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O V Miklukho[1], A Yu Kisselev[2], G M Amalsky, V A Andreev, G E Gavrilov, D S Ilyin, A A Izotov, N G Kozlenko, P V Kravchenko, M P Levchenko, D V Novinskiy, D A Maysuzenko, V I Murzin, A N Prokofiev[3], A V Shvedchikov, S I Trush and A A Zhdanov

Konstantinov Petersburg Nuclear Physics Instinute, National Research Center "Kurchatov Institute", Gatchina, 188300 Russia

E-mail: [1]`miklukho_ov@pnpi.nrcki.ru`, [2]`kisselev@mail.desy.de`, [3]`prokofiev_an@pnpi.nrcki.ru`

Abstract. The secondary proton polarization, differential cross section, and cross section ratios were measured in the (p, p') inelastic reaction with nuclei at 1 GeV and a laboratory scattering angle of $\Theta = 21^0$. The data were obtained over a wide range of the scattered proton momentum covering the pN quasielastic peak and high momentum region up to a momentum corresponding to excited level of the nucleus under investigation. Scattered protons were detected by the magnetic spectrometer equipped with a polarimeter based on multiwire proportional chambers and carbon analyzer. A structure in the polarization and cross section data, possibly related to the in-medium elastic scattering on nucleon correlations arising in nuclei, and a scaling of the scattering cross section ratios of the nuclei were observed in the high momentum range.

1. Introduction

This work is a part of the experimental program in the framework of which the effects from scattering off nucleon associations (nucleon correlations, NCs) in nuclei [1] are studied with a 1 GeV proton beam at the synchrocyclotron of the Petersburg Nuclear Physics Institute (PNPI). These effects also were investigated in other experiments by various nuclear reactions (e.g., [2–9]).

In PNPI exclusive experiments [10], an essential difference in polarization of two secondary protons from the (p, 2p) reaction with nuclei was found. This effect can be explained as the scattering on the NCs in a low-energy arm of the two-arms magnetic spectrometer.

In the first PNPI inclusive experiment [11], a growth of the polarization with the final proton momentum K in the (p, p') reaction with the ^{40}Ca nucleus at the scattering angle of 21^0 was observed. At a value of K corresponding to kinematics of the quasielastic scattering on a ^{4}He-like nucleon cluster inside of calcium nucleus, the polarization turned out to be close to that in free elastic p^4He scattering.

In new inclusive experiments [12–14], we studied in details the inelastic (p, p') reaction with different nuclei with a better statistic accuracy. The secondary proton polarization P and differential cross section $\sigma^{\mathrm{incl}} = \frac{d^2\sigma}{d\Omega dK}$ of the reaction were measured as a function of the scattered proton momentum K in narrow intervals of K ($\sim$10 MeV/c).

2. Experimental method and reaction kinematics

A general layout of the experimental setup is presented in Fig. 1 [13].

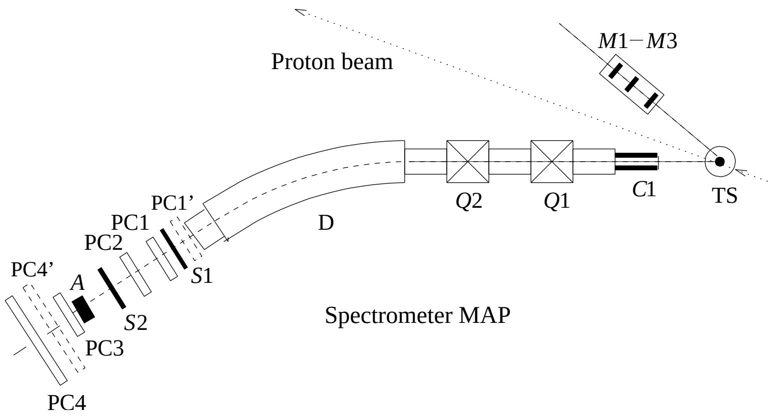

Figure 1. Layout of the experimental setup: (TS) target of the MAP spectrometer, ($Q1$−$Q2$) magnetic quadrupoles, (D) dipole magnet, ($C1$) collimator, ($S1$−$S2$ and $M1$−$M3$) scintillation counters, (PC1−PC4, PC1', and PC4') proportional chambers of the MAP polarimeter, and (A) its carbon analyzer.

The secondary protons from the reaction under investigation were detected by means of the magnetic spectrometer MAP equipped with a polarimeter based on multiwire proportional chambers and carbon analyzer. The spectrometer was installed at an angle of 21^0 with respect to the direction of the proton beam. Its momentum resolution for this scattering angle can be estimated on a width of the clearly separated 2^+ excited level in the reaction with the carbon nucleus (Fig. 2). This resolution was about $\pm$2.5 MeV/c in this experiment.

The scattering differential cross sections of the reaction were found at different momentum settings of the spectrometer using information from the proportional chamber PC2-X, which was located in a focal plane of the spectrometer. The polarization of the secondary protons was defined on an azimuthal angular asymmetry of their scattering off a carbon analyzer. The analyzing power of the MAP polarimeter was calibrated on the basis of polarization data obtained for elastic pp scattering in the present experiment. In order to perform a calibration over a wide range of secondary proton energies, polarization measurements were performed with polyethylene (CH_2) and carbon (C) targets for various angular and proper momentum settings of the spectrometer. The values found for the pp polarization were compared with the predictions of the phase-shift analysis. A correction to the analyzing power of the polarimeter was introduced thereupon [13].

We performed measurements in a wide range of the scattered proton momentum K covering the pN quasielastic peak with its maximum at $K = K_{\mathrm{pN}}$ $\sim$1480 MeV/c and a high momentum region ($K >$ 1530 MeV/c) up to the momentum (K_{L}) corresponding to excited level of the nucleus under investigation. At $K > K_{\mathrm{pN}}$, the quasielastic pNC scattering off the nucleon correlations (NCs) is kinematically preferable since they are more massive than the nucleon. In this region, the four-momentum transfer Q remains almost invariable ($\sim$600 MeV/c). Consequently, the Bjorken variable $x_{\mathrm{B}} = \frac{Q^2}{2m\nu}$ is actually determined only by the K momentum. The momentum interval between K_{pN} and K_{L} covers a range of $x_{\mathrm{B}} = 1$−4. The momentum $K_{\mathrm{N}}^{\mathrm{min}}(\Theta)$ is a minimum momentum which a nuclear nucleon must have to scatter a beam proton with the final momentum K. This momentum is a monotonically increasing function of K. The dashed vertical line in Fig. 3 at $K = K_{\mathrm{C}}$ $\sim$1575 MeV/c separates a K momentum region where the $K_{\mathrm{N}}^{\mathrm{min}}(21^0)$ momentum is more than the Fermi momentum k_{F} for the carbon nucleus ($\sim$220 MeV/c) [14]. In a range $K > K_{\mathrm{C}}$, a contribution from quasielastic scattering off the uncorrelated nuclear nucleons is essentially suppressed [12].

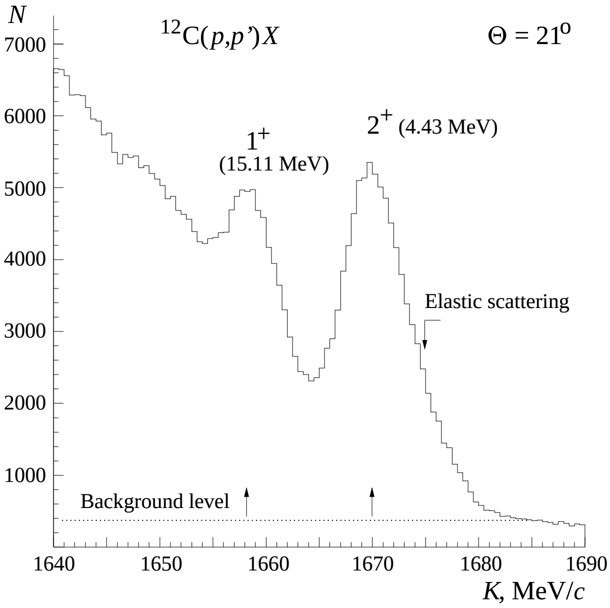

Figure 2. Momentum distribution in the inclusive reaction ^{12}C$(p, p')X$ at the scattering angle of $\Theta = 21^0$ [13].

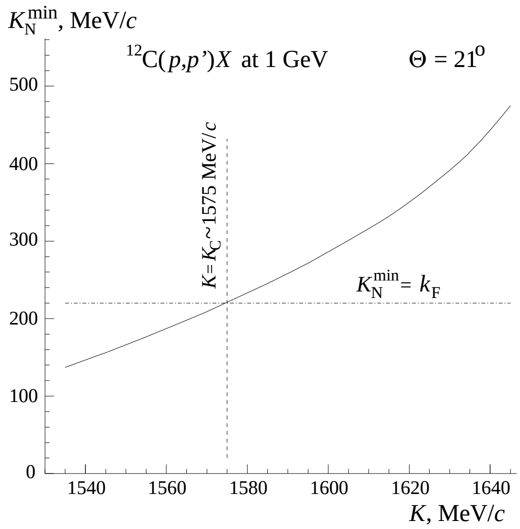

Figure 3. The solid curve is an averaged estimation of the $K_N^{\rm min}$ momentum for the carbon nucleus versus the scattered proton momentum K [14]. The momenta $K_N^{\rm min}$, k_F, and K_C, the dashed vertical and dash-dotted horizontal lines were defined in the text.

3. Experimental data and observations

In Fig. 4, the secondary proton polarization (black squares) and cross sections (circles) of the (p, p') inelastic reaction with the carbon nucleus are presented as a function of the scattered proton momentum K [13]. The left and right vertical axes refer to the polarization and scattering cross section, respectively. The dashed curve is the result of the polarization calculation in the framework of the spin-dependent Distorted Wave Impulse Approximation (DWIA) taking into account the relativistic distortion of the nucleon spinor in a nuclear medium DWIA* [10]. For the calculations, the known ThreeDee code was used.

At the K momentum greater than the momentum corresponding to a maximum of the quasielastic pN peak ($K_{\rm pN}$ ~1480 MeV/c), it is possible to distinguish the momentum intervals indicated by the dotted-line segments and marked with the Roman numerals II (1535−1570 MeV/c), III (1570−1600 MeV/c), and IV (1600−1635 MeV/c). The characteristics by which these intervals were picked out:

1. The polarization within each interval practically does not change and grows from the interval II to the interval IV.

2. The beginning of each interval is determined by slowing down of the scattering cross section (indicated by an arrow) which may be due to scattering by a heavier nuclear particle.

Suppose that the intervals II, III, and IV correspond to the elastic scattering in nuclear medium on two-, three-, and four-nucleon correlations. Note here that a high-momentum region, just above the IV range, possibly corresponds to the quasielastic scattering off a residual nucleus X from the reaction under investigation.

To verify the last assumption, we calculated the momenta K_2, K_3, and K_4 corresponding to the quasielastic maxima in the scattering on these correlations (Fig. 4). In the kinematical calculations we assumed:

1) A nucleon correlation (NC) is immovable. 2) A NC mass is equal to a mass of the real light nucleus with a simple structure like ^{2}H, ^{3}He (^{3}H), and ^{4}He. 3) The residual nuclei (X) in

the (p,p') reaction are in the ground state.

One can see that the momenta K_2, K_3, and K_4 are within the momentum intervals II, III, and IV, respectively. This is so in the case inclusive where the NC mass is smaller (because of the in-medium modification [10]) than the mass of the corresponding free light nucleus. A decrease of about 10% in the NC masses reduces the momenta K_2, K_3 (K_3^*), and K_4 by about 12, 8, and 6 MeV/c, respectively. Note, for the ^{12}C data the K_3 and K_3^* momenta corresponding to the scattering off the ^{3}He and ^{3}H nuclei are virtually identical.

We suppose that a width of each momentum interval is determined by a NC movement in the transverse direction with respect to the proton beam. The setup horizontal angular acceptance in the medium elastic scattering by a moving four-nucleon cluster ($\sim 4.5^0$) is many time larger than that in the scattering by a resting correlation ($\sim 1^0$). This enables us to observe an angular distribution of the polarization $P_{\rm IV}$ in the scattering on a ^{4}He-like nucleon cluster within the IV momentum range. We expected to see a homogeneous distribution of the polarization as it was observed in the free elastic p^4He scattering shown in Fig. 5 [15]. Two horizontal oppositely

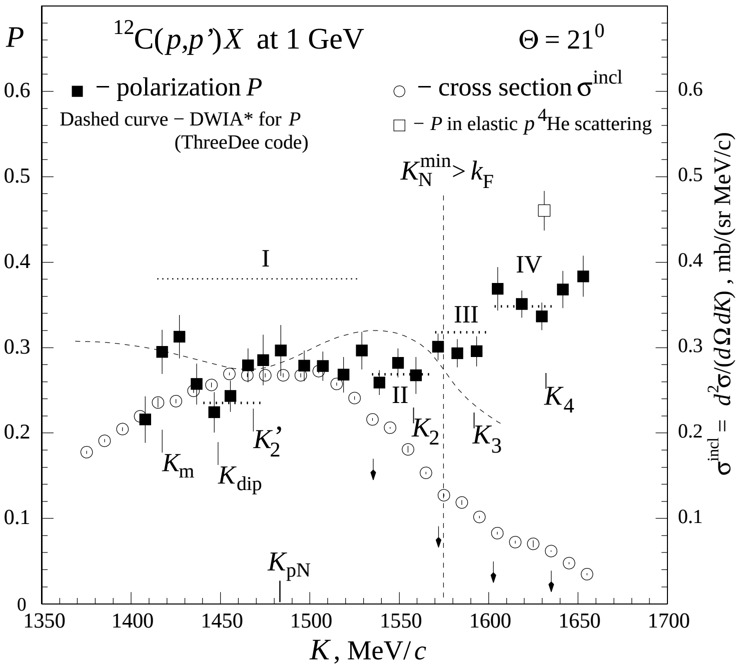

Figure 4. Polarization (black squares) and cross section (circles) of the ^{12}C$(p,p')X$ reaction at the angle of $\Theta = 21^0$ versus the scattered proton momentum K [13]. The empty square is the polarization in free elastic p^4He scattering [15]. The momentum intervals I–IV and corresponding dotted-line segments, the momenta $K_{\rm m}$, $K_{\rm dip}$, K_2', $K_{\rm pN}$, and K_2, K_3, K_4, and $K_{\rm N}^{\rm min}$, $k_{\rm F}$, the dashed curve and dashed vertical line (Fig. 3) were defined in the main body of the text.

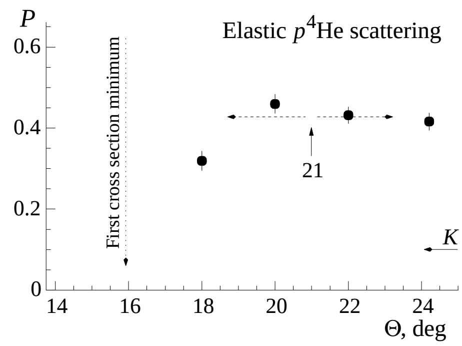

Figure 5. Angular dependence of the polarization in elastic p^4He scattering at 1 GeV [15]. The dashed horizontal arrows were defined in the text.

directed arrows indicate the angular range corresponding to the effective acceptance seen in the inclusive reaction in the momentum interval IV.

Important observation. The polarization ($P_{\rm IV}$) in the interval IV is less than that ($P_{^4{\rm He}}$) in the free elastic p^4He scattering (empty square) [15]. This can be due to the in-medium modification of proton interaction with the four-nucleon cluster. The relative polarization drop in the nuclear medium is about 20%. We found an approximately the same polarization drop in the scattering on the uncorrelated nuclear nucleons from a comparison of the polarizations calculated with (P_{DWIA^*}) and without (P_{DWIA}) taking into account the nuclear medium effect [13].

In the region I (indicated by a dotted-line segment), around the momentum K_{pN}, a contribution from multistep processes of nucleon knockout from nucleus can be sizable [16]. The outgoing proton momentum in these processes is lower than in the one-step (p, p') reaction under investigation. The two-step nucleon knockout process decreases the polarization at K less than K_{m} (Fig. 4) as well as the analyzing power in the similar experiment (LAMPF) at O.8 GeV [16]. We also see a dip in the polarization in a range of K around the momentum K_{dip} (for all nuclei investigated). There is no similar dip in the LAMPF analyzing power A_{y} in both experimental and theoretical data. The latter was obtained taking into account the multistep processes. This dip in the polarization may be due to the inelastic scattering by a two-nucleon correlation leading to its decay into two nucleons. The polarization in the process, as well as in the in-medium elastic scattering off the correlation in the range II, can be essentially smaller than that in the in-medium elastic scattering off the uncorrelated nuclear nucleons. In the short range correlation approach [9], two nucleons belonging to the two-nucleon correlation have oppositely directed momenta of nearly equal magnitude close to the Fermi momentum ($\sim$250 MeV/c, it corresponds to nucleon kinetic energy $\sim$35 MeV). The momentum K_2' (Fig. 4) was obtained in the kinematical program at an excitation energy ($\sim$70 MeV/c) of the residual nucleus (X = ^{10}B) equal to total kinetic energy of the nucleons into the resting correlation. The K_2' momentum is shifted with respect to the momentum K_2 (for the interval II) toward lower values of K. The momentum range, marked by the dotted-line segment, covering the momentum K_2' is determined by the correlation motion.

In Fig. 6, the data obtained in investigating the inelastic ^{40}Ca$(p, p')X$ reaction is presented [13]. All designations in the figure is the same as in Fig. 4. For the calcium nucleus we determined

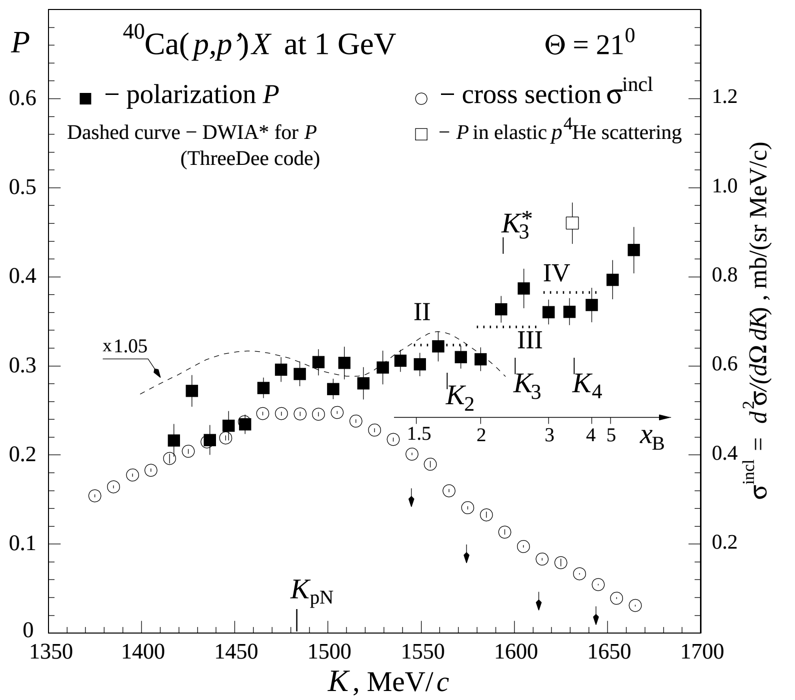

Figure 6. Polarization (black squares) and cross section (circles) of the ^{40}Ca$(p, p')X$ reaction at the angle of $\Theta = 21^0$ versus the scattered proton momentum K [13]. The empty square is the polarization in free elastic p^4He scattering [15]. The momentum intervals II–IV and corresponding dotted-line segments, the momenta K_{pN} and K_2, K_3, K_3^*, K_4, and the dashed curve were defined in the main body of the text. An additional axis for the Bjoken variable indication x_{B} was given.

the aforementioned momentum intervals II (1545–1575 MeV/c), III (1575–1610 MeV/c), and IV (1610–1645 MeV/c). Comparison with the carbon data:

1. The beginning of each interval for the ^{40}Ca nucleus is shifted with respect to that for the carbon nucleus by about 5 to 10 MeV/c toward higher values. The investigation of the ^{56}Fe

nucleus showed that this effect is not related to a bigger mass of the calcium nucleus.

2. The polarization in the interval III for the calcium data increases with K unlike the polarization in the scattering off the ^{12}C nucleus. It is possible that this is due to a dispersion effect because of a meaningful difference ($\sim$7 MeV/c) of the momenta K_3 and K_3^* corresponding to the in-medium elastic scattering on the ^{3}He and ^{3}H nuclei (the spectrometer momentum resolution was about $\sim$2.5 MeV/c). It is also assumed that the polarization in the elastic scattering on the ^{3}He nucleus is much bigger than that on the tritium nucleus [13]. In this case, when K is more than K_3^*, the scattering on the ^{3}He nucleus dominates and the averaged polarization has a largest value. In the region, where K is less than K_3^* (within the III momentum interval), processes of the scattering off these three-nucleon correlations are mixed and the averaged polarization decreases.

3. The polarizations in the interval IV (P_{IV}) in the scattering of the calcium and carbon nuclei are nearly identical [$P_{\rm IV}$(Ca) = 0.363 ± 0.009, $P_{\rm IV}$(C) = 0.348 ± 0.010].

In Fig. 7, the scattering cross section ratios for the (p, p') reaction with the ^{56}Fe and ^{12}C nuclei η(Fe/C), with the ^{56}Fe and ^{28}Si nuclei η(Fe/Si), and with the ^{56}Fe and ^{40}Ca nuclei η(Fe/Ca) are presented [14]. Main observations:

1. We see a step-function behavior of the scattering cross section ration η(Fe/C) in the region of K from 1560 to 1630 MeV/c covering the momentum intervals III and IV indicated by the dotted-line segments. Within the intervals a value of the η(Fe/C) ration does not depend substantially on K (i.e., scaling). This intervals coincide with analogues intervals observed in the polarization and cross section data for the carbon nucleus (Fig. 4), which are presumably due to the in-medium elastic scattering off three- and four-nucleon correlations [13]. According to the JLAB work [9], observation of such steps in the cross section ratio is a crucial test of the dominance of inclusive scattering off the short range correlations, and the steps are due to that an average nucleon density in the iron nucleus is bigger than that in the carbon nucleus [14].

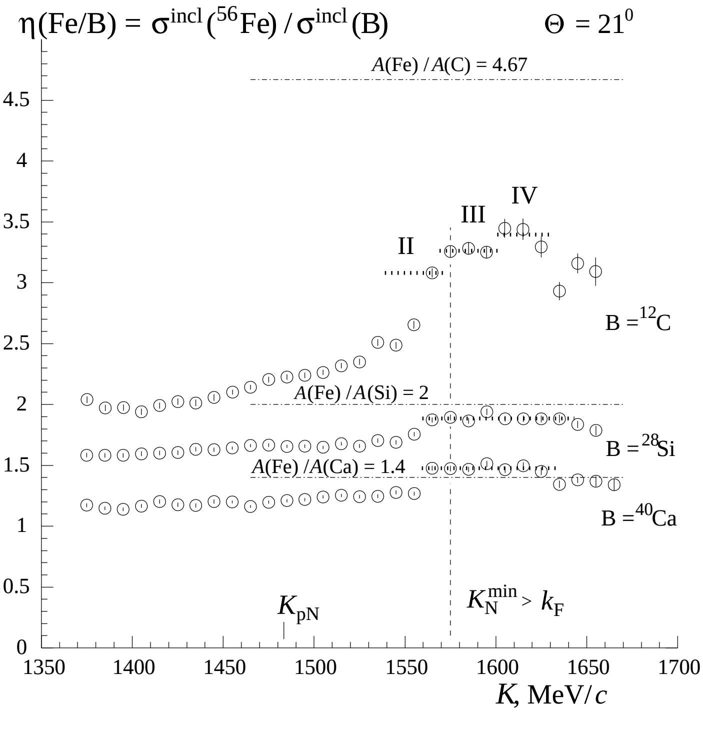

Figure 7. Scattering cross section ratios η(Fe/B) (circles), where B corresponds to the ^{12}C, ^{28}Si, or ^{40}Ca nucleus, versus the scattered proton momentum K [14]. The dashed vertical line represents the same as in Fig. 3 and Fig. 4. The dash-dotted horizontal lines correspond to the ratios of appropriate atomic numbers of the nuclei under investigation. The dotted-line segments cover the intervals II, III, IV, and 1560−1635 MeV/c. These intervals and momenta $K_{\rm pN}^{min}$, $k_{\rm F}$, and $K_{\rm pN}$ were defined in the text.

2. The scaling of the cross section ratios η(Fe/Si) and η(Fe/Ca) are observed in the same K region mentioned above. We do not see any steps in these ratios. It is possible that an average

nucleon density in the nuclei ^{28}Si, ^{40}Ca, and ^{56}Fe is the same. It is interesting that the values of these ratios are close (within the systematic errors of their determination) to those of the atomic number ratios A(Fe/Si) and A(Fe/Ca) (indicated by the dash-dotted line segments) [14].

4. Conclusion

A structure in the polarization and cross section of the (p, p') inelastic reaction with the nuclei ^{12}C and ^{40}Ca at 1 GeV and a laboratory scattering angle of $\Theta = 21^0$ was observed. This structure can be related to the in-medium elastic scattering on nucleon correlations in nuclei.

The scaling of the scattering cross section ratios off the nuclei under investigation (a value of the ratio is independent of the secondary proton momentum K) was observed in the high momentum range of $K = 1560{-}1635$ MeV/c.

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