ENERGY DEPENDENCE OF POLARIZATION PARAMETERS IN pp INTERACTION

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Introduction

We describe here the results of measuring the energy dependence of the polarization parameters in $\vec{p}p$ elastic scattering at proton energies in the range of 550–950 MeV and in the reaction $\pi\vec{d} \to pp$ at pion energies in the range of 350–450 MeV. The measurements were carried out in collaboration with the Nuclear Problems Laboratory (JINR, Dubna) and the Institute for Experimental Nuclear Physics (University of Karlsruhe, Germany).

The fundamental importance of investigation of the nucleon-nucleon interaction is evident, these processes being closely related both to the particle and nuclear physics. This justifies the amount of efforts in theoretical and experimental research of the NN interaction during the last 30 years. The remarkable success achieved in this field is mainly due to the detailed study of pp and np interactions and, most recently, due to study of the $p\overline{p}$ system.

These results were closely related to the progress achieved in the experimental technique and, first of all, in development of polarized beams and polarized targets.

The data analysis methods have been developing in two main directions. The first one was justification of the phase shift analysis method, elimination of the ambiguities, and creation of the algorithm for direct reconstruction of the scattering amplitude. Complementary to this approach requiring to carry out the "complete" experiment (or at least to measure many independent parameters at each energy) there was another way considering the phenomenological analysis of the behaviour of the observables which allowed to observe the characteristic features (such as resonances) in specific spin states.

The development of the research of the NN interactions in the 80s was, no doubt, stimulated by the search for dibaryon resonances which were widely discussed at that time. In spite of a certain decrease of interest to this problem in the last years, its stimulating influence cannot be neglected while discussing the nucleon-nucleon interaction.

Already the first experiments studying the NN interaction in pure spin states ($\Delta\sigma_L$, $\Delta\sigma_T$), as well as the data analysis in the $pp \to d\pi$ reaction, indicated existence of some peculiarities in the energy dependence and justified the detailed study of the nucleon-nucleon interaction at the energies above 500 MeV in the experiments allowing to isolate the interaction in specific spin states (especially, pp system in $^1D_2$, $^3F_3$, $^1G_4$ states). It is quite evident that this problem could only be solved studying the energy dependence of the spin parameters in the elastic nucleon-nucleon scattering or in the reactions with the NN system in the initial or final states. The latter statement is of importance also because it allows to extend the research area at the PNPI synchrocyclotron into the region of higher energies by studying the $\pi\vec{d} \to pp$ reaction. The c.m.s. total energy in pp scattering is $\sqrt{s} = 2.3$ GeV for 0.95 GeV protons, that corresponds to the maximum energy of polarized protons achievable at PNPI, and it is $\sqrt{s} = 2.45$ GeV in the reaction $\pi d \to pp$ for 0.5 GeV pions also available at PNPI. It is important to note that the scarcity of the experimental data by the start of our research left no hopes for any reliable phase shift analysis at that time. Accumulating data for such analysis was one of the main tasks in the studies of the polarization characteristics of the NN interaction at intermediate energies.

In the course of studying the behaviour of the polarization characteristics of the nucleon-nucleon interaction at the PNPI synchrocyclotron there were measured the analyzing power A_{00N0}, the polarization transfer coefficients K_{N00N}, the depolarization D_{N0N0}, and the spin-spin correlation A_{00NN} in pp elastic scattering at the energies of 550–950 MeV, as well as the vector analyzing power iT_{11} in the reaction $\pi\vec{d} \to pp$ at the pion energies of 350–450 MeV.

Experiment

For the mentioned above measurements of the spin-dependent parameters of the strong interaction, a beam of polarized protons [1] produced by scattering of the primary 1 GeV protons on a beryllium target as well as on the proton and deuteron polarized targets [2] was created at PNPI. The energy of the polarized protons was varied using the absorbers. The beam polarization was shown to be at the 30% level throughout the whole range of the energies from 650 MeV to 950 MeV. The corresponding variation of the beam intensity was in the range from $2.4 \cdot 10^5$ s^{-1} to 10^7 s^{-1}. The beam polarization could be reversed by changing the scattering angle of the primary proton beam on the polarizator target PTg (Fig. 1a).

The polarized proton and deuteron frozen spin targets were created on the base of the ^{3}He in ^{4}He dilution refrigerator and operated at the temperatures about 50 mK and in the 25 kG magnetic field. The targets were made of propanediol or butanol (deuterated one for the deuteron polarized target) with a CrV admixture for the paramagnetic centres creation. The target volume was about 10 cm^3. The obtained polarization reached 85–95% for the proton target and 45–50% for the deuteron target. This polarization was defined by measurements of the nuclear magnetic resonance signal from the target samples. The precision of these measurements was about 3%. The development of the methods and devices for measurements of the target polarization was an important part of the experiment which determined the success of this experimental program.

The experimental setups in the polarized proton beam and in the pion beam are presented in Fig. 1a and Fig. 1b, respectively.

The separation of the pp elastic scattering channel was done by registration of both outgoing protons at kinematically conjugated angles that allowed to reduce the background substantially and to ensure a good isolation of the process under study.

The experimental setup presented in Fig.1a includes the elements for formation of the polarized proton beam (bending magnets M1, M2, beryllium polarizator target PTg, collimators Col1, Col2, a triplet of magnetic quadrupole lenses L1–L3) and the beam polarimeter C1–C8 registering the right-left asymmetry in the scattering of the incident protons on the hydrogen-containing target at the angle 45° in the centre-of-mass system. These measurements allowed to find the beam polarization (taking into account the world's data on the analyzing power of the pp elastic scattering) with the precision of 0.5%. The systematic error was eliminated by performing measurements with the reversed direction of the beam polarization vector. The sum of the counts at both polarimeter arms was used also for the beam monitoring. Further on, the beam was shaped by the collimator Col3 and monitored by the counters C1–C3, as well as by the monitor C4–C6 which registered the particles scattered on the CH_2 target in the vertical plane. The beam profile on the polarized target and its aperture were controlled by proportional chambers PC1, PC2.

The asymmetry of scattering on the polarized target PT was measured with the detectors D1–D8 under the kinematically conjugated angles. These detectors have been a subject to

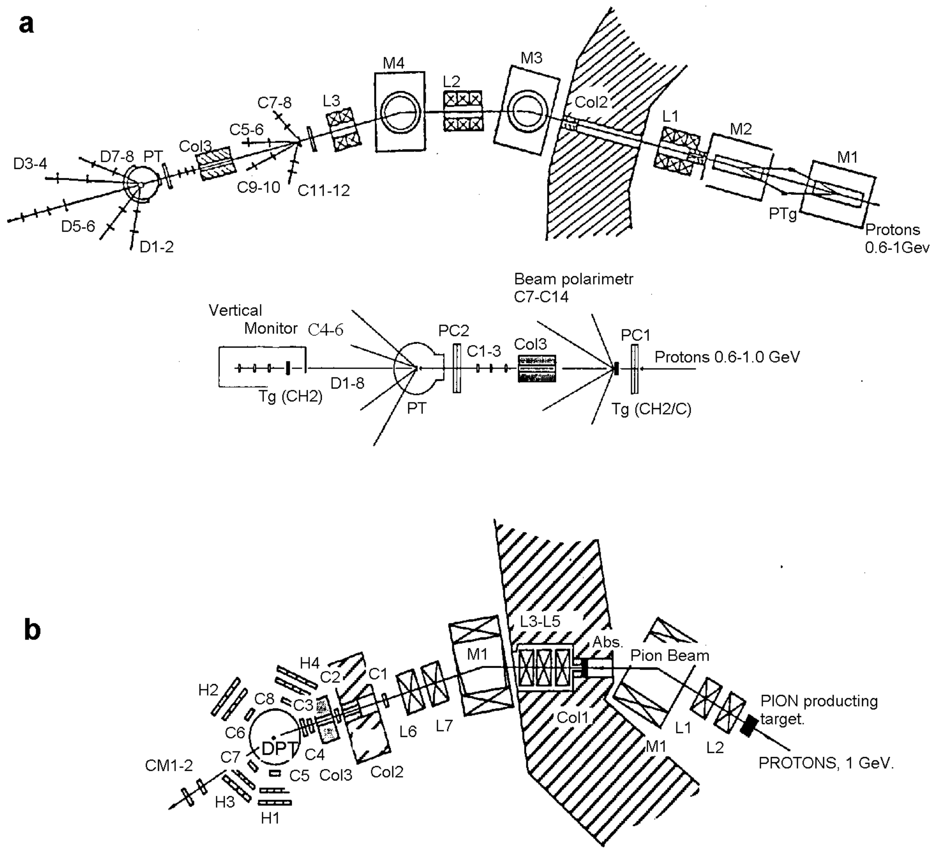


Fig. 1. Experimental setups for investigation of the polarization parameters in pp elastic scattering (a) and in $\pi\vec{d} \rightarrow pp$ reaction (b):
a) PTg – beam polarizing target; PT – proton polarized target; Tg(CH2/C) – polarimeter targets; L1–L3 – magnetic quadrupole lenses; Col1–Col3 – collimators; M1–M4 – dipole magnets; C1–C12 and D1–D8 – scintillator counters.
b) DPT – deuteron polarized target; H1–H8 – hodoscopes of scintillation counters; Abs – CH2 absorber. The others notations are as in Fig. 1a.

modifications in the course of the experiment, depending on the specific tasks. Used were telescopes of scintillator counters, a carbon polarimeter based on proportional chambers with the coded read-out [3], and multichannel hodoscopes composed of proportional chambers with delay line read-out and scintillator counters [4]. During the methodological studies we designed the analog [5] and the coded [3] read-out for proportional chambers.

The experimental setup for polarization measurements in the reaction $\pi\vec{d} \to pp$ in the pion channel of the PNPI synchrocyclotron is presented in Fig. 1b [6]. The main difficulty of this experiment was separation of the $\pi d \to pp$ channel from the background processes (elastic scattering, scattering on nuclei etc.). In order to solve this problem, the time of flight and the energy losses (dE/dx) were measured for the reaction products along with using the kinematics criteria. To separate the proton and the pion components in the beam, the time of flight of the projectile particles was measured with the counters C1–C3. To measure the scattering asymmetry on the polarized deuteron target we used a 4-arm detector consisting of the counters C5–C8 and the hodoscopes of scintillator counters H1–H4 (2×4 counters per arm).

In all our experiments, the measurements for each possible relative spin orientation of the beam and the target, as well as independent measurements on the dummy targets (containing no hydrogen or deuterium), were carried out. The background due to scattering on the cryostat elements and on the cooling ^{3,4}He mixture was also measured independently. The normalized background was subtracted during the data processing.

Results and discussion

pp elastic scattering

Measurements of the analyzing power A_{00N0}, of the spin-spin correlation coefficient A_{00NN} [7–9] and the polarization transfer coefficient K_{N00N} [3] for pp elastic scattering were carried out at the PNPI synchrocyclotron in the energy region 600–1000 MeV and in the angular range $30° - 100°$ in c.m.s. The results of the measurements are presented in Fig. 2. These data were the first results of measuring the polarization parameters in the region close to 1000 MeV. Later on, these results were confirmed by F. Lehar's group at the SATURN accelerator at Saclay, France. In the energy region in question, only measurements of the differential cross sections and analyzing power in pp elastic scattering and also measurements (at the Argonne National Laboratory) of the cross sections differences in pure spin states ($\Delta\sigma_L$, $\Delta\sigma_T$) had been realized prior to our experiments. These earlier measurements had indicated an existence of some structures in the energy dependences of the observables related, possibly, to the manifestation of the resonance states in the two-nucleon system. Listed below are the proposed resonance states and their spectroscopy characteristics according to A. Yokosawa's review [Physics Reports, 64, 47 (1980)].

Table 1
Candidates for resonances

Resonance	Energy $\sqrt{s}$, GeV	Width Δ, MeV	State
B_1^2	2.14 – 2.18	50 – 100	$^1D_2$
B_1^2	2.18 – 2.22	100 – 200	$^3P_{0,1,2}$
B_1^2	2.20 – 2.26	100 – 200	$^3D_3$
B_1^2	2.43 – 2.50	150	$^1G_4$

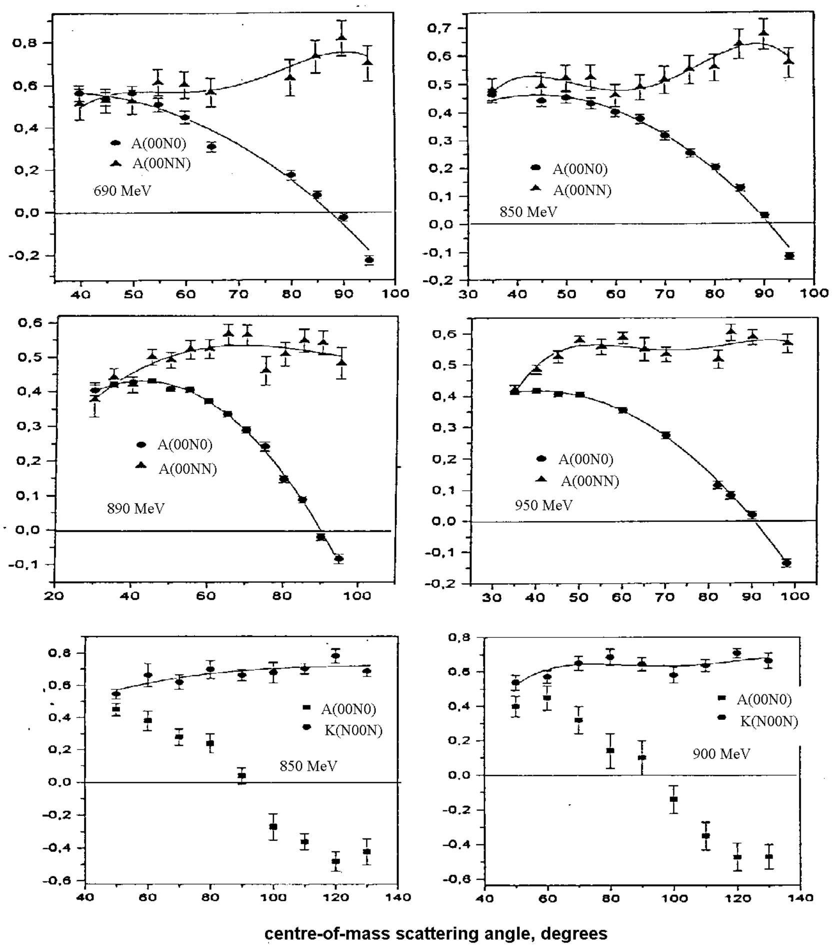


Fig. 2. Polarization parameters: analyzing power A_{00N0}, correlation of polarizations A_{00NN}, and polarization transfer parameter K_{N00N} for pp elastic scattering.

Thus, the research field close to 1 GeV seemed to be of a substantial interest both for the consistent study of the energy behaviour of the pp elastic scattering phase shifts and for the search for specific features of the spin-dependent scattering parameters caused by the possible existence of the resonances. Naturally, measurement of only two or three spin parameters is not enough for a direct reconstruction of the pp scattering matrix which includes five independent complex amplitudes. However, a "minimum data set" can allow to determine the module of the scattering matrix amplitudes. According to of O.G. Grebenyuk and G.M. Shklyarevsky [Preprint LNPI-853, 1983], this minimum set must contain the following quantities:

$$\sigma_t, \quad \Delta\sigma_L, \quad \Delta\sigma_T, \quad I_{0000} = d\sigma/d\Omega, \quad A_{00N0}, \quad A_{00NN}, \quad D_{N0N0}, \quad K_{N0N0}.$$

The measurement at PNPI of the latter four parameters made possible a phase shift analysis of pp elastic scattering at the energies of 850 MeV, 900 MeV, and 950 MeV. The energy dependence of the ${}^1D_2$ and ${}^3F_3$ partial amplitudes is presented by the Argand plot in Fig. 3. It manifests a resonance-like behaviour in these waves. The results of the phase shift analysis have also allowed to reject the solution obtained in 1986 by the Saclay group which indicated a rapid increase of the imaginary part of the $^3F_3$ partial amplitude in the region close to 1 GeV. The obtained solutions proved to be quite stable with further accumulation of the experimental data and coherent with the constantly updated VPI–95 analysis by the Arndt's group.

Another way to analyze the obtained data is to study the behaviour of the polarizations correlation coefficient A_{00NN} for the scattering at 90° in the centre-of-mass system. In this case the following relations can be derived allowing to separate the contributions of the singlet and triplet states in pp elastic scattering:

$$d\sigma/d\Omega(90^\circ) = 1/4|M_{ss}|^2 + 1/2|M_{01}|^2 + |M_{10}|^2, \tag{1}$$

$$d\sigma/d\Omega(90^\circ)[1 - A_{00NN}(90^\circ)] = 1/2|M_{ss}|^2, \tag{2}$$

and

$$A_{00NN}(90^\circ) = \frac{d\sigma_t/d\Omega - d\sigma_s/d\Omega}{d\sigma_0/d\Omega}, \tag{3}$$

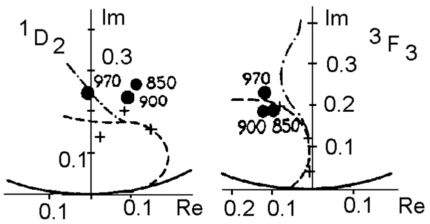
$$\alpha \equiv \frac{1 + A_{00NN}(90^\circ)}{1 - A_{00NN}(90^\circ)} = \frac{d\sigma_t/d\Omega}{d\sigma_s/d\Omega} \tag{4}$$

where M_{ss}, M_{01}, M_{10} are the matrix elements of the scattering in the singlet and triplet states, $d\sigma_s/d\Omega$, $d\sigma_t/d\Omega$ are differential cross sections of the scattering in the singlet and triplet states, $d\sigma_0/d\Omega \equiv d\sigma/d\Omega$ is the unpolarized differential cross section.

The energy dependence of the polarizations correlation coefficient A_{00NN} at 90° in the region of 550–970 MeV measured by the PNPI–JINR group is presented in Fig. 4 along with the results of calculations according to the phase shift analysis VPI–95. The dependence manifests a weak wide resonance around 700 MeV. On the other hand, determination of the square matrix element of the singlet state scattering according to (2) changes the situation dramatically: a sharp peak arises at about 450 MeV which may be interpreted as the $^1D_2$ resonance (Fig. 5). The observed maximum in the singlet interaction is nowadays attributed to the $N\Delta$ interaction in the lowest state.

The available data also allow to analyze the energy dependence of the ratio of the triplet to singlet scattering cross sections according to (4). The results are presented in Fig. 6; a maximum seen at the energy ≈690 MeV can be attributed to some strengthening of the interaction in the $^3P_{0,1,2}$ wave, according to the expectations as indicated in Table 1. Making the latter statement, we take into account also the smooth behaviour of the matrix element M_{ss} in the region above 600 MeV.

In conclusion, the PNPI measurements of the polarization parameters in pp elastic scattering at the energies between 650 MeV and 950 MeV allowed to perform the phase shift analysis on the base of the "minimum set of data", and the evidence was obtained for resonance interaction in the $^1D_2$, $^3P_{0,1,2}$, and $^3F_3$ states.



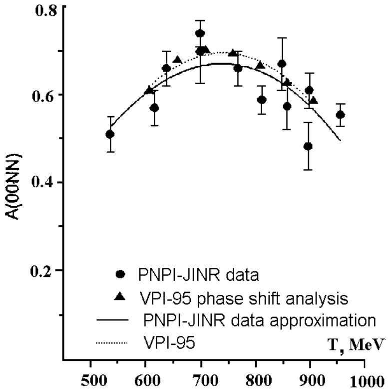
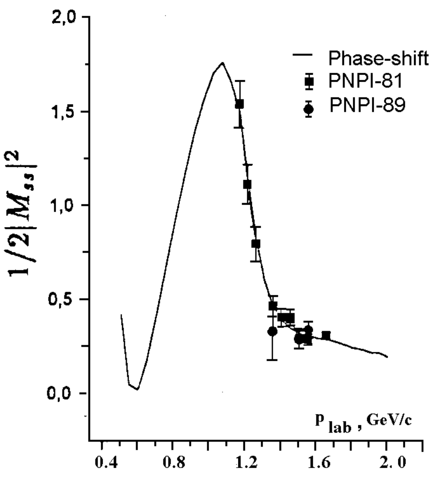


Fig. 3 Argand plots for $^1D_2$ and $^1F_3$ partial amplitudes of pp elastic scattering.
Fig. 4. Energy dependence of the A_{00NN} parameter for pp elastic scattering at 90°. Full dots and solid curve are PNPI data and their polinomial approximation; triangles and dashed curve are from the phase shift analysis VPI–95.



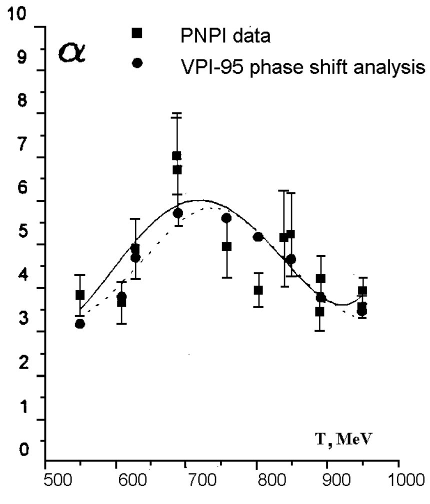


Fig. 5. The momentum dependence of the singlet scattering matrix element M_{ss} in the region of $^1D_2$ resonance.
Fig. 6. The ratio of triplet to singlet scattering cross sections at 90°. Curves are an approximation of PNPI data and VPI–95 prediction.

Reaction $\pi\vec{d} \rightarrow pp$

The study of the spin parameters of the nucleon-nucleon interaction at the energies higher than 1 GeV could not be realized at the PNPI synchrocyclotron in the direct pp channel. It was possible, however, to use the reaction $\pi\vec{d} \rightarrow pp$ where the value of $\sqrt{s} \approx 2.4$ GeV is achievable at the pion energies of 450–500 MeV. The interest to this range of energies was enforced by the results of measurements of the A_{Y0} parameter in the inverse channel $pp \rightarrow \pi^+ d$ where (R. Bertini's experiment at Saclay) some wide structures had been found in the energy dependence at $\sqrt{s} = 2.41$ GeV and 2.66 GeV. The evidence of the correlations in various waves exists also in the phase shift analysis performed for this reaction by I. Strakovsky and R. Arndt [Phys.Rev.,C48,1926(1993)].

The results of our measurements of the vector analyzing power iT_{11} in the reaction $\pi\vec{d} \rightarrow pp$ at the energies 350 MeV, 400 MeV and 450 MeV are presented in Figs. 7,8. The results for 350 MeV are in good accordance with those obtained at 325 MeV at PSI. The data obtained at 400 MeV and, especially, at 450 MeV ($\sqrt{s} \simeq 2.4$ GeV) indicate a steep rise of iT_{11} up to the values close to the theoretically predicted limit. Lacking an adequate theoretical description of the process under study at the energies above 350 MeV, we could only compare our data with the results of the amplitude analysis carried out at PNPI by I. Strakovsky. Later on, our results were used as a part of the input data in the phase shift analysis effectuated at the Virginia Polytechnic Institute by R. Arndt et al.

The predictions of the VPI phase shift analysis (SAID program), as well as the results of calculations with the corrected formulae, are also presented in the figures. A fairly good agreement was reached between the calculations and the experimental data at 350 MeV and 400 MeV. The results obtained at 450 MeV fail to be described in the standard framework, without implementation of some resonance contributions.

The presented data are for the moment the only results of measuring the vector analyzing power iT_{11} in the reaction $\pi\vec{d} \rightarrow pp$ at the energy of 350 MeV and above. They indicate a marked rise of iT_{11} in the energy region under study and are still waiting for an unambiguous explanation. The comparison of our data with the results of measurements of the differential cross sections and analyzing power in the inverse channel $pp \rightarrow d\pi^+$ at $\sqrt{s} = 2.4$ GeV confirms the manifestation of some peculiarity connected apparently to the behaviour of the $^1G_4$-wave in pp scattering. The nature of this peculiarity has been discussed many times, as a possible indication of existence of the dibaryon resonances or as the threshold phenomenon in the $N\Delta$ excitation spectrum where this feature can be related to the $L_{N\Delta} = 2$ state.

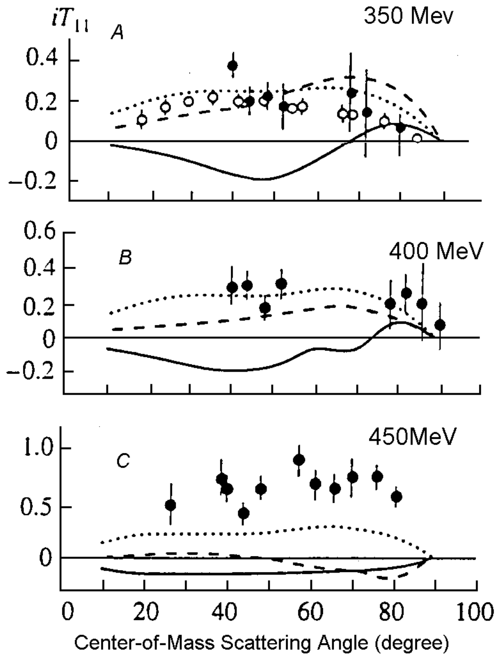


Fig. 7. Vector analyzing power iT_{11} for the reaction $\pi\vec{d} \to pp$ at $T_\pi = 350$ MeV, 400 MeV, 450 MeV. Solid and dashed curves are the amplitude analysis by I.Strakovsky [Yad. Fiz., 40, 429 (1984)] and by M.G.Ryskin [private comm.]. Dotted curve is the prediction of the phase shift analysis VPI–95.

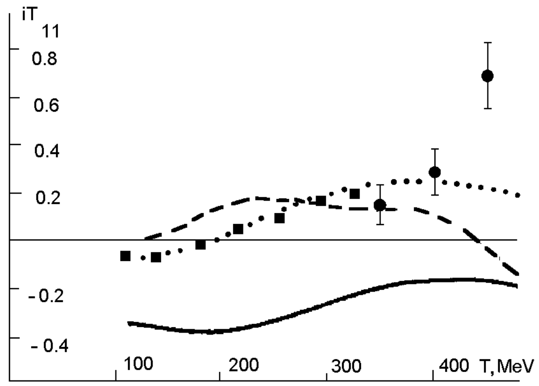


Fig. 8. Energy dependence of the vector analyzing power iT_{11} for the reaction $\pi\vec{d} \to pp$ at the scattering angle $\theta = 50°$. Full squares are PSI results, full dots are PNPI data. Other notations are as in Fig. 7.

Summing up we can say that the results obtained at PNPI in studying the nucleon-nucleon interactions at intermediate energies were a substantial contribution to the world data in this field making a base for the analysis of the *pp* interaction both in the elastic and inelastic reaction channels. Based on these data, a phase shift analysis was carried out allowing to correct and update the earlier results. The data obtained reveal some peculiarities in the energy dependence of the polarization parameters which can be related to the $^1D_3$, $^3P_{0,1,2}$, $^3F_3$, and $^1G_4$ resonances.

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