STUDY OF PION-NUCLEON SCATTERING IN THE REGION OF πN RESONANCES

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Introduction

The program "Baryon spectroscopy with π-mesons in the energy range from 300 to 2000 MeV" is under way at PNPI from 1970. In the period after 1989 investigations are being carried out in collaboration with Institute for Experimental and Theoretical Physics (Moscow), the University of California at Los Angeles (USA) and Abilene Christian University (USA).

It is assumed now that the quantum chromodynamics (QCD) is the best candidate for the theory of strong interactions. Having a noticeable success at extremely high energies, QCD has not been shown to describe adequately all those physical states which are observed in nature. Due to difficulties arising in attempts to use QCD at distances, where the perturbation theory is not applicable, and because of a lack of understanding the confinement mechanism we need till now to rely upon different models in baryon physics. There exist many quark models of the structure of the baryons, and a task of physicists is to choose the correct one among them. Baryon spectroscopy based on an analysis of experimental data presents an excellent multiparameter test for checking these quark models.

It is known that all information about πN amplitudes and characteristics (masses, widths, decay modes) of pion-nucleon resonances is obtained only from phase shift analyses of experimental data. Till now the spectroscopy of nonstrange baryons was based on three global phase shift analyses performed by groups from Karlsruhe–Helsinki (KH, 1979), Carnegie-Mellon University and Lawrence Berkeley Laboratory (CMU–LBL, 1980) and Virginia Polytechnic Institute (VPI, 1995). The phase shift analyses KH and CMU–LBL were performed more than ten years ago using experimental data-base existed before 1977. These analyses resulted in essentially diverse characteristics of πN resonances. In the mass range up to 2400 MeV the manifestation of 43 resonances was observed. The phase shift analysis VPI was completed later. Some of its results agree with neither KH no CMU–LBL. Discrepancies between results of different phase shift analyses are due mostly to incompleteness and nonsystematic character of used experimental data and to their insufficient accuracy. The goal of the experimental baryon spectroscopy is to make up for this deficiency.

PNPI pion channel

For studying πp interactions a pion channel [1] allowing to get intense beams of π^+ and π^- mesons with energies up to 650 MeV was built at PNPI. At present, pion beams of comparable intensity in the above energy range exist only at Brookhaven National Laboratory (USA) and at KEK (Japan). Last years the PNPI pion channel has been modernized. A hodoscope of 8 narrow vertical scintillation counters was placed in a dispersive plane of the channel. It allowed to improve the momentum resolution from 6% to 1.5% (FWHM) without a loss of total intensity. A scheme of the PNPI pion channel is presented in Fig. 1 – together with a setup (described in the next section) for measuring the differential cross sections of $\pi^\pm p$ elastic scattering. Besides experiments on studying πp scattering, an investigation of the process $\pi^+ d \to pp$ [2] and a test of charge symmetry in $\pi^\pm d$ elastic scattering at the energy $T_\pi = 417$ MeV [3] were performed in the PNPI pion channel.

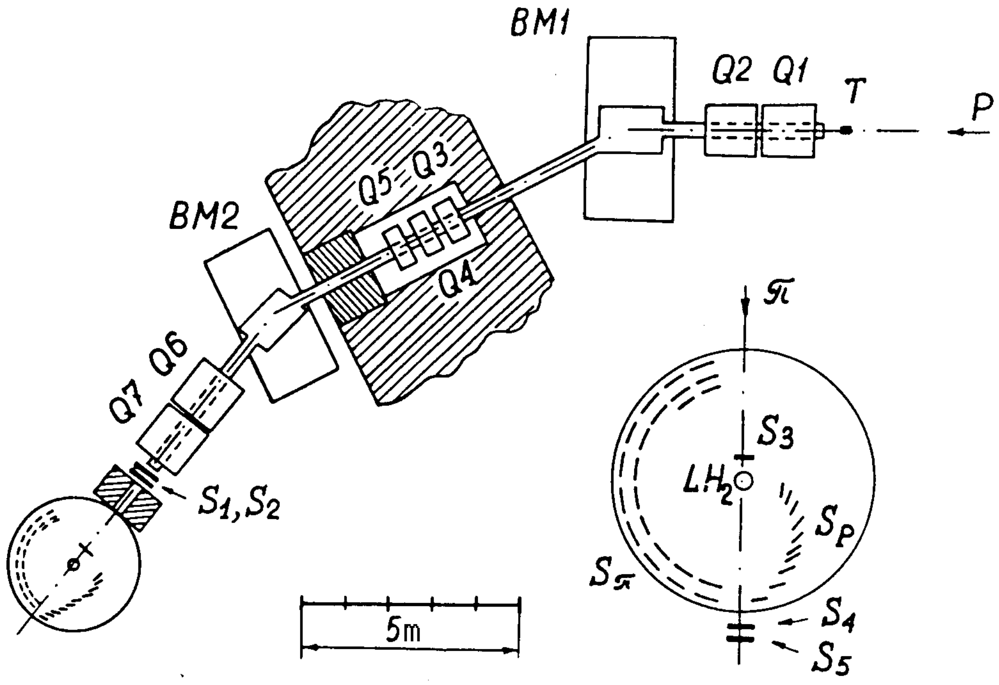

Fig. 1. Scheme of the PNPI pion channel together with the hodoscope setup placed in the focus of the channel (enlarged view of this setup is shown in the right lower corner). BM1–BM2 – bending magnets; Q1–Q7 – quadrupole lenses; S1–S5, S_p, S_π – scintillation counters; T – meson-production target; LH_2 – liquid hydrogen target.

Differential cross sections of $\pi^\pm p$ elastic scattering

At PNPI, the differential cross sections (DCS) of $\pi^+ p$ and $\pi^- p$ elastic scattering were measured with a high accuracy at twelve energies of incident pions in the range from 300 to 640 MeV. More than three hundreds new values of DCS were obtained with a typical statistical error of 2–5% and a systematic uncertainty about 2.5%. Pions of the incident beam were scattered on a liquid hydrogen target located in the centre of the hodoscope setup. This ten-channel setup consisted of 40 scintillation counters (Fig. 1). Coincidences between the scattered pions and recoil protons as well as the time-of-flight criterion were used. Results obtained at PNPI for $\pi^+ p$ and $\pi^- p$ elastic scattering [4] are presented in Fig. 2. These results were confirmed later by the data of the Rutherford Laboratory (UK) and the Los Alamos Meson Physics Facility (USA).

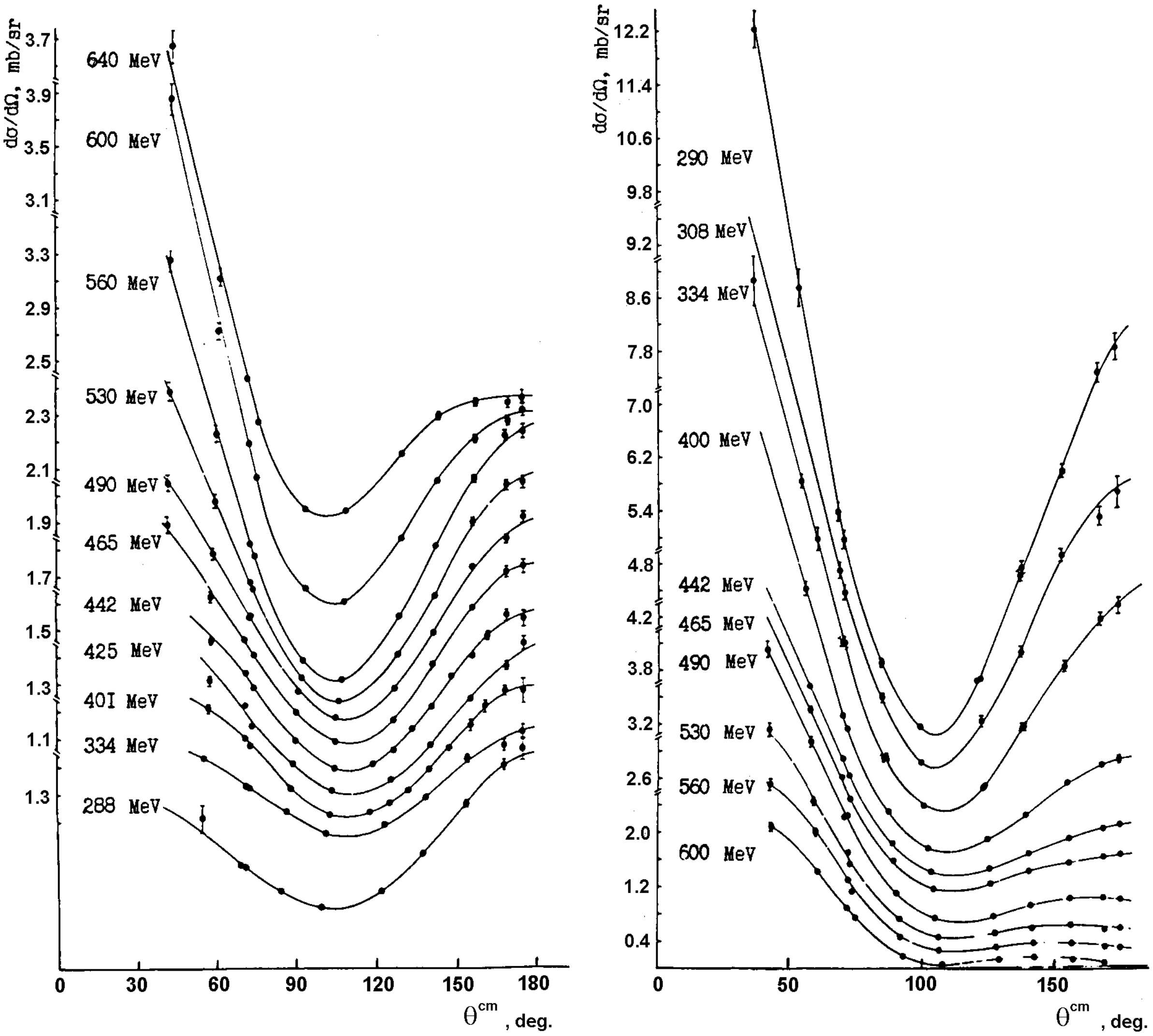

Fig. 2. Results of measurement of the differential cross sections of $\pi^- p$ (on the left) and $\pi^+ p$ (on the right) elastic scattering.

The polarization parameter P

The polarization parameter P was determined both by a double scattering method and by means of measuring an asymmetry of πp scattering in experiments on a polarized target – see Fig.3. The experiments were carried out at seven energies for $\pi^+ p$ and $\pi^- p$ elastic scattering [5,6]. Several arrays of magnetostrictive spark chambers (four chambers in each array) were used for reconstructing trajectories of particles after scattering. The precise reconstruction of kinematics of πp scattering allowed to select the elastic scattering events from the background. Results of measurements are shown in Figs. 4,5. Having used PNPI data on DCS$^\pm$ and $P^\pm$, we calculated [6] bounds for the parameter P^0 in the reaction $\pi^- p \rightarrow \pi^0 n$, which are defined by the equations of the isospin conservation. A comparison of these bounds with the values of P^0 measured at LAMPF has shown that there was no experimental evidence of the isospin violation.

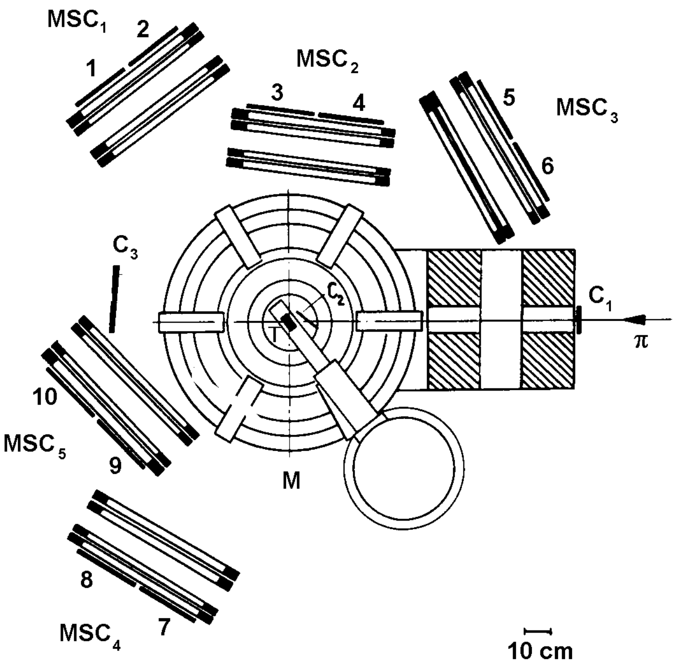

Fig. 3. Scheme of setup for measurement of the polarization parameter P. T – polarized target; M – magnet of the polarized target; MSC_1–MSC_5 – magnetostrictive spark chambers; C_1–C_3 – monitor scintillation counters; 1–10 – counters for triggering spark chambers.

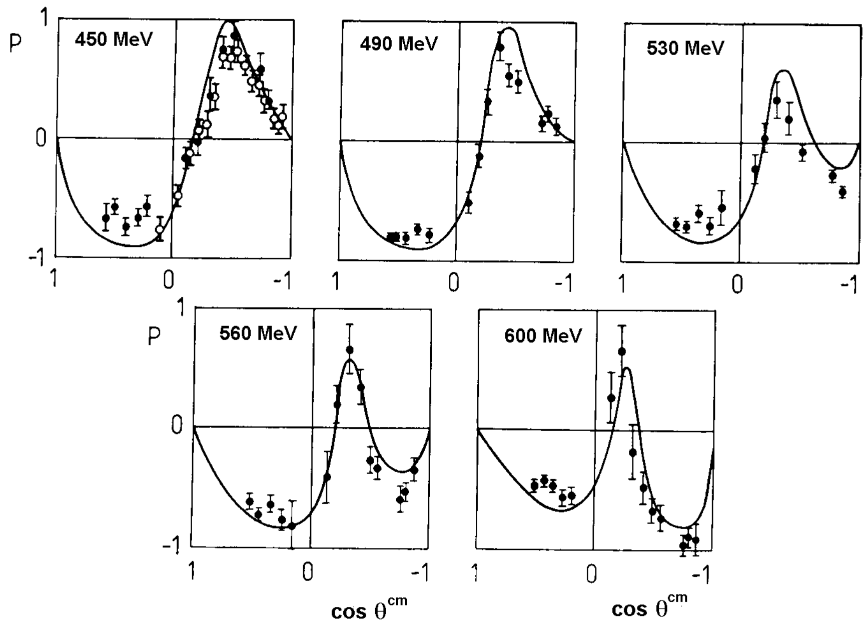

Fig. 4. Results of measurement of the polarization parameter P in π^-p elastic scattering performed by the double scattering method (∘) and using the polarized target (•). Shown by curves are the predictions of the phase shift analysis KH.

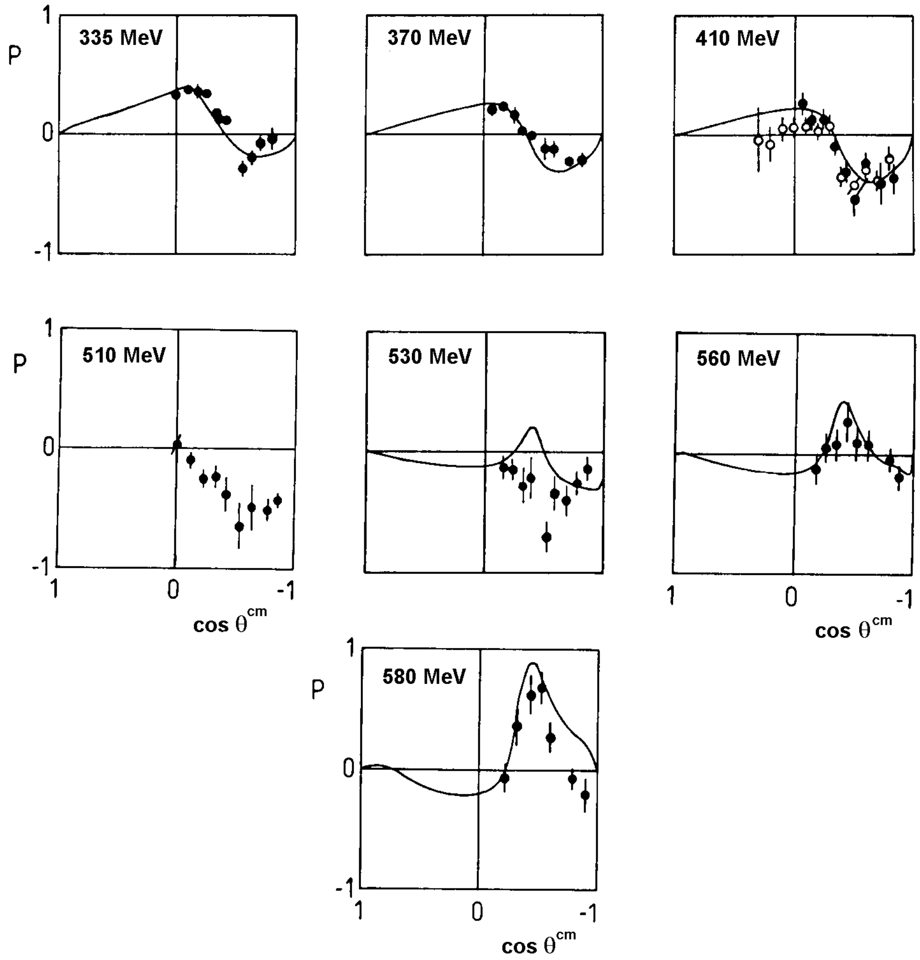

Fig. 5. The same as in Fig. 4 but for π^+p elastic scattering.

The spin rotation parameters A and R

Only measurements of the spin rotation parameters permit to remove discrete ambiguities arising in the course of phase shift analyses. This experiment requires development of a special type of polarized proton target [7] with a polarization vector lying in the horizontal plane. Scattering of the incident pions on such a target results in the recoil protons polarization which value P_f is connected with the parameters A and R. Experimentally the P_f value is determined by measuring the asymmetry of the secondary scattering of the recoil protons by nuclei of a substance (usually carbon) with the known analyzing power. To perform such measurements, a multiplate carbon polarimeter was built at PNPI. It consists of optical spark chambers with graphite electrodes. The special automatic television system was designed and created at PNPI for performing filmless read-out from these optical chambers. The polarimeter with the TV system provides the accuracy of 0.8° in measuring the secondary scattering angle and of 8 MeV in determining the kinetic energy of the recoil protons in the second vertex. Arrays of magnetostrictive spark chambers were used for determining trajectories of the scattered pions. The experimental layout is shown in Fig. 6.

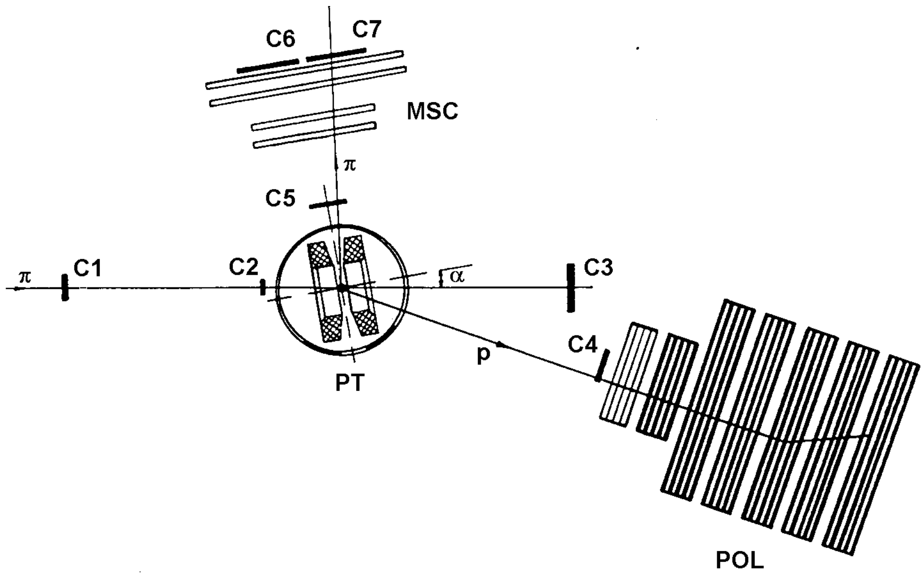

Fig. 6. Setup for measurement of the spin rotation parameters. PT – polarized target; POL – polarimeter made of optical spark chambers with television read-out; MSC – magnetostrictive spark chambers; C1–C7 – scintillation counters.

Results of measurements of the spin rotation parameters A and R in $\pi^- p$ elastic scattering [8] are shown in Fig. 7. The use of obtained data in the new phase shift analysis PNPI-94 allowed to find the unique solution in the energy range up to 600 MeV. Angular dependences of the spin rotation parameters calculated on the base of this solution are shown by curves in Fig. 7.

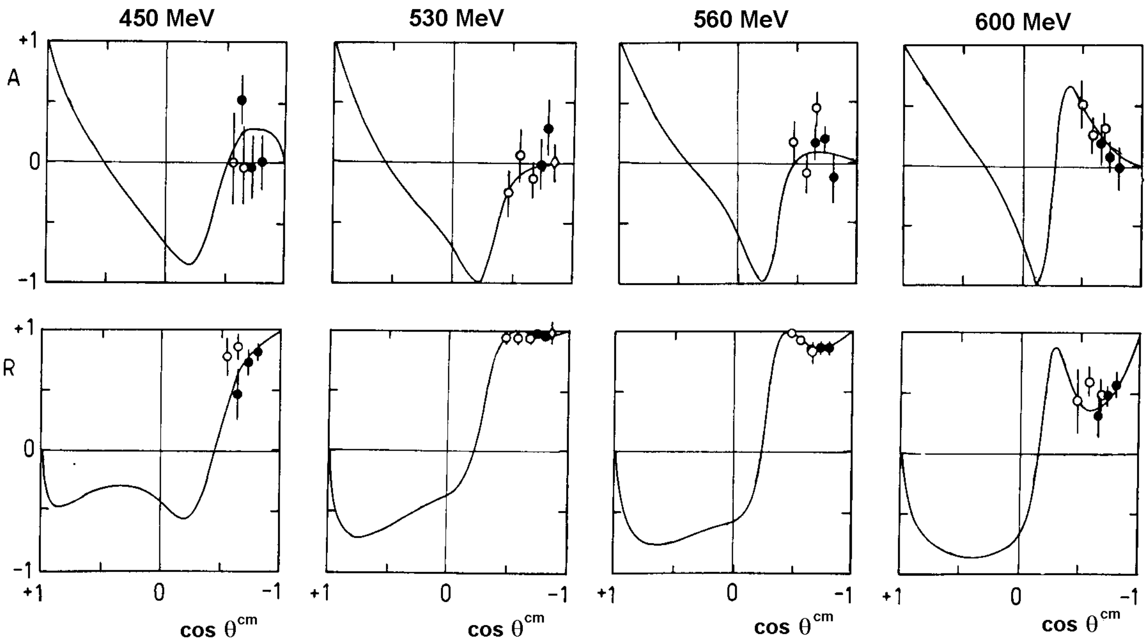

Fig. 7. Results of measurement of the spin rotation parameters in elastic $\pi^- p$ scattering. Shown by curves are angular dependences calculated on the base of the phase shift analysis PNPI-94.

The list of all experimental results obtained at PNPI is given in Table 1.

Table 1

DCS^-		DCS^+		P^-		P^+		A^-, R^-	
T_π, MeV	Number of exp. points	T_π, MeV	Number of exp. points	T_π, MeV	Number of exp. points	T_π, MeV	Number of exp. points	T_π, MeV	Number of exp. points
288	10	277	9	450	12	335	10	450	10
344	10	290	12	490	14	370	9	530	12
401	14	293	17	530	12	410	9	560	12
425	10	308	9	560	14	510	10	600	12
442	14	334	16	600	14	530	9		
465	11	400	10			560	8		
490	11	442	10			580	8		
530	11	466	10						
560	11	490	11						
600	11	530	11						
640	11	560	13						
		600	12						

Phase shift analysis PNPI-94

While performing the phase shift analysis PNPI–94 [9], the last experimental data obtained at PNPI and LAMPF were used. A principally new feature of this analysis was employing the generator of discrete ambiguities, which has made the search for a unique solution more effective. Another peculiarity was that the analysis did not imply the assumption of charge symmetry of πN partial amplitudes.

The phase shift analysis (PSA) PNPI-94 resulted in obtaining the most precise amplitudes for energies of the incident pions from 160 to 600 MeV (corresponding values of centre-of-mass energy $\sqrt{s} = 1210 - 1510$ MeV). These amplitudes differ in many essential features from the amplitudes obtained in the "old" PSAs KH and CMU–LBL.

The new precise amplitudes of πp scattering can be used for both the description of pion-nucleus interaction and interpretation of pion photoproduction experimental data.

One of the most interesting results obtained in the PSA PNPI-94 is an observation of charge splitting in the P_{33} phase shifts; quantitatively this effect can be characterized by the difference $\delta_{33}^{++} - \delta_{33}^{0}$. This difference depends on energy and varies from +2 degrees at $T_\pi = 200$ MeV to −2 degrees at $T_\pi = 450$ MeV changing a sign at $T_\pi = 350$ MeV – see Fig. 8. Shown by curve in Fig. 8 are results of fitting made taking into account the Breit-Wigner resonance term and the nonresonance background. Following values for the masses (M) and widths (Γ) of the P_{33} resonances were obtained after such parametrization:

$$M^0 = 1233.1 \pm 0.3 \text{ MeV}, \qquad M^{++} = 1230.5 \pm 0.2 \text{ MeV},$$
$$M^0 - M^{++} = 2.6 \pm 0.4 \text{ MeV}, \quad \Gamma^0 - \Gamma^{++} = 5.1 \pm 1.0 \text{ MeV}.$$

These values are very close to those obtained earlier on the base of analysis of total cross section data (E.Pedroni et al., 1978).

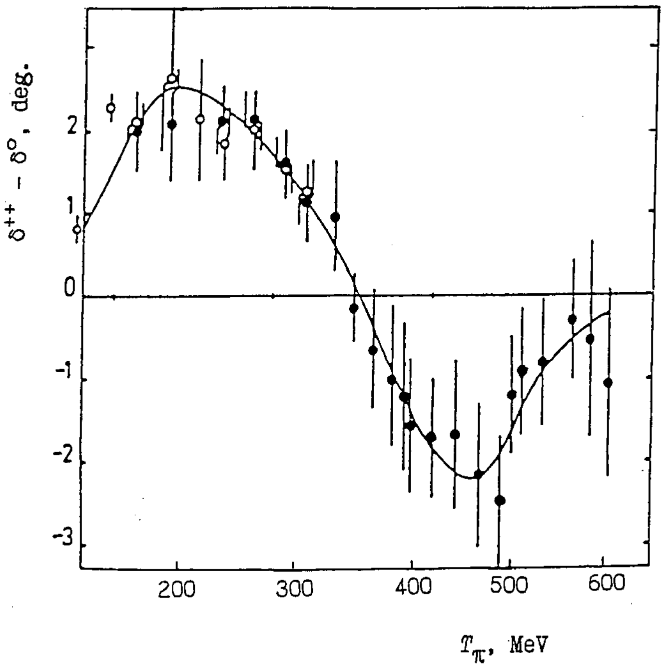

Fig. 8. Energy dependence of the difference between P_{33} phase shifts $\delta_{33}^{++} - \delta_{33}^{0}$ obtained as a result of the phase shift analysis PNPI-94 (•) and by D.Bugg et al (∘).

Baryon spectroscopy at pion energies above 1000 MeV

The most of pion-nucleon resonances are located at energies above 1000 MeV. Many of them have status three, two or even one star. It means that the existence of such resonances is only "probable" and their characteristics are still undefined. These resonances were found in the phase shift analyses KH and CMU–LBL which have been completed before new experimental πp scattering data appeared, in particular prior to measurements of the spin rotation parameters.

Spin rotation data obtained recently by the collaboration PNPI–ITEP [10] for πp elastic scattering in the region from 1000 to 2000 MeV contradict to the predictions of the phase shift analyses KH and CMU–LBL. It leads to a conclusion that a new global phase shift analysis of πp scattering is needed in the energy range up to 2000 MeV with the aim to revise the characteristics of πN resonances presented in Tables of the Particle Data Group. For performing such analysis not only the spin rotation parameters A and R are required, but also new precise data on DCS of $\pi^- p$ interactions with neutral particles in the final state ($\pi^- p \to \pi^0 n$; $\pi^- p \to \eta n$; $\pi^- p \to \pi^0 \pi^0 n$ etc.) are needed. Experimental program aiming at obtaining such data is now under way at PNPI at energies up to 600 MeV and at BNL at energies up to 1800 MeV (the Crystal Ball Collaboration with participation of PNPI physicists). The multichannel 4π detector "Crystal Ball" consisting of 672 crystals NaI(Tl) is used at BNL for detecting gammas and neutral mesons.

Results obtained by the collaboration PNPI–ITEP are shown in Fig. 9. The experiment was carried out at the positive pions energy of 1300 MeV. The setup consisted of a longitudinally polarized proton target, a multiplate polarimeter made of optical spark chambers with the television read-out, and magnetostrictive spark chambers. Results of the experiment agree well with the predictions of the phase shift analysis VPI and contradict to the phase shift analyses

KH and CMU–LBL. Since all presented in PDG Tables characteristics of πN resonances are obtained on the base of just the analyses KH and CMU–LBL which seem to be not entirely correct in the light of the last experimental results, it is necessary to revise and specify these fundamental constants by means of performing a new phase shift analysis.

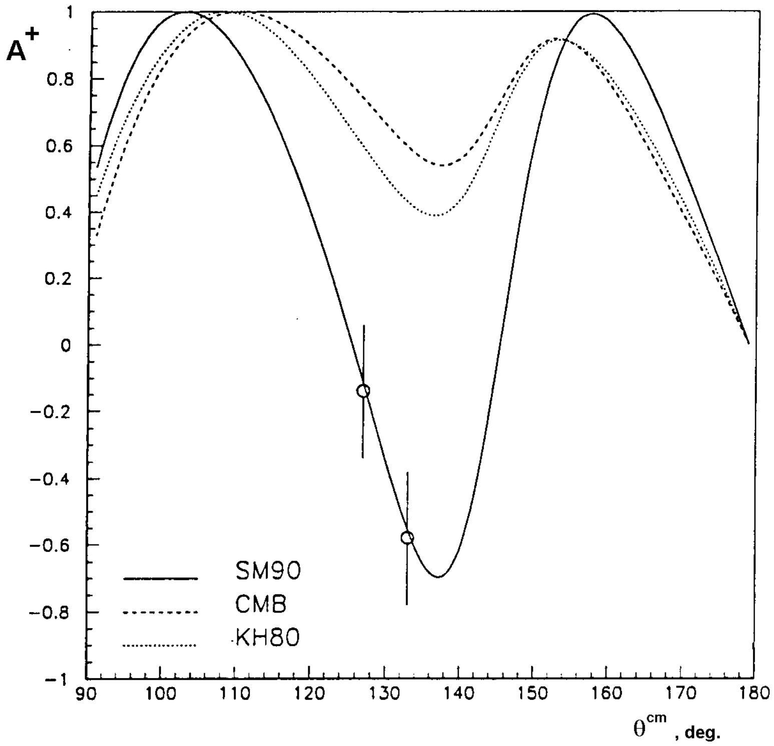

Fig. 9. Results of measurement of the spin rotation parameter A in $\pi^+ p$ elastic scattering at the energy of 1300 MeV.

Summary

1. The baryon spectroscopy gives the possibility to extract the fundamental constants – the characteristics of πN resonances – from experimental data-base using a procedure of a phase shift analysis.

2. The characteristics of πN resonances are used for checking quark models and can serve as a multiparameter test for the quantum chromodynamics.

3. The charge splitting in the P_{33} partial amplitude reflecting the quark structure of πN resonances is found at PNPI as a result of the phase shift analysis PNPI-94.

4. For the first time in the world the spin rotation data were obtained at 1300 MeV by the collaboration PNPI–ITEP. These data contradict to the phase shift analyses KH and CMU–LBL and cast doubt on the characteristics of πN resonances determined on the base of these analyses.

5. New precise and systematic data on the spin rotation parameters A and R for $\pi^{\pm}p$ elastic scattering and on the differential cross sections for the processes $\pi^-p \to \pi^0 n$, $\pi^-p \to \eta n$, $\pi^-p \to \pi^0\pi^0 n$ in the energy range from 600 to 2000 MeV are needed for performing a new phase shift analysis in this range with the aim to obtain new characteristics of πN resonances.

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