MEASUREMENT OF POLARIZATION PARAMETERS AND ANALYSIS OF pp ELASTIC SCATTERING AT 1 GeV

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The nucleon-nucleon scattering is not considered any more as the elementary interaction. Nevertheless, the nucleon-nucleon scattering is still the base for the description of principal properties of nuclei. Such parameters as the spin structure and the angular and energy dependence of the scattering amplitude define the dynamics of the nucleon-nucleus interaction.

The study of pp scattering (isospin $I = 1$) is the major source of nucleon-nucleon interaction data. The polarization data allow to reconstruct the scattering amplitude using either a direct reconstruction procedure or a phase shift analysis (PSA). Both methods are closely related but the PSA method requires the set of experimental data only in the restricted angular interval. Due to the analytical properties of the scattering matrix, it is possible to continue observables into the whole angular interval.

It is possible to express the pp scattering amplitude through the spin-dependent amplitudes:

$$M = a + b\sigma_{1n}\sigma_{2n} + c(\sigma_{1n} + \sigma_{2n}) + e\sigma_{1m}\sigma_{2m} + f\sigma_{1l}\sigma_{2l}, \tag{1}$$

where σ_{1i} and σ_{2i} – the spin components in the c.m.s. along $\vec{n}$, $\vec{m}$, $\vec{l}$ directions. The presentation of the scattering matrix in terms of phase shifts is the experimental base of the dynamic theory of the nucleon-nucleon interaction.

The program of pp scattering investigation was intended to fill the gap in present experimental data. As the first stage of the program, the Wolfenstein parameters $D(D_{nono}$ and $K_{onno})$, $R(D_{s'oso}$ and $K_{os'so})$, $A(D_{s'oko}$ and $D_{os'ko})$ [1)] were measured. These parameters were obtained by measuring the horizontal and vertical proton polarization after scattering of a polarized proton beam on an unpolarized target. Here $\vec{n}$, $\vec{k}$, $\vec{s}$ and $\vec{n}'$, $\vec{k}'$, $\vec{s}'$ – the unit vectors related to incident and scattered protons: $\vec{k}$ и $\vec{k}'$ – the momentum directions; $\vec{n} = \vec{k} \times \vec{k}' = \vec{n}'$, $\vec{s} = \vec{n} \times \vec{k}$ and $\vec{s}' = \vec{n} \times \vec{k}'$. Later on the parameters A_{oonn} and $M_{s'oko}$ were measured using the frozen spin polarized proton target (FSPT).

To measure the polarization parameters in a wide range of scattering angles, a proton beam polarized in all possible directions: vertical, horizontal, longitudinal was designed [1] and the analyzing power of carbon was measured in the energy range 650 to 1000 MeV [2]. The polarized beam was obtained by scattering of the extracted proton beam on the target-polarizer (TP).

Fig. 1 gives the layout of the polarized beam transportation line and the setup for measurements of the polarization parameters. The unpolarized proton beam was directed by the magnet RM_1 to TP. Protons scattered at the angle Θ_1 were returned back to the initial direction by the magnet RM_2. The magnets RM_1 and RM_2 were able to rotate around the beam axis. This gives the possibility to get the horizontally or vertically polarized proton beam. The polarization reversal was reached by changing the RM_1 and RM_2 polarity and the appropriate TP shift. Because the scattering angle was equal to the previous one, the absolute polarization value remained unchanged. The polarized proton beam was formed by a set of magnetic lenses and collimators and was directed by the magnets DM_1, DM_2 to the target-scatterer. Each

[1)] Polarization parameters indices are defined according to the Madison convention and are given in the article of J.Bystricky et al., J. Physique, 1978. V.39. P.1.

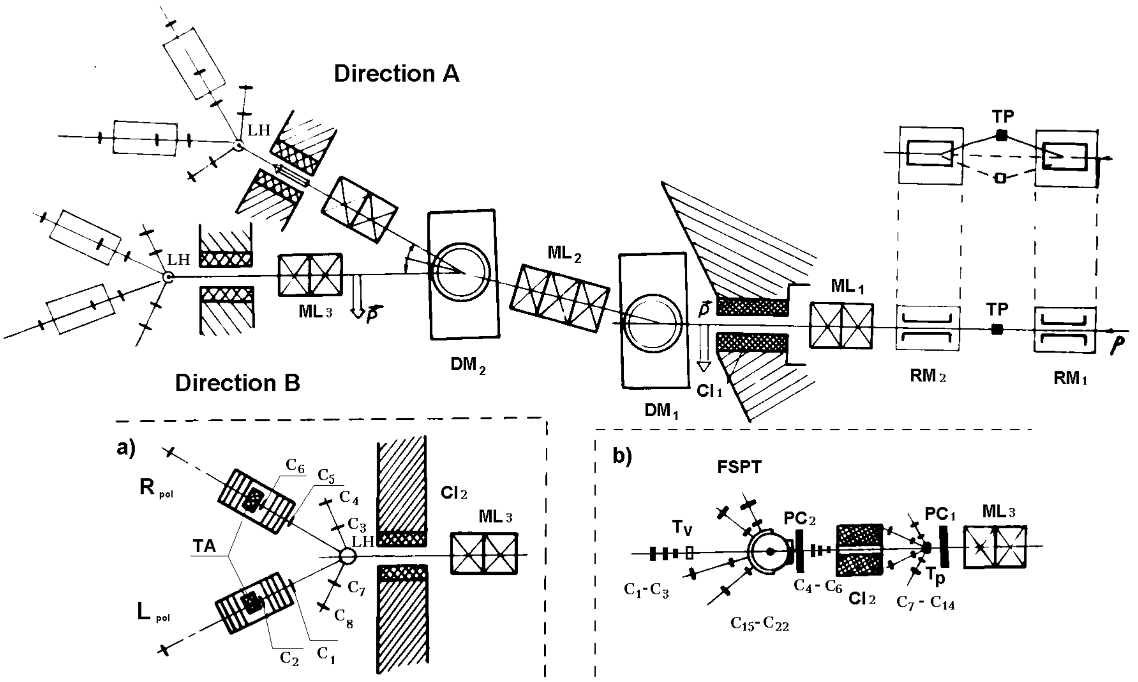

Fig. 1. The layout of the polarized beam transportation line and the setup for measurement of the polarization parameters: DM_1, DM_2, RM_1, RM_2 – magnets, ML_1–ML_3 – quadrupole lenses; Cl_1, Cl_2 – collimators; TP – target-polarizer; LH – liquid hydrogen target.
1a) Setup for measurement of the parameters D, A, R: LH – liquid hydrogen target; TA – analyzer; C_1–C_4, C_5–C_8 – left, right arm scintillation counters; L_{pol}, R_{pol} – polarimeters.
1b) Setup for measurement with FSPT: FSPT – frozen spin polarized proton target; T_v, T_p – vertical monitor and polarimeter targets. C_1–C_3 – vertical monitor counters; C_4–C_6 – beam monitor counters; C_7–C_{14} – beam polarimeter counters; C_{15}–C_{22} – trigger counters; PC_1, PC_2 – proportional chambers for the beam monitoring.

magnet $DM_{1,2}$ deflected the polarized beam by 12.3°. In the case of the horizontally polarized beam, the deflection angle of 24.6° corresponded to the spin rotation by 90° at the energy of 970 MeV. Due to such spin rotation, the horizontally polarized beam was converted to the longitudinal one (direction A). To conserve the polarization direction, the magnets DM_1, DM_2 deflected the beam to the opposite direction (direction B). The vertically polarized beam also passed through the directions A, B.

Such polarization and transportation system had some advantage over similar polarization systems. The principal advantages were:

1. Left-right and up-down scattering gave the opportunity to invert the polarization sign. The transportation system maintained the identity of the beam parameters in the interaction region. It was confirmed that $|+\vec{P}_B| - |-\vec{P}_B| = 0$ with the statistically available precision ($\Delta P_B \leq 0.008$).

2. Matching the vertical and horizontal scattering on TP provided the transportation identity for all polarization directions.

The setup for measurements of the parameters D, R and A (Fig. 1a) consisted of scintillation counters and polarimeters. Scintillation counters (C_1–C_4 and C_5–C_8) separated the pp elastic events. Polarimeters measured polarization of scattered and recoiled protons after scattering on the liquid hydrogen target (LH). Each polarimeter consisted of two blocks of spark chambers and carbon analyzer (TA). Measurements of the parameters D, A and of the parameter R were performed in the directions A [2, 3] and B [4], correspondingly.

For the measurement of the parameters A_{oonn} and $M_{s'okn}$ the liquid hydrogen target was replaced by the frozen spin polarized target [2)] (FSPT, Fig. 1b) with the polarization (P_T) about 100%. Polarization of the scattered protons was measured by polarimeters on the base of multiwire proportional chambers. The accuracy of the beam transportation and the precision of the polarization and intensity measurement had the principal importance (see comments to Fig. 1b).

The measured angular distribution of protons scattered on the polarized and hydrogen target (I_{ij}) gave the asymmetry of pp scattering $A_{oono} \equiv A_{ooon}$ and the component of the asymmetry tensor $A_{oonn} \equiv C_{nnoo}$ [5]:

$$A_{oono} = \frac{1}{P_B}\frac{I_{+0} - I_{-0}}{\sum I_{ij}}, \qquad (P_B \neq 0, P_T = 0); \tag{2}$$

$$A_{ooon} = \frac{1}{P_T}\frac{(I_{++} - I_{-+}) - (I_{--} - I_{+-})}{\sum I_{ij} - 2(I_{+bg} + I_{-bg})}, \qquad (P_B \neq 0, P_T \neq 0); \tag{3}$$

$$A_{oonn} = \frac{1}{P_B P_T}\frac{(I_{++} - I_{--}) - (I_{+-} - I_{-+})}{\sum I_{ij} - 2(I_{+bg} + I_{-bg})}, \qquad (P_B \neq 0, P_T \neq 0). \tag{4}$$

Here the first of two indices gives the beam polarization (along and against the direction $\vec{n}$), the second index gives the target polarization direction, I_{bg} – the background intensity, $\sum I_{ij}$ – the sum of intensities over all indices.

The polarization of the scattered and recoiled particles was determined by scattering on the carbon target-analyzer (TA). The dependence of this scattering on the angle ϕ_A is described through the left-right ϵ and up-down δ asymmetries as

$$I_A(\phi_A) = I_{A_0}[1 + \epsilon\cos\phi_A + \delta\sin\phi_A].$$

The asymmetries ϵ, δ depend on the polarization parameters and the carbon analyzing power A_{pC} averaged over the polar scattering angle θ_A.

In the case of scattering of the polarized protons on the liquid hydrogen target:

$$\epsilon = \frac{[P_{nooo} + D(\vec{P}_B\vec{n})]}{[1 + A_{oono}(\vec{P}_B\vec{n})]}A_{pC}, \tag{5}$$

$$\delta = [A(\vec{P}_B\vec{k}) + A(\vec{P}_B\vec{s})]A_{pC}. \tag{6}$$

In the case of scattering of the longitudinally polarized protons on the vertically polarized target [6]

$$\epsilon = \frac{P_{onoo} + K_{onno}(\vec{P}_T\vec{n})}{[1 + A_{ooon}(\vec{P}_T\vec{n})]}A_{pC}, \tag{7}$$

[2)] N.S.Borisov et al., Prib. Tekh. Eksp., 1978, No 2, P.32.

$$\delta = \frac{A(\vec{P_B}\vec{k}) + M_{s'okn}(\vec{P_B}\vec{k})(\vec{P_B}\vec{n})}{[1 + A_{ooon}(\vec{P_T}\vec{n})]} A_{pC}, \tag{8}$$

$P_{nooo} \equiv P_{onoo} = P$ is the polarization of the scattered (recoiled) proton after scattering of the unpolarized protons.

The Wolfenstein parameters were measured with two polarimeters for the two opposite polarization directions $(\pm\vec{n}, \pm\vec{k}, \pm\vec{s})$, which gave 4 values of the asymmetries ϵ, δ and thus defined parameters to be derived. Such measurement scheme practically eliminated the hardware asymmetry [2, 3, 4]. Measurements with a polarized target were performed for the opposite directions of the beam and the target polarization, and also for a dummy target. It allowed to get 4 values of asymmetries ϵ and δ and also a contribution of background from alien nuclei of the FSPT. As a result, it was possible to estimate the instrumental asymmetry and the background from the polarized target. However, the instrumental asymmetry ϵ (if existed) was present in the polarization P. The experimentally approved consequence of the T invariance of the scattering matrix – the equality polarization-asymmetry $P_{nooo} = A_{ooon}$ – confirmed the correctness of measurements.

The measured values of the polarization parameters are presented in Fig. 2. Solid circles give the results of the experiments with the polarized target, open circles – the results of the experiments with the unpolarized target. In Fig. 2a the values P and A_{ooon} are compared with the averaged world data of $<P>$ (the solid line). The agreement between the polarization and asymmetry means that the contribution of the background was estimated correctly and the instrumental asymmetry was negligible.

Using the measured values of the parameters D, R, A, A_{oonn} and the polarization (asymmetry), we have performed the phase shift analysis (PSA) of *pp* scattering at the fixed energy of 970 MeV [7]. The Stapp parametrization of S-matrix was used. Partial amplitudes were expressed through the complex phase shifts $\delta(^{2S+1}L_J)$, where L, S, J – the orbital momentum, spin and angular momentum of the *pp* system. Real parts of phase shifts were varied up to L_{max}, imaginary parts – up to L^{in}_{max}. The contribution of the highest partial waves was taken into account according to the OPE approach with the coupling constant $g^2_{\pi N}/4\pi = 14.3$. Mixing parameters were considered as real values. Due to using in PSA our experimental data, the number of independent parameters and the accuracy of their determining in the energy range up to 1 GeV have increased significantly. It allowed us to accept statistically reliable values $L_{max} = 7$ and $L^{in}_{max} = 5$. Further increasing of the number of varied parameters did not lead to decreasing of χ^2. As a starting point, we used 20 solutions from previous PSAs. Additionally the random search for PSA solutions was performed. Also, the correct position of the zeros of the Barrelet amplitude f_1 [8] was taken into consideration. As a result, two solutions were found. The difference between these solution was in the angular momenta J and in the predictions for the angular dependence of the parameters $M_{s'okn}$ and $M_{s'osn}$.

After measuring the parameter $M_{s'okn}$ and updating the values of A in the angular region $70° - 110°$ c.m.s., the PSA was redone. In this PSA the recent values of the parameters A_{oosk} и A_{ookk} [3)] obtained at the accelerator SATURN (France) with a high accuracy were also included. As a result, both solutions were merged, and Fig. 2 shows the values of D, R, A, $M_{s'okn}$ and A_{oonn} corresponding to this solution (solid line). The PSA predictions for the parameter P coincides with the averaged curve $<P>$. The latest PSA of Arndt's group [4)] is in a good

[3)] J.Bystricky et al., Nucl. Phys., 1988. V.B297. P.653.

[4)] R.A.Arndt et al., Phys. Rev., 1992. V.D45. P.3995.

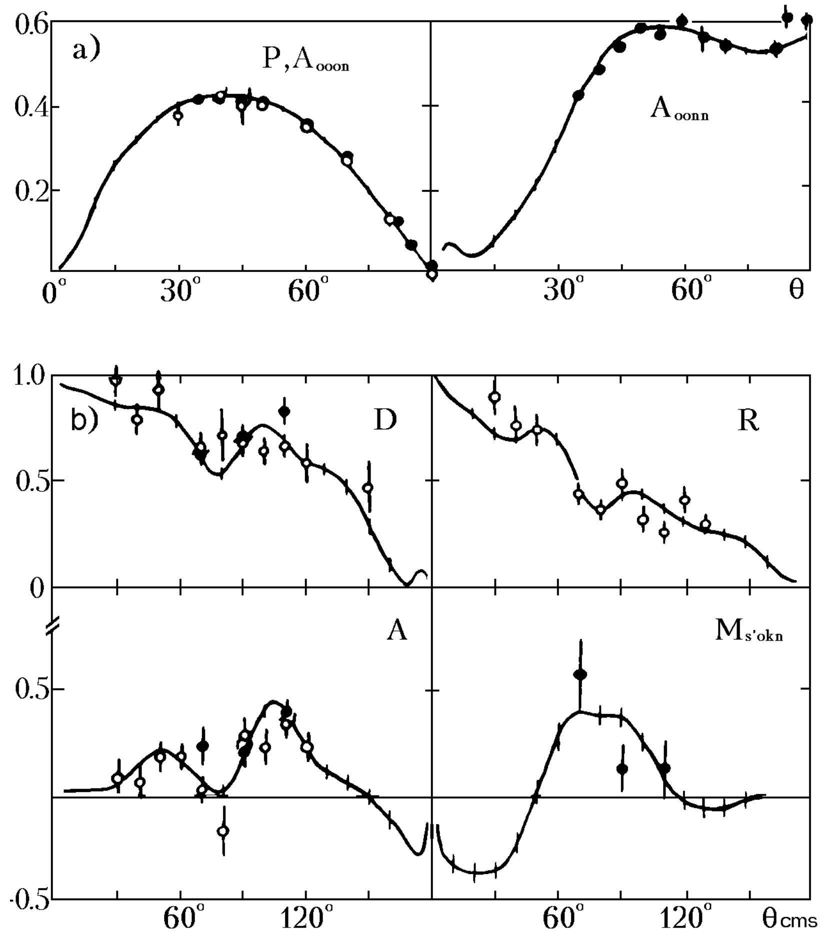

Fig. 2. Results of measurements of the polarization parameters:
ϕ – measurement with the liquid hydrogen target,
● – measurement with the polarized proton target.
Shown by solid lines are the predictions of PSA.

agreement with ours. Some difference exists only in mutual relations of the imaginary parts of phase shifts with equal angular momenta (e.g. $^1S_0$–$^3P_0$, $^3P_2$–$^1D_2$–$^3F_2$ etc.). This difference is due, probably, to the restricted set of existed inelastic nucleon-nucleon scattering data. Only the total inelastic cross section was used in the PSA. In spite of this disagreement, the difference between the predicted observables is within the statistical errors.

The Wolfenstein parameters D, A, R, and A_{oonn} define the spin-dependent pp interaction. The energy dependence of these parameters means that the spin-dependent part of interaction changes. We used the following integral amplitudes as the parameters defining interaction:

$$<a> = \frac{1}{2}\int |a(\theta)|^2\, d\Omega, \qquad <b> = \frac{1}{2}\int |b(\theta)|^2\, d\Omega, \qquad <c> = \int |c(\theta)|^2\, d\Omega,$$

$$<e> = \frac{1}{2}\int |e(\theta)|^2\, d\Omega, \qquad <f> = \frac{1}{2}\int |f(\theta)|^2\, d\Omega;$$

$$\sigma_{el}^{tot} = <a> + <c> + <b> + <e> + <f>.$$

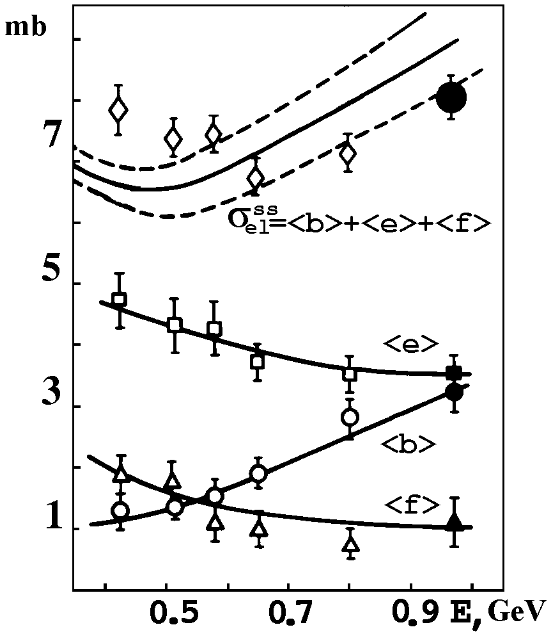

Fig. 3. Energy dependence of the spin-spin interaction contribution to the cross section of *pp* elastic scattering. The open points were extracted from the PSA up to 800 MeV [5)], the solid points are results of the present PSA. Shown by solid lines are results of the polynomial fitting.

Fig. 3 shows the energy dependence of the contribution of spin-spin interaction to the *pp* elastic scattering.

So, the contribution of spin-spin terms to the cross-section of *pp* elastic scattering does not decrease, at least, if the energy increases from the meson-production threshold up to 1 GeV. The same conclusion follows from the well known measurement of the parameter $A_{oonn}(90°)$ from 1.85 to 11.75 GeV/c at ANL (USA) [6)], so called “Argonne” effect.

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