MEASUREMENT OF THE POLARIZATION PARAMETERS IN *pp* ELASTIC SCATTERING AT 1 GeV IN THE SMALL ANGLE REGION

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1. Introduction

At this moment, a wide set of the polarization parameters in proton-proton elastic scattering at the energy of 1 GeV was measured. It includes the depolarization parameter D_{0n0n} measured using a polarized proton beam of the PNPI synchrocyclotron [1] and the polarization transfer parameter K_{n00n} [2] measured using an unpolarized beam of the synchrocyclotron and a polarized proton target. Mostly these parameters are attributed to middle angles $40° < \theta \leq 90°$ (the data are reduced to the interval $0° \leq \theta \leq 90°$, here θ is the c.m.s. angle). As to small angles, experimental data here are very scarce and include preferably the differential cross section and polarization. At present, the experimental situation is characterized by the following figures: the number of independent observables is 17 in the angular range $50° < \theta \leq 90°$ and only 2 in the angular range $\theta < 30°$. A lack of experimental data in the region of small angles leads to an uncertainty of the large angular momentum partial amplitudes and, hence, to an uncertainty of the reconstruction of nucleon-nucleon interaction amplitudes.

In this work the polarization transfer parameter K_{n00n}, the polarization P_{n000} and the analyzing power A_{000n} in the proton-proton elastic scattering were measured at laboratory angles of 9°, 11°, 13°, and 17°. Measurements were carried out using an unpolarized proton beam and a frozen-spin polarized proton target FSPT [3]. The elastic channel separation from a background caused by other channels was performed with the help of the high resolution magnetic spectrometer MAP [4] where the entrance proportional chambers were installed to maintain a high momentum resolution of the spectrometer in spite of a large target size. To subtract the background due to protons scattered on nucleons of nuclei of the polarized target, additional measurements were performed with a dummy target.

2. Experimental setup

The experimental setup is presented in Fig. 1. A proton beam of the synchrocyclotron, formed by a system of quadrupole lenses and collimators, fell on the FSPT in which propanediol was used as a working substance. The beam size on the target was 10×15 mm^2. A working intensity was about 10^8 s^{-1}. This value was limited by the requirement that the relaxation time (which is reduced due to heating of the target substance by the ionization losses of beam protons) must be more than 200–300 hours. The value of target polarization was measured at the beginning and at the end of each run of statistics accumulation, and later on its value p_T in the middle of a time interval was used in all calculations. Below in the text positive and negative polarization orientations are marked by indices *U* and *D*, accordingly.

The main criterion for the selection of *pp* elastic scattering on the FSPT was the scattered proton momentum measured by the magnetic spectrometer, a turning angle of this spectrometer being set within ±0.1°. The trajectories of scattered protons passed the FSPT magnetic field were recorded by the proportional chambers PC_{01} and PC_{02}. The trajectories of protons after the magnetic field of the spectrometer were recorded by the proportional chambers $PC_{1,2}$ and $PC_{3,4}$. The distribution of protons *N(x)* in a focal plane of the spectrometer was used to get the momentum spectrum of these protons.
Two scintillation counters C_1, C_2 covered the total registration solid angle of the spectrometer ("wide aperture"). The counter C_3 with a scintillator size of 50×80 mm^2 separated the central part of beam for an analysis of polarization ("narrow aperture"). The carbon block of 17 cm (29 g/cm^2) thickness was used as an analyzer-target AT. The trajectories of protons after the analyzer-target were recorded by two proportional chambers PC_5 and PC_6. The control of beam intensity was provided by scintillation counters C_{1M}, C_{2M} and C_{3M} which registered protons scattered in the vertical plane on a polyethylene monitor target MT.

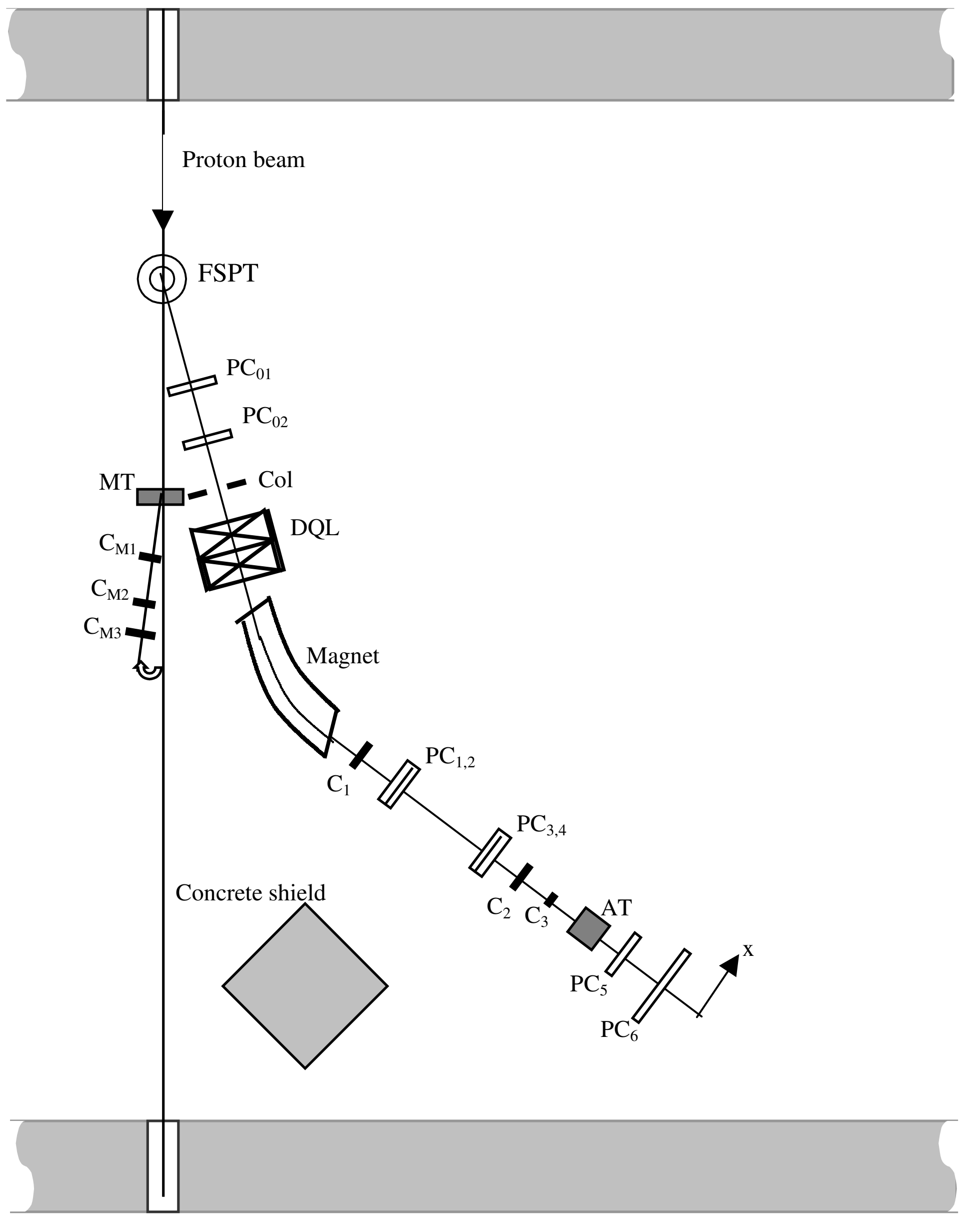

Fig. 1. Experimental setup. FSPT – frozen-spin polarized target, PC – proportional chambers, C – scintillation counters, Col – collimator, DQL – doublet of quadrupole lenses, AT – analyzer-target, MT – monitor target. Shown is the *x*-axis of coordinate system

3. Measurement results and discussion

3.1. Proton spectra

So far as free protons in propanediol are mixed together with carbon and oxygen nuclei, it is necessary to separate contribution of *pp* elastic scattering from protons scattered on nucleons of nuclei (later on we will call this channel "quasielastic" scattering). This contribution was calculated using the momentum losses spectra which were obtained from the momentum spectra $N(x)$ after introducing two compensation terms in the value of x-argument. These terms took into account the rise of beam energy during the extraction from the accelerator (twc, see Ref. [4]) and the x-coordinate of the interaction point at the FSPT (xtc). Values of these compensation terms were obtained by minimizing the distribution width.

The contribution from *pp* elastic scattering was described by a Gaussian distribution, and every spectrum was given by expression:

$$S(x) = n_{pp}\cdot \exp(-(x-x_0)^2/(2d^2)) + n_{qe}\cdot S_{qe}(x), \qquad (1)$$

where n_{pp}, n_{qe} – normalizing factors for elastic and quasielastic channels,

x_0 – the position of *pp*-peak in the distribution,

d – the dispersion of this distribution,

$S_{qe}(x)$ – the spectrum measured using the dummy target.

The parameters n_{pp}, x_0, d and n_{qe} were calculated by minimizing the functional:

$$F(n_{pp},x_0,d,n_{qe}) = \Sigma((N(x) - S(x))/\Delta N(x))^2, \qquad (2)$$

where $N(x)$, $\Delta N(x)$ are the number of events at the point x and its statistical error, the summation is made over all discrete x-values in the accepted range.

In Fig. 2 the spectra in the "narrow aperture" at the angle of 9° restored using a) twc – compensation and b) twc+xtc – compensation are presented. The quasielastic channel contributions equal to the normalized spectra from the dummy target (the second term of formula (1)) are shown also. The peaks from *pp* elastic scattering like Gaussian distributions are the first term of (1). As shown in Fig. 2, the xtc-compensation decreases the width of *pp* peak by a factor of 1.6.

3.2. *pp* scattering analyzing power A_{000n}

Owing to the used way of normalizing the *pp* elastic scattering channel, the analyzing power was calculated only at 9° and 11°. It was calculated by two methods.

In the first method, A_{000n} was calculated using the momentum losses spectra of protons at different signs of the target polarization and the measurements with the dummy target. The spectra from the FSPT and from the dummy target at 9° and the separated channels are shown in Fig. 2b. The intensity of elastic scattered protons was normalized to the accompanying intensity of a quasielastic channel. Such approach has taken off a question about the device asymmetry due to the error of setting the scattering angle and excluded the error connected with the uncertainty of the beam monitoring. In accumulated data the relative statistical uncertainty of the normalizing factor was ≈ 0.002. As the spectra were accumulated at different p_T values, the following formula was used for calculation of the analyzing power:

$$A_{000n} = (1-r)/(r\cdot p_T^U + |p_T^D|), \qquad (3)$$

where $r = i^D/i^U$ and $i^j = n_{pp}^j\cdot d/(n_{qe}^j\cdot S_{qe})$ is the intensity of *pp* elastic scattering channel normalized to the quasielastic channel intensity (an inessential numerical factor is omitted in this expression), $j = D,U$.

In the second method, the analyzing power A_{000n} was calculated directly from the spectra in which the normalizing factor contained the parameter A_{000n} evidently:

$$S^j(x) = n_{pp}^j\cdot(1+p_T^j\cdot A_{000n})\cdot \exp(-(x-x_0^j)^2/(2d^2)) + n_{qe}^j\cdot S_{qe}(x). \qquad (4)$$

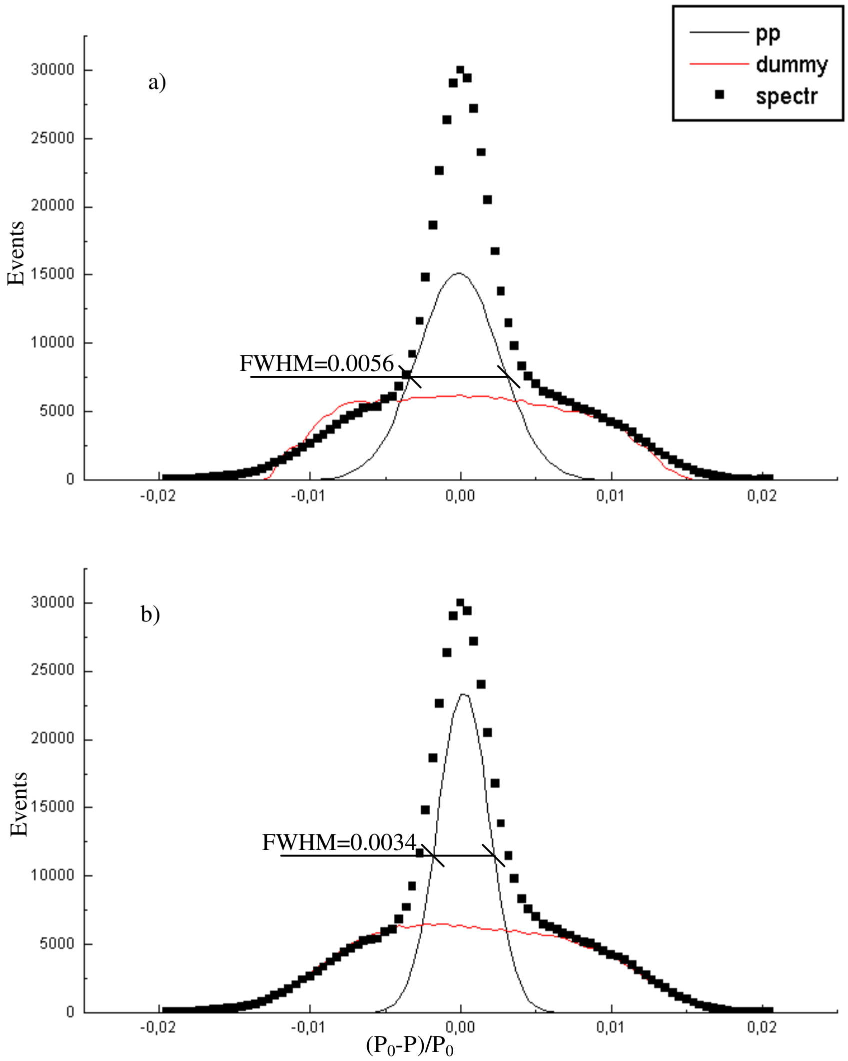

Fig. 2. The momentum losses spectra of protons at $\theta_{l.s.} = 9°$: a) twc compensation only, b) twc+xtc compensation. P_0 is the momentum in the centre of *pp* peak. Spectra from the FSPT and from the dummy target and the contributions of the Gauss-like distribution of elastic scattering channel are shown. The x value in text and $(P_0\text{-}P)/P_0$ are differed by a factor equal to the value of the spectrometer dispersion

The analyzing power A_{000n} was obtained by minimizing the functional similar (2). Another distinction of the second method is that all spectra with different signs of p_T were included in sum like (2). The total number of points included in the functional was 200. The minimization program calculated the analyzing power and its error. The stability of the A_{000n} values in respect to the width of x-variable range of the functional was tested. At small widths, approaching to the pp-peak width, the error due to an uncertainty of the quasielastic channel contribution increased. So the A_{000n} values were obtained using all the range with 160–180 points depending on the angle. The test showed that the decrease of the number of points by 40 changed the A_{000n} value not more than by 0.004.

The analyzing power at 9° and 11° (22.5° and 27.5° in the c.m.s.) was obtained by both above mentioned methods. The maximum distinction of values obtained with different methods and associated with the uncertainty of the quasielastic channel contribution was 0.02. Finally, the mean value A_{000n} was accepted with a systematic uncertainty of ±0.01. An error estimation obtained in the procedure of minimizing the functional was accepted as a statistical error. The relative error due to the uncertainty of the target polarization was 2%.

3.3. The polarization P_{n000} and the parameter K_{n00n}

The parameters P_{n000} and K_{n00n} were calculated from the azimuthal distribution of protons scattered on the analyzer-target. In common, for the fixed angle θ the distribution is:

$$i(\varphi) = i_0 \cdot (1 + \varepsilon \cdot \cos\varphi + \delta \cdot \sin\varphi)\ , \qquad (5)$$

where i_0 – the intensity of the unpolarized beam scattering,

φ – the azimuthal angle,

ε – the left-right asymmetry,

δ – the up-down asymmetry.

The left-right asymmetry ε is connected with the parameters P_{n000} and K_{n00n} by the equation:

$$\varepsilon = A_{pw} \cdot (a_1 \cdot (P_{n000} + K_{n00n} \cdot p_T))/((1+ P_{n000} \cdot p_T) + a_2 \cdot P_{qe}), \qquad (6)$$

where A_{pw} – the analyzing power of the carbon-proton scattering, a_1, a_2 – the elastic and quasielastic channel contributions, accordingly, in the separated part of the spectrum, $a_1 + a_2 = 1$.

In formula (6) P_{qe} is the quasielastic channel polarization. The contributions a_1 and a_2 are calculated from the spectra similar to those shown in Fig. 2b, which were accumulated simultaneously with the azimuthal distributions. It may be applied only to measurements with the polarized target. The dummy target does not contain free protons, and $a_1 = 0$. At angles 13° and 17° (32.5° and 42.5° in the c.m.s.), where the quasielastic channel contribution was negligible, $a_1 = 1$ has been taken. The analyzing power A_{pw} was calculated as a mean weighted pC analyzing power in the angular interval $4° \leq \vartheta_{pC} \leq 17°$ with the weight being equal to the differential cross section for the corresponding angle. Data from Ref. [5] were used.

The parameters were found by minimizing the functional:

$$F(K_{n00n}, P_{000n}, P_{qe}, \delta) = \Sigma_k \Sigma_j ((N^j(\varphi_k) - i^j(\varphi_k))/\Delta N^j(\varphi_k))^2\ ,$$

where $N^j(\varphi_k)$ – the accumulated azimuthal distribution for the run with index j in the k-th φ interval,

$i^j(\varphi_k)$ – the distribution (5) at the p_T^j value of the target polarization.

The free parameters were K_{n00n} , P_{000n} , P_{qe} and δ. The parameters and their statistical errors are given in Table. The relative errors of K_{n00n}, P_{000n} and P_{qe} due to the A_{pw} uncertainty are 5%. The relative error of K_{n00n} due to the p_T uncertainty is 2%, the error due to the uncertainty in calculation of the elastic channel contribution does not exceed 0.005 for the angles 22.5° and 27.5°. The hypothesis $a_1 = 0.9$ led to the increase of K_{n00n} by 0.03 at 32.5° and by 0.04 at 42.5°.

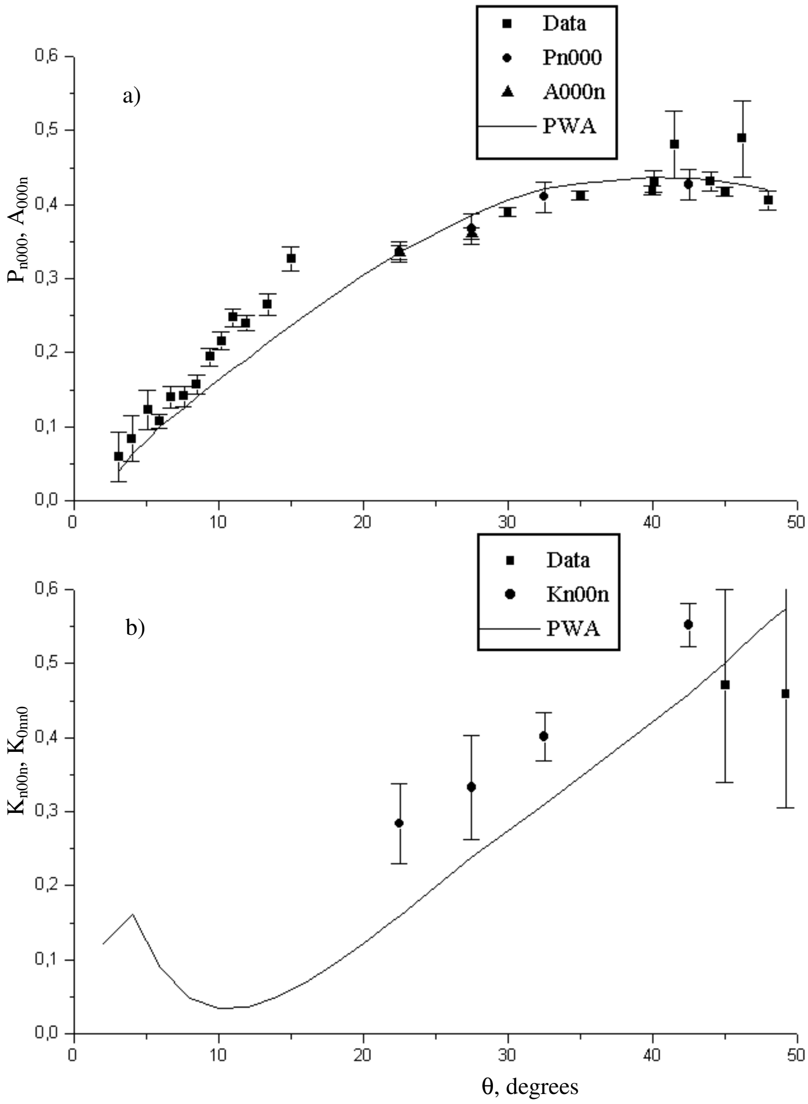

Fig. 3. The angular distribution of the polarization parameters. The obtained parameters P_{n000}, A_{000n}, K_{n00n}, are shown by symbols in windows. "Data" are the data-base from article of R.Arndt *et al.*

The values P_{qe} were obtained at the angles 22.5° and 27.5° in the c.m.s. from the azimuthal distributions for the dummy target and for the FSPT; in the last case the momentum region out of *pp* peak was concerned.

Table

Experimental results

θ	A_{000n}	P_{n000}	P_{qe}	K_{n00n}
22.5°	0.335 ± 0.010	0.336 ± 0.014	0.303 ± 0.018	0.284 ± 0.054
27.5°	0.361 ± 0.008	0.367 ± 0.020	0.339 ± 0.021	0.333 ± 0.070
32.5°	–	0.410 ± 0.021	–	0.401 ± 0.033
42.5°	–	0.427 ± 0.021	–	0.552 ± 0.029

The values of A_{000n} and P_{n000} in Table are very close. This coincidence is pure accidental taking their both statistical and systematic errors into account. However, so far as they were obtained by the independent methods, the fact of their hit into the error corridor indicates the following: a) the correctness of separating *pp* elastic and quasielastic channels in the spectrum, b) the absence of noticeable errors in determining p_T value, c) the absence of a noticeable device asymmetry of the polarimeter, d) the correctness of the analyzing power value. Thus enumerated factors cannot be sources of possible errors of K_{n00n}. It is necessary to notice that K_{n00n} in contrast to P_{n000} does not depend on the device asymmetry of a polarimeter.

In Fig. 3a A_{000n} and P_{n000} are presented together with the known experimental data and with the predictions of the Arndt partial-wave analysis (PWA)[1] . To keep a diagram clearness, not all the data are shown. The most of excluded data cover the angular interval $\theta > 36°$. The data obtained in this work widened the angular range filled up with the experimental values. In Fig. 3a one can see the agreement of our data with the data of previous works at angles $\theta = 32.5°$, 42.5° and with the PWA predictions at all angles.

In Fig. 3b the measured parameters K_{n00n} are shown together with the PWA predictions and earlier data: $K_{n00n}(45°)$ equaled to $D_{n0n0}(135°) = 0.47 \pm 0.13$ [1] and $K_{0nn0}(49.2°) = 0.458 \pm 0.152$[2]. Because of large errors of these data, our value $K_{n00n}(42.5°)$ cannot be concerned to contradict them. At the same time, our data lie higher than the PWA predictions. So far as this discrepancy cannot be connected with the error in determining *pp*-scattering angle or other systematic errors discussed above, it should be taken that the Arndt PWA does not describe the K_{n00n} angular dependence. The reason of this is a lack of experimental data in the angular range $\theta < 45°$ which can be filled after including our data.

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