 Bolshaya Cheremushkinskaya, Moscow, 117218, Russia*
[16] *II. Physikalisches Institut, Justus–Liebig–Universität Gießen, Heinrich–Buff–Ring 16, 35392 Giessen, Germany*
[17] *Department of Physics, Indian Institute of Technology Indore, Khandwa Road, Simrol, Indore–453552, Madhya Pradesh, India*
[18] *High Energy Physics Division, Petersburg Nuclear Physics Institute named by B.P. Konstantinov of National Research Centre "Kurchatov Institute", 1 mkr. Orlova roshcha, Leningradskaya Oblast, Gatchina, 188300, Russia*
[19] *Veksler and Baldin Laboratory of High Energiy Physics, Joint Institute for Nuclear Physics, 6 Joliot–Curie, Dubna, 141980, Russia*
[20] *August Chełkowski Institute of Physics, University of Silesia, Uniwersytecka 4, 40-007, Katowice, Poland*
[21] *Department of Physics, Malaviya National Institute of Technology Jaipur, JLN Marg Jaipur - 302017, Rajasthan, India*
[22] *JARA–FAME, Jülich Aachen Research Alliance, Forschungszentrum Jülich, 52425 Jülich, and RWTH Aachen, 52056 Aachen, Germany*
[23] *Institut für Experimentalphysik I, Ruhr–Universität Bochum, Universitätsstr. 150, 44780 Bochum, Germany*
[24] *Department of Physics, Indian Institute of Technology Bombay, Powai, Mumbai–400076, Maharashtra, India*
[25] *Department of Physics, Tomsk State University, 36 Lenina Avenue, Tomsk, 634050, Russia*
[26] *High Energy Accelerator Research Organisation KEK, Tsukuba, Ibaraki 305–0801, Japan*
[27] *Department of Astrophysics, National Centre for Nuclear Research, 90–950 Łódź, Poland*

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Taking advantage of the high acceptance and axial symmetry of the WASA-at-COSY detector, and the high degree of the polarized proton beam of COSY, the reaction $\vec{p}p \to pp\eta$ has been measured close to threshold to explore the analyzing power A_y. The angular distribution of A_y is determined with the precision improved by more than one order of magnitude with respect to previous results allowing a first accurate comparison with theoretical predictions. The determined analyzing power is consistent with zero for an excess energy of $Q = 15$ MeV signaling s wave production with no evidence for higher partial waves. At $Q = 72$ MeV the data reveals strong interference of Ps and

Pp partial waves and cancellation of $(Pp)^2$ and Ss^*Sd contributions. These results rule out the presently available theoretical predictions for the production mechanism of the η meson.

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In recent decades hadron physics has been rich in discoveries in the low energy region where the interaction between hadrons is a manifestation of the strong force between their components [1–5]. However there are still many open questions involving the non-perturbative dynamics and details of hadron production processes. Spin observables offer an essential new tool to probe this physics. The internal spin structure of the proton, understanding why quarks contribute just $\sim 30\%$ of the proton's spin, has been one of the driving themes in QCD research in the last 30 years [6]. In this Letter we focus on η meson production in low-energy proton-proton collisions with a spin polarized proton beam. We report the first precise measurements of the analyzing power for the $\vec{p}p \to pp\eta$ reaction at two energies close to threshold. These measurements yield powerful new constraints on models of the η production process.

The presented results are based on about 200 times larger statistics and drastically reduced systematic uncertainties with respect to the previous experiments [7–9]. The main improvement of systematics is due to: (i) axial symmetry and full acceptance of the WASA-at-COSY detector (more than 20 times larger than for the COSY-11 experiment [10]), (ii) no magnetic field in the detector and, in addition the systematics was controlled by the measurements (iii) for two spin orientations and (iv) for two different decay channels of the η meson.

Previous studies by the CELSIUS [11–14], COSY [15–19] and SATURNE [20–22] experiments of the total and differential cross section for η meson production in pp and pn collisions revealed that the η meson is predominantly produced via the excitation of one of the nucleons to the S_{11} current via exchange of virtual mesons with the subsequent decay into the proton-η pair. This conclusion was obtained from the observation of a large η production cross-section relative to the η' meson production and the isotropic angular distribution of the η mesons in the center of mass system (CMS). Measurements of the total cross-section for η production in different isospin channels [14, 19] revealed a strong contribution from isovector exchanges which is additive in proton-neutron collisions and which (partially) cancels in proton-proton collisions, bringing more constraints to theoretical models. While much progress has been achieved, the mechanism for the excitation of the colliding proton to a resonance state still remains very much incomplete with a host of models each with different weighting of exchanges proposed to explain the dynamics.

Here we use spin as a tool to gain further insights. The experiment involves a polarized proton beam with incident momentum in the z direction and transversely polarized in the y direction colliding with an unpolarized fixed proton target. The analyzing power is a sensitive extra constraint on the details of the η production mechanism.

The η meson production process proceeds through exchange of a complete set of virtual meson hadronic states, which in models is usually truncated to single virtual meson exchange. Theoretical models have been proposed involving π, η, ρ, ω and σ (correlated two-pion) exchanges [23–28] and excited nucleon resonances, primarily the $S_{11}(1535)$ plus small contributions from the $D_{13}(1520)$ and $P_{11}(1440)$ [24, 25]. OZI violating gluonic excitations might also couple to the flavour-singlet part of the η meson in short distance proton-proton interaction [29]. These exchanges induce very different spin dependence in the production process. Polarized beams and measurement of the analyzing power can therefore put powerful new constraints on theoretical understanding of the η production process. For example, ρ exchange and π exchange models predict a near threshold analyzing power with different sign [23, 25]. Pure s-wave production would give zero analyzing power.

The measurements of the $\vec{p}p \to pp\eta$ reaction were conducted by means of the large acceptance close to 4π and axially symmetric WASA-at-COSY spectrometer, operating as an internal fixed-target facility at the Cooler Synchrotron COSY [30]. The vertically polarized proton beam was circulating through the vertical stream of the hydrogen pellets leading to the $\vec{p}p \to pp\eta$ reaction in the center of the WASA-at-COSY detector. The measurements were performed for the beam momentum values of 2026 MeV/c and 2188 MeV/c, corresponding to excess energies in the CMS of $Q = 15$ MeV and 72 MeV, respectively. The orientation of the proton beam polarization was flipped from cycle to cycle.

The charged hadronic ejectiles were registered by means of forward scintillator hodoscopes and the straw tube trackers and were identified using the energy deposited in the subsequent scintillator layers. The η mesons were detected by the electromagnetic calorimeter and the plastic scintillator barrel. The production of the η meson via the $\vec{p}p \to pp\eta$ reaction was identified using missing and invariant mass techniques. In total more than 400000 η meson events were identified and used for the determination of the analyzing power.

The center of the interaction region where the polarized proton beam collided with the pellet target was monitored with a precision of about 0.5 mm by the concurrent measurement of elastically scattered protons. The superconducting solenoid was switched off in order to minimize losses of the spin polarization. Only neutral decay prod-

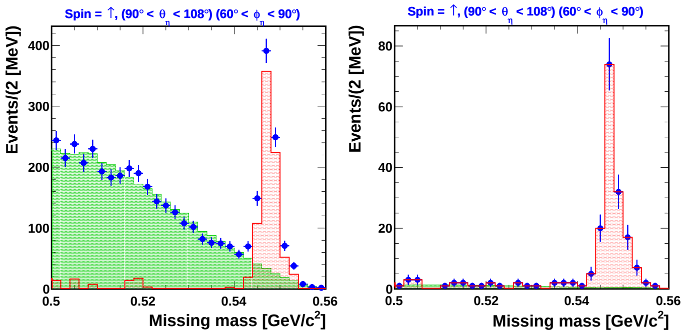

FIG. 1. Examples of missing mass distributions obtained for the excess energy Q = 15 MeV: (left) $\vec{p}p \to pp2\gamma$, and (right) $\vec{p}p \to pp\ 3\pi^0 \to pp\ 6\gamma$ reactions. The legends above the figures indicate the spin orientation and the angular intervals. Experimental data are denoted by solid blue circles. Vertical bars indicate the statistical uncertainty. The shaded green area denotes the simulated contribution from multipion production background. The shaded red histograms corresponds to the η events obtained by subtracting the multipion background.

ucts of the η meson were reconstructed. In particular, the $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0 \to 6\gamma$ decay channels with the highest branching ratios (altogether over 71% [31]) were used in the presented analysis. A detailed description of the WASA-at-COSY experiment as well as methods and results of the monitoring of the interaction region have been described in details in the dedicated articles [32–35].

The analyzing power $A_y(\theta_\eta)$ for the given polar angle θ_η of the emission of the η meson in the CMS was determined from the asymmetry of the efficiency corrected η meson production yields N_η

$$Asymmetry(\theta_\eta, \phi_\eta) \equiv \frac{N_\eta(\theta_\eta, \phi_\eta) - N_\eta(\theta_\eta, \phi_\eta + \pi)}{N_\eta(\theta_\eta, \phi_\eta) + N_\eta(\theta_\eta, \phi_\eta + \pi)} \tag{1}$$

extracted as a function of the azimuthal angle ϕ_η

$$Asymmetry(\theta_\eta, \phi_\eta) = P \cdot A_y(\theta_\eta) \cdot \cos(\phi_\eta), \tag{2}$$

where P denotes the degree of the spin polarization of the proton beam. In the presented analysis the Madison convention [36] was applied to fix the sign of the asymmetry.

The yields of the η meson production N_η were determined based on the missing mass spectra, independently for each (θ_η,ϕ_η) angular range. Exemplary spectra for a chosen angular range are presented in Fig. 1. The spectra show only a small range of masses close to the kinematical limit where a clear signal from the production of the η meson is seen on top of the multi-pion production background. It is important to stress that the missing mass spectra for the $pp \to pp2\gamma$ reaction channel shown in Fig. 1 (left) include a background which is much larger when compared to the nearly negligible background observed for the $pp \to pp6\gamma$ reaction shown in Fig. 1 (right) [37]. The contribution of the background was estimated by a fit to the experimental spectra of the shapes of missing mass distributions simulated for the production of the π^0, $2\pi^0$ and $3\pi^0$. The data simulated for the multi-pion production reaction included the response of the detector system and were analyzed using the same procedures as used for the analysis of the experimental events. Next, after subtraction of the background the number of the registered η mesons was determined.

Fig. 2 shows exemplarily an asymmetry for the $\vec{p}p \to pp\eta$ reaction yield as a function of the azimuthal angle ϕ_η of the η meson momentum vector in the CM system. A fit of Eq. 2 to the angular dependence of the asymmetry enables one to determine the product $P{\cdot}A_y$ which divided by the polarization P gives the value of the analyzing power A_y.

The polarization P was determined for each spin orientation and each excess energy separately, by the simultaneous measurement of asymmetries for the elastically scattered protons for which the analyzing power is known [38, 39]. The method of the polarization analysis is described in detail in references [37, 40, 41], and the resulting values together with corresponding statistical uncertainties are listed in Tab. I. The systematic uncertainty of the polarization determination amounts to about 0.01 and, as it is shown in detail in Ref. [42], it is predominantly due to the uncertainty of the reconstruction of the position of the interaction region. It is also important to stress that the spin polarization was stable during the whole run [37, 40, 41] and that, as expected, the analysis of the data taken with the unpolarized beam resulted in the asymmetry equal to zero within the uncertainties [37, 41].

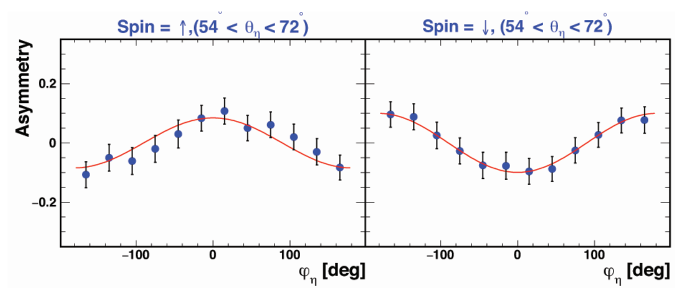

FIG. 2. Example of asymmetry distributions as a function of the ϕ_η angle for a chosen θ_η angular bin, for an excess energy Q = 72 MeV and the $\vec{p}p \to pp\eta \to 6\gamma$ reaction. Filled blue points denote extracted asymmetry values with the statistical uncertainty, while the red curves indicates the fit of Eq. 2 to the experimental points. The legend above the figures indicates spin orientation and the angular intervals. It is evident that the results obtained for different spin orientations are consistent. The asymmetry is shown in the full ϕ_η range though the fit was performed only in the range between 0° and 180° since $Asymmetry(\phi_\eta) = -Asymmetry(\phi_\eta + 180°)$ per definition.

TABLE I. The average polarization degree

p_{beam} [MeV/c]	Spin mode	Polarization
2026	up (↑)	0.793 ± 0.010
	down (↓)	-0.577 ± 0.007
2188	up (↑)	0.537 ± 0.009
	down (↓)	-0.635 ± 0.011

Calculations of the analyzing power A_y were conducted separately for spin *up* and spin *down* orientation, and for each spin mode the A_y was determined separately for two decay channels: $\eta \to 2\gamma$ and $\eta \to 6\gamma$. Moreover, for all above cases, the number of events N_η corresponding to the $\vec{p}p \to pp\eta$ reactions, have been determined for each angular bin (θ_η, ϕ_η) separately. This enabled us to control systematic uncertainties which may occur due to the misalignment of the detector and due to the methods of events reconstruction. The final results obtained as a mean average of values determined for both spin orientations and both decay channels are given in Tab. II and are presented in Fig. 3. The systematic uncertainties listed in the table have been estimated by calculating changes in the values of A_y to the variation of the parameters used in the analysis. After changing a tested parameter the full analysis chain was repeated and a new A_y values were determined. In particular the following contributions to the systematic error were taken into account [37]: (i) selection criteria used in the particle identification, (ii) range in the missing mass spectra used for counting the number of produced η mesons, (iii) differences between A_y values obtained for different decay channels (iv) uncertainty of the values of polarization, and (v) differences between A_y values obtained for spin-up and spin-down measurements.

Integrating over the proton degrees of freedom results in the analyzing power $A_y(\theta_\eta)$, which in a partial-wave decomposition may be expressed as follows:

$$A_y(\theta_\eta)\frac{d\sigma}{d\Omega_\eta} = 2\pi[G_1^{y0}\sin\theta_\eta + (H_1^{y0} + I^{y0})\sin 2\theta_\eta]. \quad (3)$$

Here the form-factors G_1^{y0}, H_1^{y0} and I^{y0} are defined in Winter et al. [7], which generalizes the analysis of spin dependence of π^0 production with polarized proton beams to η production [43]. The superscript $y0$ indicates beam polarization along the y-axis and an unpolarized target.

We use the usual spectroscopic notation to describe the $pp \to pp\eta$ process, viz. ${}^{2S^i+1}L^i_{J^i} \to {}^{2S+1}L_J, l$. Here, the relative orbital angular momentum of the two outgoing protons in their rest frame is denoted by capital letters L_p = S, P, D, ..., the one of the η meson in the CMS by the small letters l_q = s,p,d, ... With this notation the individual terms G_1^{y0}, H_1^{y0} and I^{y0} correspond to (Ps*Pp), (Pp)^2 and (Ss*Sd) interference, respectively. The Pauli principle means that even and odd partial waves of the protons in the final state cannot interfer with each other. In total with polarized beams there are one Ss, two Ps, nine Pp and two Sd final state production amplitudes [43]. For example, the Ss amplitude corresponds to the process ${}^3P_0 \to {}^1S_0, s$. The (Pp)^2 and Ss*Sd interference amplitudes always appear together in the analyzing power and angular distribution [43].

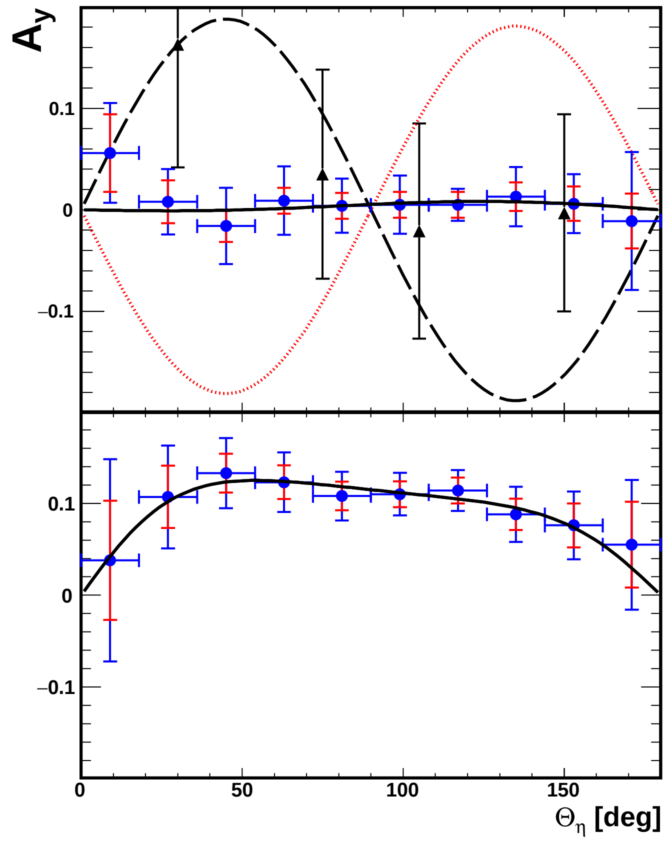

FIG. 3. *(upper panel)* Analyzing power for the $\vec{p}p \to pp\eta$ reaction as a function of θ_η for Q = 15 MeV. The full circles represents the results obtained in this work, while the triangles are the values of the analyzing powers measured by the COSY-11 Collaboration for Q =10 MeV [8]. Horizontal error bars indicate the angular range. The vertical bars show total uncertainties with statistical and systematic errors separated by dashes. The superimposed dashed line denotes the predictions based on pseudo-scalar meson exchange model [25], whereas the dotted line represents the vector exchange model [23]. The result of the fit of Eq.(4) to the data is presented by the solid line. *(bottom panel)* Analyzing power for the $\vec{p}p \to pp\eta$ reaction for the Q = 72 MeV. Horizontal bars indicate the angular range. The vertical bars show total uncertainties with statistical and systematic errors separated by dashes. The solid line denotes the result of the fit of Eq.(4).

Following Eq.(3) we fit the data as

$$A_y(\theta_\eta)\frac{d\sigma}{d\Omega_\eta} = C_1\sin\theta_\eta + C_2\cos\theta_\eta\sin\theta_\eta, \quad (4)$$

where C_1 and C_2 are treated as free parameters. For $Q = 15$ MeV the angular distribution of the cross

TABLE II. Analyzing power A_y with statistical and systematic uncertainties detemined for the $\vec{p}p \to pp\eta$ reaction at excess energies of Q = 15 MeV and Q = 72 MeV.

θ_η [deg]	$A_y(\theta_\eta)$ for Q = 15 MeV	$A_y(\theta_\eta)$ for Q = 72 MeV
0 - 18	0.056 ± 0.038 ± 0.011	0.038 ± 0.065 ± 0.045
18 - 36	0.008 ± 0.021 ± 0.011	0.107 ± 0.034 ± 0.022
36 - 54	-0.016 ± 0.016 ± 0.022	0.133 ± 0.021 ± 0.017
54 - 72	0.009 ± 0.013 ± 0.021	0.123 ± 0.018 ± 0.014
72 - 90	0.004 ± 0.013 ± 0.014	0.108 ± 0.016 ± 0.011
90 - 108	0.005 ± 0.013 ± 0.046	0.110 ± 0.014 ± 0.009
108 - 126	0.005 ± 0.013 ± 0.003	0.114 ± 0.014 ± 0.008
126 - 144	0.013 ± 0.014 ± 0.015	0.088 ± 0.017 ± 0.013
144 - 162	0.006 ± 0.017 ± 0.012	0.076 ± 0.024 ± 0.013
162 - 180	-0.011 ± 0.027 ± 0.041	0.055 ± 0.047 ± 0.024

section $\frac{d\sigma}{d\Omega_\eta}$ was assumed to be constant as determined by the COSY-11 [17] and COSY-TOF [16] experiments. For the fit at $Q = 72$ MeV the $\frac{d\sigma}{d\Omega_\eta}$ determined by the WASA-CELSIUS collaboration [13] was used. For $Q = 15$ MeV we find $C_1 = (0.001 \pm 0.001)\ \mu b/sr$ and $C_2 = (-0.002 \pm 0.003)\ \mu b/sr$. For $Q = 72$ MeV we obtain the fit parameters: $C_1 = (0.104 \pm 0.006)\ \mu b/sr$ and $C_2 = (0.020 \pm 0.012)\ \mu b/sr$.

At $Q = 15$ MeV we find no evidence for partial waves beyond s-wave production. At $Q = 72$ MeV we find evidence for a significant contributions of higher partial waves. If we conclude from the finite coefficient C_1 of the $\sin\theta_\eta$ term that both Ps and Pp give significant contributions, then the vanishing (within errors) coefficient C_2 points to a cancellation between $(\mathrm{Pp})^2$ and Ss Sd contributions.

Previously, in the COSY-11 analysis of the 15.5 MeV M(pp) shape it was suggested that the high mass region was a signal for a Ps contribution at $Q = 15$ MeV [17]. If this is indeed present in the data, then the small coefficient C_1 would indicate small Pp contribution at this excess energy. At $Q = 72$ MeV Petren et al [13] found that a sizable Pp contribution is needed to get the valley along the diagonal of the Dalitz plot for the $pp \to pp\eta$ reaction. Maximal Ss^*Sd interference there was suggested to explain the angular distribution of η production at $Q = 40$ MeV.

These results have the following interpretation.

First, the data indicate just s-wave production at $Q = 15$ MeV. This result contradicts predictions based on single meson exchange as shown in Fig. 3.

Measurements of the isospin dependence of η meson production in proton-nucleon collisions have revealed that the total cross-section for the quasi-free $pn \to pn\eta$ exceeds corresponding cross section for $pp \to pp\eta$ by a factor of about three at threshold and by factor of six at higher excess energies between about 25 and 100 MeV [14, 19]. This isospin dependence is interpreted as evidence for a strong isovector exchange contribution which exhibits (partial) cancellation in proton-proton collisions and addition in proton-neutron collisions. This isovector exchange was interpreted in terms of the ρ meson in Ref. [23] and π exchange in [25]. These one-boson exchange models, when fit to early data on η production, made predictions for A_y as shown in Fig. 3 with $A_y(\theta_\eta) = \mathcal{A}\sin 2\theta_\eta$ where $|\mathcal{A}| = 0.18$ at $Q = 15$ MeV. Note here that these ρ [23] and π [25] exchange curves come with the opposite sign, i.e. the distribution is shifted by $\theta_\eta = 90$ degrees. One possible explanation might be cancellation through destructive interference between π and ρ exchanges in η production in proton-proton collisions very close to threshold together with a strong (spin independent) scalar σ exchange contribution.

Cancellation of $(\mathrm{Pp})^2$ and $\mathrm{Ss^*Sd}$ interference terms at $Q = 72$ MeV suggests a phase cancellation of various meson exchanges and resonance contributions, e.g. associated with the nucleon resonances $S_{11}(1535)$, $D_{13}(1520)$ and $P_{11}(1440)$.

To summarize, we have measured the spin analyzing power for η production close to threshold with precision improved by one order of magnitude. For excess energy $Q = 15$ MeV the data is consistent with η production process in pure s-wave. We find evidence of higher partial waves at $Q = 72$ MeV. The $\mathrm{Ps^*Pp}$ interference determines the shape of the measured analyzing power with cancellation of $\mathrm{Ss^*Sd}$ and $(\mathrm{Pp})^2$ interference terms. The data contradicts predictions of presently available meson exchange models of the production mechanism. The analyzing power complements previous measurements of the energy and angular distribution of η meson production and provides valuable new constraints for future model building.

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* present address: Institut für Kernphysik, Johannes Gutenberg–Universität Mainz, Johann–Joachim–Becher Weg 45, 55128 Mainz, Germany

† present address: Peter Grünberg Institut, PGI–6 Elektronische Eigenschaften, Forschungszentrum Jülich, 52425 Jülich, Germany,
and
Institut für Laser– und Plasmaphysik, Heinrich–Heine Universität Düsseldorf, Universitätsstr. 1, 40225 Dsseldorf, Germany

‡ present address: Jülich Centre for Neutron Science JCNS, Forschungszentrum Jülich, 52425 Jülich, Germany

§ present address: Department of Physics, Harvard Uni-

versity, 17 Oxford St., Cambridge, MA 02138, USA
¶ present address: INFN, Laboratori Nazionali di Frascati, Via E. Fermi, 40, 00044 Frascati (Roma), Italy

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