Eur. Phys. J. C 45, 383–386 (2006)
Digital Object Identifier (DOI) 10.1140/epjc/s2005-02454-y

THE EUROPEAN PHYSICAL JOURNAL C

Measurement of the spin rotation parameter A in the elastic pion-proton scattering at 1.43 GeV/c

I.G. Alekseev[1,a], N.A. Bazhanov[2], P.E. Budkovsky[1], E.I. Bunyatova[2], V.P. Kanavets[1], A.I. Kovalev[3], L.I. Koroleva[1], S.P. Kruglov[3], B.V. Morozov[1], V.M. Nesterov[1], D.V. Novinsky[3], V.V. Ryltsov[1], V.A. Shchedrov[3], A.D. Sulimov[1], V.V. Sumachev[3], D.N. Svirida[1], V.Yu. Trautman[3], V.V. Zhurkin[1]

[1] Institute for Theoretical and Experimental Physics, Moscow, 117218, Russia
[2] Joint Institute for Nuclear Research, Dubna, Moscow area, 141980, Russia
[3] Petersburg Nuclear Physics Institute, Gatchina, Leningrad district, 188300, Russia

Received: 6 October 2005 / Revised version: 11 November 2005 /
Published online: 21 December 2005 –

Abstract. The ITEP-PNPI collaboration presents new results of the measurements of the spin rotation parameter A in the elastic scattering of negative pions on protons at $P_{beam} = 1.43\,\text{GeV/c}$. The results are compared to the predictions of several partial wave analyses. The experiment was performed at the ITEP proton synchrotron, Moscow.

1 Introduction

The present experiment is the last in the series of spin rotation parameter measurements performed by the ITEP-PNPI collaboration during the last decade [1]. The main goal of these studies was to enrich the experimental database of partial wave analyses (PWA) with qualitatively new information on the spin rotation parameters, which have never been measured in the incident momentum interval under consideration. The momentum range (0.8–2.1) GeV/c available at the ITEP beam-line is very important for the baryon spectroscopy because it contains nearly 65% of the known light quark resonances. There are three clusters of resonances in this region corresponding to the peaks in the pion-proton total elastic cross-section. The current interest to the light baryon spectroscopy is enhanced by several experimental observations which do not well fit the constituent quark models. As examples one can mention the existence of resonance clusters with masses 1.7 and $1.9\,\text{GeV/c}^2$, the presence of the negative parity resonances in the cluster at $\sqrt{s} = 1.9\,\text{GeV}$, indications for the parity doublets in both mentioned clusters and "missing resonances" problem near $\sqrt{s} = 2.0\,\text{GeV}$. At the same time the current status of the experimental light baryon spectroscopy is far from satisfactory.

Partial wave analysis is the most powerful tool of the baryon spectroscopy. Yet the data on the resonances presented even in the latest versions of RPP [2] are based mainly on the two PWA: KH80 [3] and CMB [4], both performed more than two decades ago. However more recent analysis by VPI group [5] did not reveal a certain number of resonances: $D_{13}(1700)$, $S_{31}(1900)$, $P_{33}(1920)$, $D_{33}(1940)$. In the recent years GWU-VPI group continued the PWA development [6].

PWA solution two-fold ambiguities lead to the significant discrepancies in the predictions of various analyses for the spin rotation parameters in certain kinematic regions. Since the measurement of the spin rotation parameters is the only source of the experimental information on the relative phase of the transverse scattering amplitude, it appears to be an unavoidable step to the unambiguous reconstruction of the pion-proton elastic scattering amplitude.

The present experiment is performed at the c.m. energy 1.9 GeV corresponding to the I=3/2 resonance cluster with complicated structure.

2 Formalism

The meaning of the A and R spin rotation measurement becomes clear from the expressions below, where the observables are expressed in terms of the transverse amplitudes f^+ and f^-:

$$\begin{aligned}
\sigma &= |f^+|^2 + |f^-|^2\,, \\
P \cdot \sigma &= |f^+|^2 - |f^-|^2\,, \\
A \cdot \sigma &= \mathrm{Re}(f^+ f^{-*}) \cdot \sin(\theta_{\mathrm{cm}} - \theta_{\mathrm{lab}}) \\
&\quad - \mathrm{Im}(f^+ f^{-*}) \cdot \cos(\theta_{\mathrm{cm}} - \theta_{\mathrm{lab}})\,, \\
R \cdot \sigma &= \mathrm{Re}(f^+ f^{-*}) \cdot \cos(\theta_{\mathrm{cm}} - \theta_{\mathrm{lab}}) \\
&\quad + \mathrm{Im}(f^+ f^{-*}) \cdot \sin(\theta_{\mathrm{cm}} - \theta_{\mathrm{lab}})\,,
\end{aligned} \tag{1}$$

the polarization parameters obeying the relation:

$$P^2 + A^2 + R^2 = 1\,. \tag{2}$$

[a] e-mail: igor.alekseev@itep.ru

In turn the transverse amplitudes correspond to the amplitudes of the scattering matrix $M = g + ih(\boldsymbol{\sigma} \cdot \boldsymbol{n})$ by simple relations: $f^+ = g + ih$, $f^- = g - ih$. It follows from (1), (2) that differential cross-section and normal polarization measurements allow to reconstruct only the *absolute values* of the transverse amplitudes, while their relative phase may be obtained only from the spin rotation parameter measurement.

3 Experiment layout

Figure 1 shows the idea of the experiment. Two components $\boldsymbol{P}$ and $\boldsymbol{A}$ of the recoil proton polarization are analyzed by its scattering on a carbon filter C, while the proton target polarization is measured by means of NMR. In the present experiment so-called A-geometry is used, i.e. the target polarization vector $\boldsymbol{P}_t$ is collinear to the pion beam direction. In this case the transverse component of the recoil proton polarization in the scattering plane is $\boldsymbol{A} = P_t \cdot A$, where P_t is the value of the target polarization, A – spin rotation parameter. The component perpendicular to the scattering plane is equal to the normal polarization P. Horizontal (vertical) component of the recoil proton polarization is determined by the measurement of the vertical A_A (horizontal A_P) asymmetry of the scattering on carbon.

The setup is located on the universal two-focus beamline of the ITEP synchrotron. The beam-line can provide pions of both signs and/or protons in the momentum range (0.8–2.1) GeV/c with the resolution $\Delta p/p = \pm 1.8\%$. The size of the beam spot in the target region is close to 30 mm FWHM in both directions.

The basic elements of the setup (Fig. 2) are: the longitudinally polarized proton target inside the superconducting solenoid, thick block carbon polarimeter, sets of the wire chambers for the tracking of the incident and scattered particles and the TOF system for the beam particle identification.

Evaporation type ^{3}He cryostat maintains 0.55 K in the 20 cm^3 target container with propanediole ($C_3H_8O_2$ doped with Cr^V complexes), while the proton polarization is achieved by the dynamic nuclear orientation in the 2.5 T magnetic field of a Helmholtz pair of superconducting coils. The polarization value is (70–80)% with the measurement uncertainty 1.5%, its sign reversed every 12 hours to suppress the false asymmetries.

The block carbon polarimeter has the thickness of 36.5 g/cm^2. Since the uncertainty of the analyzing power directly contributes to the systematic error of the measured

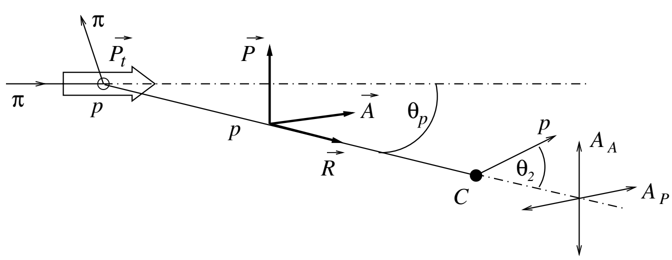

Fig. 1. The A experiment idea

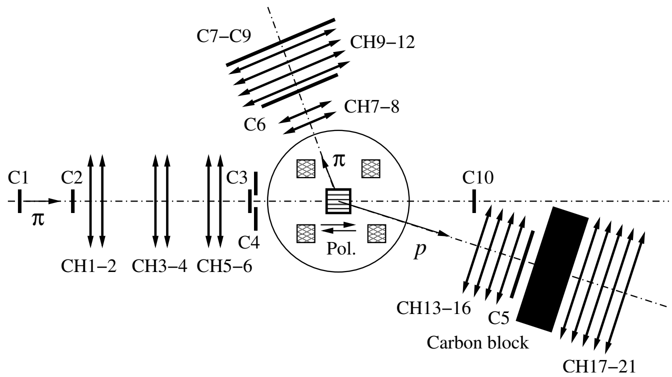

Fig. 2. Experiment layout

A-parameter, the polarimeter was calibrated in advance using the polarized beam of protons elastically scattered from the internal accelerator targets (polyethylene or carbon). The carbon analyzing power was measured as a function of proton momentum and scattering angle with the ≈4% error of its average in the angular interval of interest.

4 Data processing

The data processing included the following main steps:

- selection of the elastic scattering events on the free protons of the polarized target;
- selection of the recoil proton on carbon scattering events in the angular interval (3–20)°;
- application of the maximum likelihood method to determine A and P parameters.

Elastic scattering events were selected by the angular correlations between the scattered pion and the recoil proton (polar angles and co-planarity). United χ^2 criteria which accounts for both correlations was:

$$\chi^2 = (\Delta\theta/\sigma_\theta)^2 + (\Delta\varphi/\sigma_\varphi)^2 ,$$

where $\Delta\varphi$ and $\Delta\theta$ are the deviations from the elastic kinematics, σ_φ and σ_θ – the widths of the corresponding distributions. Figure 3 shows the χ^2- distributions for the events from the polarized target and its carbon replacement. One can see that the quasi-elastic scattering background under the elastic peak can be properly estimated by the linear extrapolation of the χ^2-distribution from the background region. The shape of the elastic histogram is consistent with the theoretical χ^2-distribution for 2 degrees of freedom. Elastic events were selected by applying the cut for their χ^2 distribution. The background fraction and the loss of the elastic events depend on the χ^2_{cut} cut value. Both dependencies are shown in the top right insertion in Fig. 3. The cut at $\chi^2_{cut} = 8$ was chosen in the present experiment, resulting in the quasi-elastic background fraction of 9% and ≈10% loss of the events.

At the next step of the data processing the vertex of the proton-carbon interaction was determined together with the scattering angle. Events in the angular region of high pC analyzing power (3–20)°were selected for further processing.

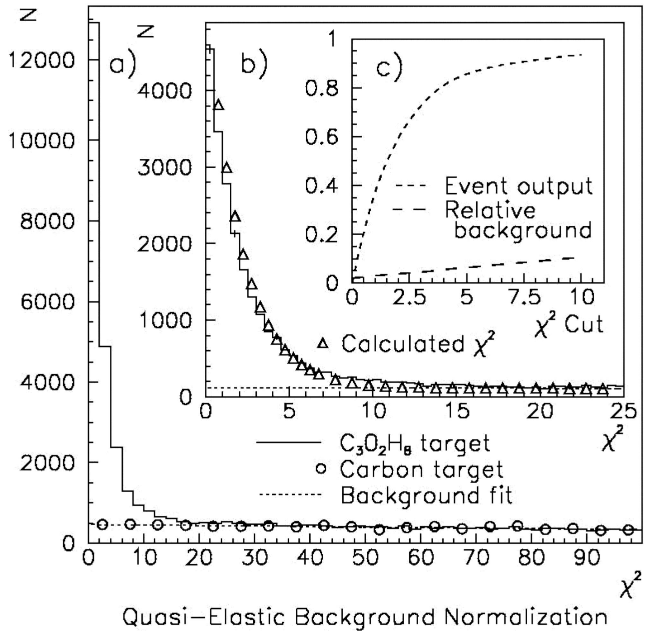

Fig. 3. χ^2 distribution for the elastic and quasi-elastic events; insertion **b**: the same but with smaller vertical scale, triangles designate the theoretical χ^2 distribution; insertion **c**: fractions of the background (long dashes) and of the event throughput (short dashes) dependent on χ^2_{cut} value

Polarization parameters A and P were chosen as independent variables for the maximum likelihood method to describe the azimuthal asymmetries of the proton-carbon scattering. The statistical material was divided into 3 subintervals in c.m. scattering angle. Average parameters over the whole angular range of the measurement were also calculated. The maximum likelihood function $L(\boldsymbol{P}, \boldsymbol{B})$ was taken in the following form:

$$\ln L(\boldsymbol{P}, \boldsymbol{B}) = \sum_{i=1}^{N} k_i \ln\left(1 + a_{pC}(\theta_{2i}, T_i) \cdot \boldsymbol{n}_2[(1-f)\boldsymbol{P}'_i + f\boldsymbol{B}'_i]\right) , \quad (3)$$

where

- $\boldsymbol{P}$ and $\boldsymbol{P}'$ – vectors of the polarization for the recoil proton from the elastic scattering events: in the polarized target and in the carbon block with the account of the spin motion in the magnetic field of the target;
- $\boldsymbol{B}$ and $\boldsymbol{B}'$ – similar values for the protons, quasi-elastically scattered in the polarized target;
- $\boldsymbol{n}_2$ – unit vector to the second scattering plane;
- f – fraction of the quasi-elastic background;
- $a_{pC}(\theta_2, T)$ – analyzing power of the pC scattering as a function of the scattering angle and of the proton kinetic energy at the pC-vertex;
- $k = \eta^{-1}(\varphi_2)$, where $\eta(\varphi_2)$ is the average polarimeter efficiency as a function of the second scattering azimuthal angle.

The vector $\boldsymbol{P}$ depends on the first scattering angle, on the target polarization and on the values of A and P parameters. The vector $\boldsymbol{B}$ is normal to the first scattering plane.

Table 1. Polarization parameters A and P in the $\pi^- p$ elastic scattering at 1.43 GeV/c

$\theta_{\rm cm}$, deg range	mean	A	P
155–162.2	160.4	-0.152 ± 0.251	-1.150 ± 0.166
162.2–165.6	163.9	-0.360 ± 0.260	-1.039 ± 0.170
165.6–172.0	167.4	-0.131 ± 0.264	-0.501 ± 0.175
155–172		-0.219 ± 0.149	-0.91 ± 0.10

Using the statistical sample corresponding to an unpolarized target the polarimeter efficiency can be expressed in the following form:

$$\eta(\varphi_2) = \frac{(N^+ + N^-)(|P^+| + |P^-|)}{4(1+\cos\varphi_2|\boldsymbol{P}'_N|)}\left(\frac{D^+(\varphi_2)}{N^+|P^+|} + \frac{D^-(\varphi_2)}{N^-|P^-|}\right) , \quad (4)$$

where signs in the superscripts correspond to the states of the polarized target and

- $D^+(\varphi_2)$, $D^-(\varphi_2)$ – densities of the azimuthal angle distributions;
- N^+, N^- – numbers of events;
- P^+, P^- – values of the target polarization;
- $\boldsymbol{P}'_N$ is the result of the transformation of the vector $\boldsymbol{P}_N = (1-f)\boldsymbol{P} + f\boldsymbol{B} = [(1-f)P + fB] \cdot \boldsymbol{n}_1$ and $\boldsymbol{n}_1$ is the unit vector normal to the first scattering plane.

For the efficiency calculations the value of P parameter may be taken from the existing experimental data or from the PWA predictions. Moreover, one can see from (4) that in the direction of the asymmetry, corresponding to the A parameter measurement (on average $\varphi_2 = \pm\pi/2$) the efficiency does not depend on the chosen value of P. Thus the parameter A can be determined unambiguously and with the correction account for the instrumental asymmetry. Contrary to that, there are no tools to compensate for the instrumental asymmetries for the P parameter determination.

In real efficiency calculations the value of P parameter was taken from the predictions of FA02 analysis [6] and averaged over the angular acceptance of the setup $155° < \theta_{\rm cm} < 172°$ resulting in the value of $< P >= -0.87$ (compare with our result in Table 1 below). The same efficiency function was used for all three angular subintervals.

5 Results and systematic errors

The resulting data for A and P parameters are summarized in Table 1 and shown in Fig. 4.

To check the independence of the fitted value of A parameter on the choice of P value for the efficiency calculations, it was varied in the range $-(0.7–0.95)$ in each of the three subintervals. The corresponding changes of A parameter were within 0.01.

The most important sources of the A parameter systematic errors are the uncertainties in the polarimeter ana-

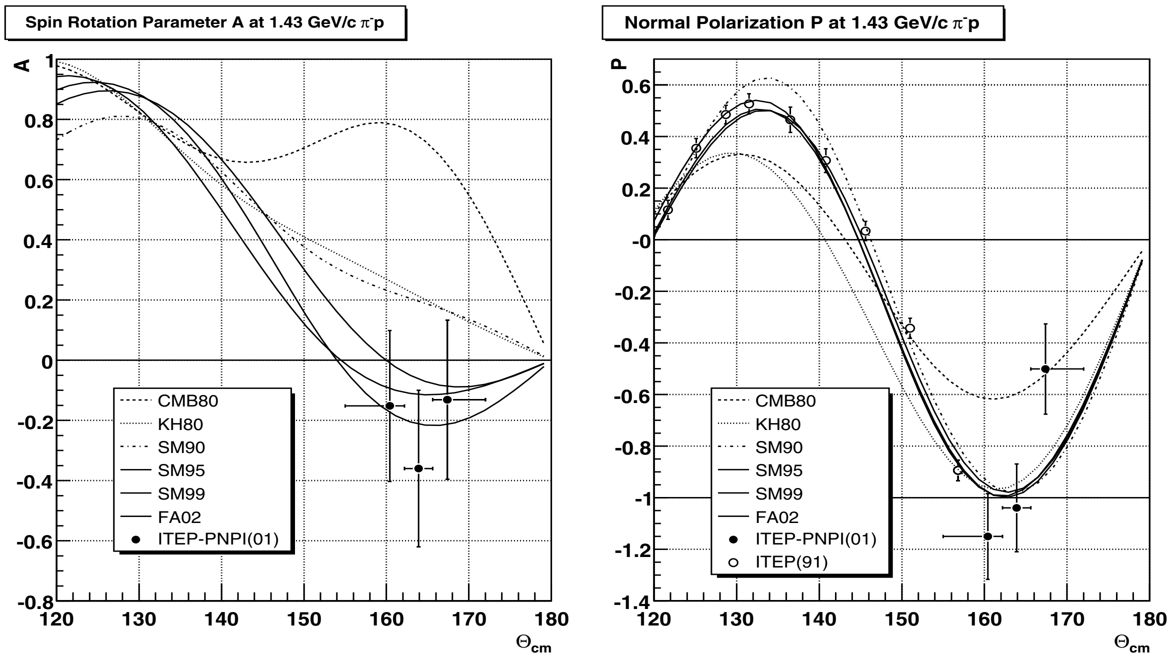

Fig. 4. Polarization parameters A and P in the $\pi^- p$ elastic scattering at 1.43 GeV/c

lyzing power ($\approx 4\%$) and in the measurement of the target polarization ($\approx 2\%$). The contribution of the uncertainties of the background polarization is negligible. This was checked by varying the value of the background polarization from 0 to normal polarization in the elastic scattering. The final value of the ratio of the background polarization to the normal elastic scattering polarization was taken equal 0.7, similar to the ratio of polarizations in the elastic and quasi-elastic pp scattering, measured in [7].

The combined estimate for the systematic error of A parameter is $\approx 8\%$.

As it was stressed above there no ways to eliminate the false asymmetry in the direction of the P parameter measurement ($\varphi_2 = 0, \pi$ plane) using our experimental data. Consequently the systematic error on P cannot be reliably evaluated. Thus the data on this parameter can be used only for qualitative comparison with the main features of PWA solutions, for example: strong angular dependence, angular position of the minimum and the value at the minimum close to -1.

6 Conclusion

Measurements of the polarization parameters were performed in the region of backward scattering where the predictions of various PWA have maximum discrepancy. The data on A parameter agree well with SM95, SM99 and FA02 PWA solutions of the GWU-VPI group. They contradict to the CMB80 analysis predictions while the deviation from KH80 is three standard errors. The data on P parameter is consistent with the main features of the latest analyses of the GWU group.

The results of this experiment along with our previous measurements of the spin rotation parameters indicate that CMB80 and KH80 analyses do not reconstruct properly the relative phase of the transverse amplitudes for the scattering to the backward hemisphere. This conclusion together with the fact that the latest analysis of the GWU group confirm only 4-stars resonances (and only one 3-stars resonance $D_{35}(1930)$) impose serious doubts about the present-day RPP spectrum and properties of the light baryon resonances. The development of a new energy independent partial wave analysis or the resurrection of KH80 analysis [8] would be extremely important to establish the modern and reliable picture of the light quark baryon resonances.

Acknowledgements. Our thanks to professor G. Höehler for the interesting and fruitful discussion. We are grateful to the staff of the ITEP accelerator for the excellent beam quality.

The work was partially supported by Russian Fund for Basic Research (grants 99-02-16635 and 00-15-96545) and by Russian State program "Fundamental Nuclear Physics".

References

1. I.G. Alekseev et al., Phys. Lett. B **351**, 585 (1995); Phys. Lett. B **485**, 32 (2000); Eur. Phys. J. A **12**, 117 (2001)
2. Phys. Lett. B **592**, (2004)
3. G. Höehler, Handbook of Pion Nucleon Scattering, Physics Data No. 12-1 (Fachinformationzentrum, Karlsruhe, 1979)
4. R.E. Cutcosky et al., Phys. Rev. D **20**, 2839 (1979)
5. R.A. Arndt et al., Phys. Rev. C **52**, 2120 (1995)
6. R.A. Arndt et al., Phys. Rev. C **69**, 035213 (2004); http://gwdac.phys.gwu.edu/analysis/pin_analysis
7. I.G. Alekseev et al., Nucl. Instrum. Methods A **434**, 254 (1999)
8. P. Piirola, E. Pietarinen, M.E. Sainio, πN-Newsletter **16**, 121 (2002)