

Measurement of Spin-Correlation Parameters A_{NN} , A_{SS} , and A_{SL} at 2.1 GeV in Proton-Proton Elastic Scattering

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At the Cooler Synchrotron COSY/J lich spin-correlation parameters in elastic proton-proton (pp) scattering have been measured with a 2.11 GeV polarized proton beam and a polarized hydrogen atomic beam target. We report results for A_{NN} , A_{SS} , and A_{SL} for c.m. scattering angles between 30° and 90° . Our data on A_{SS} —the first measurement of this observable above 800 MeV—clearly disagrees with predictions of available pp scattering phase-shift solutions while A_{NN} and A_{SL} are reproduced reasonably well. We show that in the direct reconstruction of the scattering amplitudes from the body of available pp elastic scattering data at 2.1 GeV the number of possible solutions is considerably reduced.

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The nucleon-nucleon (NN) interaction as one of the fundamental processes in nuclear physics has been studied over a broad energy range and its contribution to our understanding of the strong interaction cannot be overestimated. NN elastic scattering data, parametrized by energy-dependent phase shifts, are used as an important ingredient in theoretical calculations of inelastic processes, nucleon-nucleus and heavy-ion reactions. Below the pion production threshold at about 300 MeV elastic scattering is described to a high level of precision [1] by a number of models, e.g., phenomenological and meson exchange. Here, also effective field theory [2] has received increased attention. An unambiguous determination of phase-shift parameters has been achieved up to about 0.8 GeV [3–7]. However, with increasing energy the number of partial waves to be determined grows, but the quality and density of the experimental data base diminishes. Recently, it has been pointed out [7,8] that above about 1.2 GeV serious discrepancies between phase-shift analysis (PSA) of different groups exist. A model-independent direct reconstruction of the scattering amplitudes (DRSA) by the Saclay-Geneva group [8] has not solved this puzzle, since usually both PSA solutions are supported by one of the two or three solutions found.

Apparently, this issue can be settled only by new, precise experimental data, especially in observables not measured to date in this energy domain. Storage rings offer an unique environment to perform internal high-statistics experiments with pure polarized hydrogen targets and polarized beams [9]. Measurements of spin-correlation parameters have been pioneered by the

PINTEX group at IUCF [10–12] at energies between 200 and 450 MeV. In the same spirit the EDDA Collaboration has made a first measurement of the spin-correlation parameters A_{NN} , A_{SS} , and A_{SL} at 2.11 GeV (In Argonne-notation [13]) at COSY/J lich [14]. For A_{SS} this is the first measurement above 0.8 GeV and challenges existing PSA and DRSA predictions, which vary considerably.

The EDDA experiment is set up at an internal target station at the COSY ring. The polarized target [15], a standard atomic beam source, is shown schematically in Fig. 1. Molecular hydrogen is dissociated in a RF-discharge and a atomic hydrogen beam is formed by a cooled nozzle. By two permanent sixpole magnets and an RF transition unit only one hyperfine state—where both proton and electron have magnetic quantum number $+\frac{1}{2}$ —is focused into the interaction region, where it crosses the COSY proton beam. After being analyzed in a Breit-Rabi-spectrometer with respect to the polarization the hydrogen beam is removed in a beam dump. In the interaction region the polarization of the hydrogen atoms is aligned by applying a weak (1 mT) magnetic guiding field in either one of six possible directions $\pm x$, $\pm y$, and $\pm z$. Data are acquired after acceleration of the COSY-beam at 2.11 GeV for 6 s. After each COSY machine cycle, where the target polarization is held constant, the polarization of the COSY-beam ($\pm y$) is flipped. Scattering data for the resulting 12 spin combinations are detected by a double-layered cylindrical scintillator hodoscope, the EDDA detector (cf. Figure 1 and Refs. [16,17]).

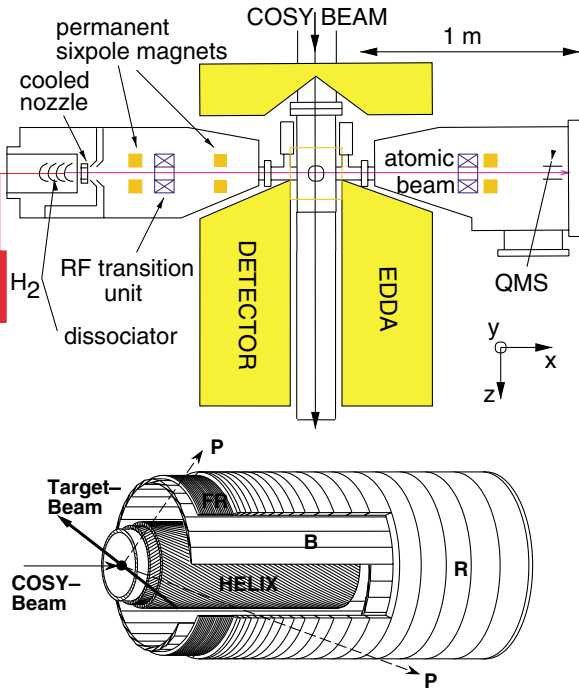


FIG. 1 (color online). Schematic overview of the atomic beam target (top) and the EDDA-detector (bottom).

Event reconstruction proceeds in three steps: First the position of hits in the inner and outer detector layer are determined. Most events show multiplicities compatible with two charged particles. Scattering vertex coordinates and scattering angles are then obtained by fitting two tracks to the observed hit pattern. For accepted elastic events the angular resolution is increased by adding constraints imposed by elastic scattering kinematics in the fit.

Elastic scattering events were selected as described in [17]. Two classes of cuts are applied: first, to match the reaction volume to the beam-target overlap, and second, to reduce unwanted background contributions from inelastic reactions. Cuts on the scattering vertex along the COSY-beam ($-15 \text{ mm} < z < 20 \text{ mm}$) are chosen to fully in-

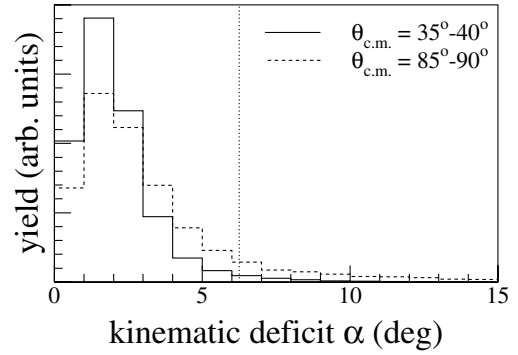


FIG. 2. Distribution of the kinematic deficit α for two ranges of c.m. scattering angles. Events with $\alpha > 6.25^\circ$, mainly due to inelastic processes or secondary reactions of the final-state protons in the detector, are discarded.

clude the width of the atomic beam-target (13 mm FWHM). Perpendicular to the COSY-beam axis, e.g., in the x - y plane, the COSY-beam location and width (standard deviation σ) can be reconstructed. Events with a reaction vertex outside a 3σ -margin of the beam position are discarded. Elastic scattering events are characterized by two protons emitted back to back in the c.m. system. A cut on the deviation from this perfect 180° angle, the so-called kinematic deficit (Fig. 2), removes inelastic reactions very effectively. However, Monte-Carlo studies have shown that contributions of three-body final states at the level of a few percent cannot be eliminated. Their relative contribution can be varied by loosening or tightening the selection criteria within reasonable limits. We found no change in the resulting spin-correlation parameters within the statistical errors. The arising absolute systematic uncertainty is typically 0.01.

The spin dependence of the NN interaction leads to a modulation of the cross section σ with the azimuthal angle ϕ , which depends on the alignment of the beam (\vec{P}) and target (\vec{Q}) polarizations with respect to the scattering plane [12,13,18]. For the beam polarization parallel to y one obtains

$$\frac{\sigma(\theta, \phi, \vec{P}, \vec{Q})}{\sigma_0} = 1 + A_N(\theta) \{ (P_y + Q_y) \cos \phi - Q_x \sin \phi \} + A_{SL}(\theta) \{ P_y Q_z \sin \phi \} \\ + A_{NN}(\theta) \{ P_y Q_y \cos^2 \phi - P_y Q_x \sin \phi \cos \phi \} + A_{SS}(\theta) \{ P_y Q_y \sin^2 \phi + P_y Q_x \sin \phi \cos \phi \}. \quad (1)$$

Here, σ_0 is the unpolarized differential cross section, θ the c.m. scattering angle, and A_N the analyzing power, which is known [17] and used as input to fix the overall polarization scale.

Apart from the spin-correlation parameters and polarizations the integrated luminosities L and detection efficiencies ϵ must be extracted from the measured number of scattering events:

$$N(\theta, \phi, \vec{P}, \vec{Q}) = \sigma(\theta, \phi, \vec{P}, \vec{Q}) L(\vec{P}, \vec{Q}) \epsilon(\theta, \phi). \quad (2)$$

We have employed two methods which yield consistent

results. First, from the sum of events in four quadrants in ϕ , asymmetries in the spirit of [19] are defined which are insensitive to L and ϵ [20], or, second, these are determined by a fit using standard χ^2 minimization techniques for the set of Eqs. (1) for the 12 spin combinations. The beam and target polarizations obtained from the data are $61.1 \pm 1.5\%$ and $69.7 \pm 1.8\%$, respectively. Measurements of the magnetic field distribution (modulus and direction) in the interaction region and a determination of unwanted magnetic field components from the data by

the χ^2 -fit show that misalignment of the target holding field is very small and has negligible effect on the spin-correlation parameter.

The experimental data have been binned in 5° wide bins in the c.m. scattering angle θ . The results for A_{NN} , A_{SS} , and A_{SL} are displayed in Fig. 3. An overall normalization uncertainty of 4.7%, not included in the error bars, arises from the statistical and normalization uncertainty of the analyzing power data [17] used in the analysis. The new data on A_{NN} are in good agreement with previous measurements and recent PSA solutions. However, for most of the angular range A_{SS} is in striking disagreement with both PSA predictions, except for $\theta = 90^\circ$ where basic symmetry considerations require $A_{SS} = 1 - A_{NN} - A_{LL}$, with the right-hand side known experimentally. For A_{SL} , nearly consistent with zero, we find agreement with [25,26] but cannot confirm the results of Ref. [24], which are significantly below zero at small angles. Our data are available upon request.

Apparently, available phase-shift parameters [7,8] have failed strongly, when confronted with data on the observable A_{SS} not present in the PSA databases. Preliminary

analysis of data taken at eight other energies between 1.35 and 2.5 GeV in subsequent running periods show the same result, with the discrepancies gradually increasing with energy. That phase-shift parameters may not yet be uniquely determined by experimental data has been pointed out previously [7,8] and would explain naturally the differences in the PSA predictions for A_{SS} in Fig. 3. To this end a direct reconstruction of the scattering amplitudes (DRSA), model independent by design, proves to be a useful tool.

Exploiting basic symmetry principles of the strong interaction, the transition matrix T for pp elastic scattering is given by five complex amplitudes [18]. In the helicity frame, where $|+\rangle$ and $|-\rangle$ are the positive or negative helicity states of the protons in the c.m., these five amplitudes are [27]

$$\begin{aligned}\phi_1 &= \langle ++|T|++\rangle, & \phi_2 &= \langle ++|T|--\rangle, \\ \phi_3 &= \langle +-|T|+-\rangle, & \phi_4 &= \langle +-|T|-+\rangle, \\ \phi_5 &= \langle ++|T|+-\rangle,\end{aligned}\quad (3)$$

which correspond to no ($\phi_{1,3}$), single (ϕ_5), and double-spinflip ($\phi_{2,4}$). All observables can be expressed by bilinear combinations [13] of these amplitudes, e.g., for A_{SS} we obtain

$$\begin{aligned}A_{SS}\sigma_0 &= \text{Re}(\phi_1\phi_2^*) + \text{Re}(\phi_3\phi_4^*) \\ &= |\phi_1||\phi_2| \cos(\alpha_1 - \alpha_2) \\ &\quad + |\phi_3||\phi_4| \cos(\alpha_3 - \alpha_4)\end{aligned}\quad (4)$$

when using $\phi_k = |\phi_k| \exp(i\alpha_k)$. Given experimental data on at least nine suitably chosen, linearly independent observables at the same beam energy and scattering angle, the helicity amplitudes are obtained by a simple χ^2 -minimization, except for an arbitrary, unobservable global phase. In addition, the choice of helicity amplitudes sheds light on contributions of the various spin-dependent parts of the NN interaction [28] to the observables. A_{SS} in particular depends on the interference between double- and nonspinflip amplitudes and thus probes aspects of the spin-spin and spin-tensor parts of the NN interaction.

We have performed a DRSA at 2.1 GeV at 11 angles, using the database described in Ref. [8] with the addition of recently published data on A_N and K_{0nn0} [17,29,30]. Differential cross section data except those of Ref. [16] were removed. In accordance with [8] we found two to four minima in the contour of the χ^2 -function for a fit of the data in terms of the amplitudes $\phi_{1\dots 5}$ (open symbols in Fig. 4). Thus, the helicity amplitudes are not uniquely determined, since different sets describe the data equally well.

In order to explore to what extent the inclusion of the new spin-correlation data of this work is a remedy, we have added these to the database and repeated the search for minima in the χ^2 -function (solid symbols in Fig. 4). First, the number of ambiguities is reduced to two in most

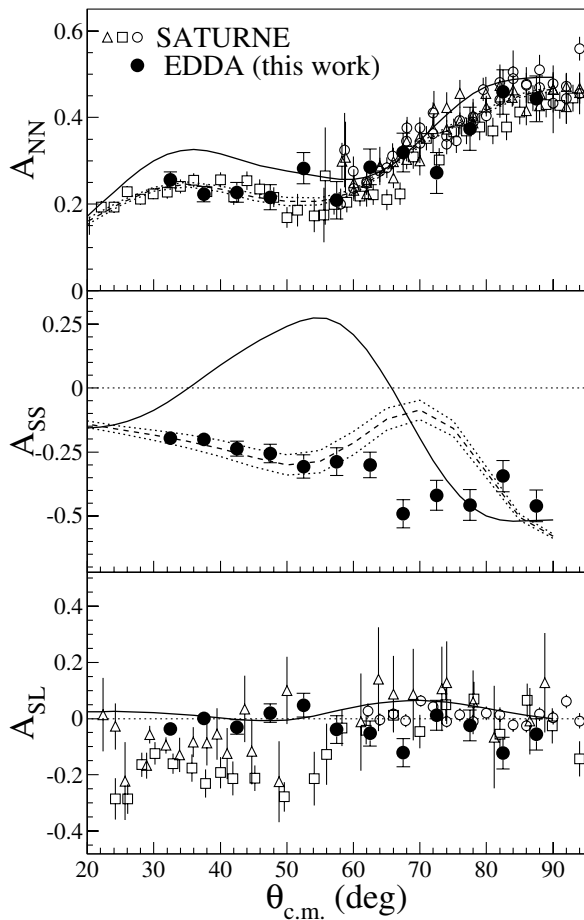


FIG. 3. Results for A_{NN} , A_{SS} , and A_{SL} in comparison to PSA predictions from the Virginia [7] (solution FA00, solid) and Saclay-Geneva [8] (dashed lines) groups as well as data from SATURNE (A_{NN} : [21–23], A_{SL} : [24–26]).

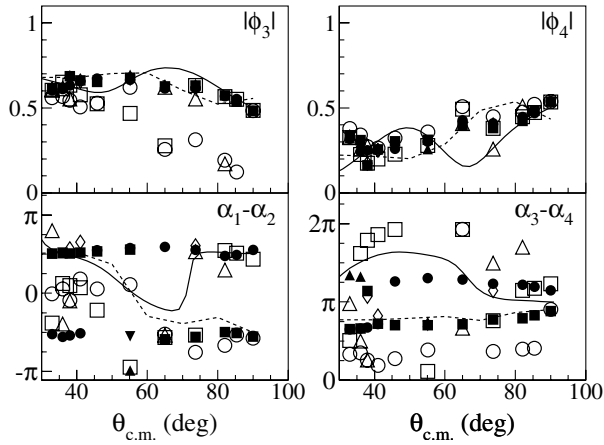


FIG. 4. DRSA solutions for some helicity amplitudes without (open) and with (solid) inclusion of the new data on A_{NN} , A_{SS} , and A_{SL} in comparison to PSA solutions (as in Fig. 3). All amplitudes have been divided by $\sqrt{2\sigma_0} = (\sum_{i=1}^5 |\phi_i|^2 + 3|\phi_5|^2)^{1/2}$. The symbols (\bullet , \blacksquare , \blacktriangle , \blacktriangledown , and \circ , \square , \triangle , \diamond , respectively) distinguish DRSA solutions, corresponding to different minima of the χ^2 -function.

cases. Second, the χ^2 is not increased by the new data on A_{SS} , although here, the aforementioned conflict of Ref. [24] with our data on A_{SL} contributes. This demonstrates that the new data on A_{SS} are perfectly compatible with all experimental information available and provide important additional constraints in determining scattering amplitudes and phase shifts.

For some helicity amplitudes the different solutions are displayed in Fig. 4. The absolute values of all amplitudes are very well determined when taking the data of this work, in particular, on A_{SS} , into account. The remaining ambiguities are in the relative phases of these amplitudes. Our DRSA yields that $|\alpha_1 - \alpha_2| \approx \frac{\pi}{2}$, such that $Re(\phi_1\phi_2^*)$ vanishes. Therefore in Eq. (4), A_{SS} is driven only by ϕ_3 (no spin flip) and ϕ_4 (double spin flip) for antiparallel spins in the initial state. In the PSA solutions $\cos(\alpha_1 - \alpha_2)$ does not vanish and they overestimate A_{SS} in the $\theta = 50^\circ - 70^\circ$ range. However, some aspects of the DRSA amplitudes are remarkably well represented by PSA predictions, like $\alpha_3 - \alpha_4$ by the solution of [8]. From the identity $(A_{NN} + A_{SS})\sigma_0 = 2Re(\phi_1\phi_2^*) + 2|\phi_5|^2$ [13] and the experimental result $A_{NN} \approx -A_{SS}$ we conclude further, that the single spin-flip amplitude ϕ_5 , mainly driven by spin-orbit forces [28], must be small at these energies.

We have reported the first results of elastic $\vec{p}\vec{p}$ scattering at COSY. Spin-correlation parameters A_{NN} , A_{SS} , and A_{SL} have been determined at 2.11 GeV between 30° and 90° in the center-of-mass. While A_{NN} and A_{SL} are at least in reasonable agreement with previous data and PSA solutions, A_{SS} as the first measurement above 0.8 GeV adds genuine new information to the field. Therefore,

current PSA solutions should be used with caution above 1.2 GeV. Including these new data has reduced the ambiguities in reconstructed scattering amplitudes, indicating that they provide an important step towards unambiguous phase shifts.

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