**Polarization parameters of the quasi–elastic \((p, 2p)\) reaction with nuclei at 1 GeV**

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New experimental data on the polarization and spin-correlation parameters in the \((p, 2p)\) reaction with nuclei at 1 GeV are presented. The experiment was aimed to study a modification of the proton–proton scattering matrix.

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1 Introduction

There were some speculations on modifications of nucleon and meson masses and sizes, and of meson–nucleon coupling constants, and, as a consequence, of nucleon–nucleon scattering matrix in nuclear medium [1–3]. These speculations were motivated by a variety of theoretical points of view, including the renormalization effects due to strong relativistic nuclear fields, deconfinement of quarks, and partial chiral symmetry restoration.

This work is a part of the experimental program in the framework of which the medium–induced modifications of the nucleon–nucleon scattering amplitudes are studied at the PNPI synchrocyclotron with the 1 GeV proton beam [4–8]. The intermediate–energy quasi–free \((p, 2p)\) reaction is a good experimental tool to study such effects, since in the first approximation, this reaction can be considered as a proton–proton scattering in the nuclear matter. Usage of S–shell protons (with zero orbital momentum) is preferred because interpretation of obtained data in this case is essentially simplified since the effective polarization is not involved [9]. The polarization observables in the reaction are compared with those in the elastic \(pp\) scattering. In our exclusive experiment, a two–arm magnetic spectrometer is used, the shell structure of the nuclei being evidently distinguished. To measure polarization characteristics of the reaction, each arm of the spectrometer was equipped with a multi-wire–proportional chamber polarirometer.

In the early PNPI–RCNP experiment [5], the polarizations \(P_1\) and \(P_2\) of both secondary protons from the \((p, 2p)\) reactions at 1 GeV with the 1S–shell protons of the nuclei \(^6\text{Li}, ^{12}\text{C}\) and with the 2S–shell protons of the \(^{40}\text{Ca}\) nucleus has been measured at nuclear proton momenta close to zero. The polarization observed in the experiment, as well as the analyzing power \(A_y\) in the RCNP experiment at the 392 MeV polarized proton beam [10, 11], drastically differed from those calculated in the framework of non–relativistic Plane Wave Impulse Approximation (PWIA) and of spin–dependent Distorted Wave Impulse Approximation (DWIA) [12], based on free space proton–proton interaction. This difference was found to have a negative value and to increase monotonously with the effective mean nuclear density \(\bar{\rho}\) [10]. The latter is determined by the absorption of initial and secondary protons in nucleus matter. The observed inessential difference between the non–relativistic PWIA and DWIA calculations pointed out only to a small depolarization of the secondary protons because of proton–nucleon re-scattering inside a nucleus. All these facts strongly indicated a modification of the proton–proton scattering amplitudes due to the modification of the main properties of hadrons in the nuclear matter.

Later, the results of the experiment with a \(^4\text{He}\) target broke the above–mentioned dependence of the difference between the experimental polarization values and those calculated in the framework of the PWIA on the effective mean nuclear density [6]. The difference for the \(^4\text{He}\) nucleus proved to be smaller than
that for the $^{12}$C nucleus. This evidently contradicts the elastic proton–nucleus scattering experiment. According to the experiment, the $^4$He nucleus has the largest mean nuclear density. The important feature of the experiment with the $^4$He nucleus was a possibility to see the medium effect without any contribution from multi–step processes (for instance, from the $(p, 2pN)$ reactions). These processes could take place when there were nucleons of outer shells as in other nuclei. Therefore, they could not cause the systematic difference between the polarizations $P_1$ and $P_2$ clearly obtained for the first time in the experiment [6].

Here we present the polarization data for the reaction with the nuclei $^4$He, $^6$Li, $^{12}$C ($1S$–shell), and $^{40}$Ca ($2S$–shell) obtained with a much better statistical accuracy in our last experiments. New data on the polarization in the reaction with the $1S$–shell protons of the $^{28}$Si nucleus are presented. The $1S$–state of the $^{28}$Si nucleus has a larger value of the mean proton binding energy $E_s$ (50 MeV) than that of the $^{12}$C nucleus (35 MeV). We also present the polarization measured in the reaction with the $P$–shell and $D$–shell protons of the $^{12}$C and $^{28}$Si nuclei, respectively.

In recent experiments, the research program was extended to measure the spin correlation parameters $C_{ij}$ in the $(p, 2p)$ reaction with the $^4$He and $^{12}$C nuclei. Measurements of the parameters in the reaction with nuclei were for the first time performed. The main attention was concentrated on the spin correlation parameter $C_{nn}$ since its value is the same in the center–of–mass and laboratory systems. Besides, this parameter is not distorted by the magnetic fields of the two–arm spectrometer because of the proton anomalous magnetic moment [13]. Since the polarization and the spin correlation parameter $C_{nn}$ are expressed differently through the scattering matrix elements [3], the measurement of both these polarization observables can provide a more comprehensive information about a modification of the hadron properties in the nuclear medium.

2 Experimental method

The general layout of the experimental setup is shown in Fig. 1 [14]. The experiment is performed at non–symmetric scattering angles of the final state protons in the coplanar quasi–free scattering geometry with a complete reconstruction of the reaction kinematics. The measured secondary proton momenta $K_1$, $K_2$ (kinetic energies $T_1$, $T_2$) and the scattering angles $\Theta_1$, $\Theta_2$ are used together with the proton beam energy $T_0$ to calculate nuclear proton separation energy $\Delta E = T_0 - T_1 - T_2$ and the residual nucleus momentum $K_r$ for each $(p, 2p)$ event. In the impulse approximation, the $K_r$ is equal to the momentum $K$ of the nuclear proton before the interaction ($K_r = -K$).

External proton beam of the PNPI synchrocyclotron was focused onto the target TS of a two–arm spectrometer consisting of the magnetic spectrometers MAP and NES. The beam intensity was monitored by the scintillation telescope.
Figure 1: The experimental setup. TS is the target of the two–arm spectrometer; Q1÷Q4 are magnetic quadrupoles; D1, D2 are dipole magnets; C1, C2 are collimators; S1÷S4 and M1÷M3 are scintillation counters; PC1÷PC4, PC1’, PC4’ (PC5÷PC8, PC5’, PC8’) and A1 (A2) are the proportional chambers and the carbon analyzer of the high–momentum (low–momentum) polarimeter, respectively.

M1, M2, M3 and was at the level of about 5·10^{10} protons/(s·cm^2).

Solid nuclear targets TS made of CH\text{2} (for the setup calibration), \textsuperscript{6}Li, \textsuperscript{12}C, \textsuperscript{28}Si, and \textsuperscript{40}Ca, as well as a cryogenic target made of liquid helium \textsuperscript{4}He (or liquid hydrogen for calibration) were used in the experiment [6, 14].

The spectrometers were used for registration of the secondary protons from the (\textit{p},\textit{2p}) reaction in coincidence and for measurement of their momenta and outgoing angles. The polarization of these protons \textit{P}_1 and \textit{P}_2, and the spin correlation parameters \textit{C}_{ij} were measured by the polarimeters located in the region of focal planes of the spectrometers MAP and NES (Fig. 1). The first index of the \textit{C}_{ij}, \textit{i} (where \textit{i} is \textit{n} or \textit{s}), and the second index \textit{j} (where \textit{j} is \textit{n} or \textit{s}) correspond to the forward scattered proton analyzed by the MAP polarimeter and the recoil proton analyzed by the NES polarimeter, respectively. The unit vector \textit{n} is perpendicular to the scattering plane of the reaction. Unit vectors \textit{s} and \textit{s'} are perpendicular to the vector \textit{n} and to the coordinate axes \textit{z} and \textit{z'} (Fig. 1) of the polarimeters.

The overall energy resolution (on \Delta\textit{E}) of the spectrometer estimated from the elastic proton–proton scattering with the 22 mm thick cylindrical CH\text{2} target was about 5 MeV (FWHM). The spectra which was analysed is presented in Fig.2 [14].

The track information from the proportional chambers of both polarimeters was used in the off-line analysis to find the azimuthal \phi_1, \phi_2 and polar \theta_1, \theta_2.
angles of the proton scattering from the analyzers A1, A2 for each \((p, 2p)\) event.

The polarization parameters were estimated by folding the theoretical functional shape of the azimuthal angular distribution into experimental one [8], using the CERNLIB MINUIT package and a \(\chi^2\) likelihood estimator. This method permits to realize the control over \(\chi^2\) in the case the experimentally measured azimuthal distribution is distorted due to the instrumental problems.

The time difference (TOF) between the signals from the scintillation counters S2 and S4 was measured. It served to control the accidental coincidence background. The events from four neighboring proton beam bunches were recorded. Three of them contained the background events only and were used in the off-line analysis to estimate the background polarization parameters and the background contribution at the main bunch containing the correlated events [14].

The recoil proton spectrometer NES was installed at a fixed angle \(\Theta_2 \simeq 53.2^\circ\). At a given value of the \(S\)–shell mean binding energy of the nucleus under investigation, the angular and momentum settings of the MAP spectrometer and the momentum setting of the NES spectrometer were chosen to get a kinematics of the \((p, 2p)\) reaction close to that of the elastic proton–proton scattering. In this kinematics, the momentum \(K\) of the nuclear \(S\)–proton before the interaction is close to zero. At this condition, the counting rate of the \(S\)-shell proton knockout reaction should be maximal.

### 3 Results and discussion

In Fig. 3, the polarizations \(P_1, P_2\) in the \((p, 2p)\) reaction with the \(S\)–shell protons of the nuclei \(^4\text{He}, ^6\text{Li}, ^{12}\text{C}, ^{28}\text{Si}, ^{40}\text{Ca}\) are plotted versus the \(S\)–shell proton binding energy \(E_s\) [14]. For all nuclei (excluding \(^4\text{He}\), the effective mean
Polarization

\[ \Theta_1 = 21 - 26 \, \text{deg} \]
\[ \Theta_2 = 53.2 \, \text{deg} \]
\[ q = 3.2 - 3.7 \, \text{fm}^{-1} \]

\( P_1, P_2 \)

\( \rho / \rho_0 = 0.07, 0.19, 0.31, 0.30 \)

\( 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 \)

Figure 3: Polarizations \( P_1 \) and \( P_2 \) of the protons scattered at the angles \( \Theta_1 \) (○) and \( \Theta_2 \) (●) in the \((p,2p)\) reaction with the \(S\)-shell protons of nuclei at 1 GeV. The points at \( E_s = 0 \) correspond to the elastic proton-proton scattering. The curves correspond the theoretical calculations described in the text.

nuclear density \( \bar{\rho} \), normalized on the saturation nuclear density \( \rho_0 \approx 0.18 \, \text{fm}^{-3} \), is given. The actual calculation of the effective mean nuclear density \( \bar{\rho} \), which is determined by absorption of the incident and both outgoing protons, was carried out following a procedure [10] using the computer code THREEdEE [12]. The potential model of a nucleus employed by the code is not correct for the \(^4\text{He}\) nucleus. The calculated value of the \( \bar{\rho} \) in this case is strongly unreliable [6]. The \(^4\text{He}\) data should be excluded in comparison with theoretical models which differ from the PWIA.

The points (○) and (●) in the figure correspond to the polarizations \( P_1 \) and \( P_2 \) of the forward scattered protons at the angle \( \Theta_1 = 21^\circ \div 25^\circ \) (with energy \( T_1 = 745 \div 735 \, \text{MeV} \)) and of the recoil protons scattered at the angle \( \Theta_2 \simeq 53.2^\circ \) (with energy \( T_2 = 205 \div 255 \, \text{MeV} \)). The points at the \( E_s = 0 \) are the polarizations \( P_1 \) and \( P_2 \) in the elastic proton-proton scattering at the angles \( \Theta_1 = 26.0^\circ \) and \( \Theta_2 = 53.2^\circ \) \((\Theta_{cm} = 62.25^\circ)\).

In Fig. 3, the experimental data are compared with the results of the non-relativistic PWIA, DWIA calculations (the dashed and solid curves, respectively) [14] and the DWIA* calculation with the relativistic effect, the distortion of the nucleon Dirac spinor in nuclear medium, taken into account (the dotted, \( M^*_N \), curve) [2,14]. For the calculations, the computer code THREEdEE was used [12] using an on–shell factorized approximation and the final energy prescrip-
A global optical potential, parametrized in the relativistic framework and converted to the Shr"odinger–equivalent form, was used to calculate the distorted wave functions of incident and outgoing protons in the case of DWIA and DWIA*. A conventional well–depth method was used to construct the bound–state wave function. The DWIA* calculations were carried out in the Shr"odinger–equivalent form [5]. In this approach, a modified NN interaction in medium is assumed due to the effective nucleon mass (smaller than the free mass), which affects the Dirac spinors used in the calculations of the NN scattering matrix. A linear dependence of the effective mass of nucleons on the nuclear density was assumed in the calculations.

The results of the polarization studies:

1. The difference of the final proton polarizations $P_1$ and $P_2$ found in the PWIA, DWIA and DWIA* is quite small (less than 0.005) for all nuclei under investigation.

2. The difference between the PWIA and DWIA results is small. This indicates that the distortion in the conventional non-relativistic framework does not play any essential role in the polarization for the kinematic conditions under consideration (the transferred momenta $q = 3.2 \div 3.7$ fm$^{-1}$).

3. Predictions of the DWIA* with relativistic corrections (distortion of the proton Dirac spinor in nuclear medium) are close to experimental data for the forward scattered proton polarization $P_1$.

4. A significant difference is observed between the measured polarization of the scattered proton $P_1$ and that of the recoil proton $P_2$.

Note that the difference between the measured polarizations $P_1$ and $P_2$ was also observed in the reaction with the $D$–shell protons of the $^{28}$Si nucleus and was not seen in the reaction with the $P$–shell protons of the $^{12}$C (Fig. 4).

The experimental data on the spin correlation parameters $C_{ij}$ in the reactions with the $^4$He and $^{12}$C are given in Fig. 5. The dashed and dotted curves in the figure correspond to the PWIA calculations of the $C_{nn}$ and $C_{s,s'}$ parameters using the current Arndt’s group phase-shift analysis (SP07). The mixed $C_{s,s'}$ parameter was found by taking into account its distortion in the magnetic field of the spectrometers. The points at the $E_s = 0$ correspond to the elastic proton-proton scattering.

As seen in Fig. 5, the $C_{nn}$ data (as well as the $C_{s,s'}$ data) are described in the framework of the PWIA. The question arises, there is no the nuclear medium modification of the $C_{nn}$ parameter as it is for the polarization of the final protons (Fig. 3)? Whether this fact is connected to the strong polarization dropping for the recoil proton? It is possible that some spin-flip mechanism compensates the nuclear medium effect in the $C_{nn}$.

Due to the parity conservation in the elastic proton-proton scattering, the spin correlation parameters $C_{n,s''}$ and $C_{s',n}$ should be equal to 0. This is confirmed by the experimental data at the $E_s = 0$ in the Fig. 5. For the $(p, 2p)$ reaction, we see some deviation of the parameters from zero. It may be related to the spin-flip
Figure 4: Polarization in the \((p, 2p)\) reaction with the external shell protons of the \(^{12}\text{C}\) and \(^{28}\text{Si}\).

Figure 5: Spin correlation parameters \(C_{ij}\) in the \((p, 2p)\) reaction at 1 GeV with the \(S\)-shell protons of the \(^{4}\text{He}\) and \(^{12}\text{C}\) nuclei at the secondary proton scattering angles \(\Theta_2 = 53.22^\circ, \Theta_1 = 24.21^\circ\) and \(\Theta_2 = 53.22^\circ, \Theta_1 = 22.71^\circ\), respectively. The points at \(E_s = 0\) correspond to the elastic proton-proton scattering (\(\Theta_1 = 26.0^\circ, \Theta_{cm} = 62.25^\circ\)). The curves are the results of calculations described in the text.
mechanism mentioned above. Note that test calculations of all spin correlation parameters for the accidental coincidence background give zero values as should be expected.

To find an explanation of the observed effects, let us assume that there is a spin-flip interaction of the recoil (nuclear) proton with the residual nucleus, which is not taken into account by the theoretical approaches. This additional interaction mechanism, governed by the Pauli exclusion principle in a nucleus, reverses the proton spin direction and, as a consequence, changes the signs of the polarization and the spin correlation parameter $C_{nn}$.

The relative contribution ($\alpha$) of the spin–flip mechanism in the interaction with a residual nucleus, which is mainly determined by the proton-nucleon rescattering at small angles, can be found from experiment via the relative polarization dropping ($g_p$) for the recoil proton. First define the averaged polarization of the recoil proton:

$$< P_2 > = \frac{P_2 + \alpha(-P_2)}{1 + \alpha} = \frac{P_1 + \alpha(-P_1)}{1 + \alpha} = \frac{(1 - \alpha)P_1}{1 + \alpha}. \quad (1)$$

In the equation we used the fact that all employed theories give equal values of the polarizations $P_1$ and $P_2$. The averaged value of the $C_{nn}$ can also be calculated using the equation:

$$< C_{nn} > = \frac{C_{nn} + \alpha(-C_{nn})}{1 + \alpha} = \frac{(1 - \alpha)C_{nn}}{1 + \alpha}. \quad (2)$$

The relative polarization dropping $g_p$ is determined as:

$$g_p = \frac{P_1 - < P_2 >}{P_1} = g_{C_{nn}} = \frac{C_{nn} - < C_{nn} >}{C_{nn}} = \frac{2\alpha}{1 + \alpha}. \quad (3)$$

It can be seen that the proposed spin–flip interaction couples in simple form the relative dropping of the polarization and the $C_{nn}$ parameter $g_p = g_{C_{nn}}$. From experimental data we find $g_p(^{4}\text{He}) = 0.153 \pm 0.018$, $g_p(^{12}\text{C}) = 0.325 \pm 0.031$ and make corrections to the PWIA calculations using the formula $C_{nn\text{-cor}} = (1-g_p)C_{nn}$ (the solid curve, PWIA-C, in Fig. 5). One can see from the figure that the the experimental $C_{nn}$ points lie above the curve. So it can be expected that the nuclear medium modification enhances the $C_{nn}$ parameter, while the polarization is reduced.

From the experimental $g_p$ data, the probability of the spin–flip interaction can be defined for the corresponding residual nuclei: $\alpha(^3\text{H}) = 0.083 \pm 0.010$, $\alpha(^{11}\text{B}) = 0.194 \pm 0.022$.

What could be the nature of the considered spin–flip interaction? It was first time proposed by D.I. Blokhintsev that there are the fluctuations of nuclear density in nuclei, or the dense nucleon associations [15]. The reflection of the recoil proton off the objects is similar to the spin–flip interaction considered above. As
a result, a proton belonging to a correlation, with opposite spin direction (due to the Pauli principle) is detected.

Nucleon correlations are intensively studied in the JLAB using electron beam. The CLAS collaboration gives the probability for a given nucleon to belong to a two-nucleon correlation in nucleus with A nucleons $a_{2N}^{(3\text{He})} = 0.080 \pm 0.016$, $a_{2N}^{(12\text{C})} = 0.193 \pm 0.041$ [16].

We can see that there is a coincidence between the PNPI $\alpha$ and the JLAB $a_{2N}$ for the corresponding residual nuclei. The model of the spin–flip interaction for explanation of the PNPI polarization data is currently being developed. Preliminary results suggest that the ratio of the $\alpha$ and $a_{2N}$ is very close to unity.
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