QUASI-ELASTIC SCATTERING OF PROTON WITH 1 GEV ENERGY ON EIGHT-NUCLEON CLUSTER INSIDE NUCLEUS

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Available data on the polarization of the secondary proton (as a function of its momentum $K$) in the inelastic ($p, p'$) reactions with the $^9$Be, $^{12}$C, and $^{40}$Ca nuclei and differential cross section data (the momentum distributions) for the reactions at the initial proton energy 1 GeV and scattering angles $\Theta=21^\circ$ and $\Theta=24.5^\circ$ were analysed in a range of the high momenta $K$ close to the momentum corresponding to the proton elastic scattering off the investigated nucleus. A structure in the polarization and momentum distribution data at the high momentum $K$, related probably to quasi-elastic scattering off a $^8$Be-like nucleon cluster inside the nuclei, was observed.

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1 Introduction

This work is a part of the experimental program in the framework of which the effects of nucleon clusterization in nuclear matter is studied in the inclusive \((p, p')\) experiments at the PNPI synchrocyclotron with the 1 GeV proton beam \([1, 2, 3, 4, 5, 6, 7]\). The general layout of the experimental setup is presented in Fig. 1.

The proton beam was focused onto the target TS of the magnetic spectrometer MAP. The beam intensity was monitored by the scintillation telescope M1, M2, M3. The spectrometer was used to measure the momenta of the secondary protons from the inclusive \((p, p')\) reaction as well as their polarization. The momentum of the scattered proton \((K)\) was determined using the coordinate information from the proportional chamber PC2-X. The momentum resolution of the spectrometer (± 2.5 MeV/c) was estimated by measuring the width of the clearly separated \(2^+\) excited level in the \((p, p')\) reaction with the \(^{12}\text{C}\) nucleus at the scattering angle 21° under investigation (Fig. 2) \([3]\). In this measurement we also observed a peak (Fig. 2) which was first identified as the \(1^+\) excited level predicted in \([8]\). The polarization of secondary protons in the \((p, p')\) reaction was found from an azimuthal asymmetry of the proton scattering off the carbon analyzer A, using the track information from the proportional chambers (PC1-P4 and PC1′, PC4′) of the polarimeter. The main parameters of the MAP spectrometer and the polarimeter are given in \([3]\).

Earlier, the secondary proton polarization \((P)\) and its momentum distribution (differential cross section \(\sigma^{incl} = \frac{d^2\sigma}{d\Omega dK}\)) in the inelastic \((p, p')\) reaction with nucleus were measured at the scattered angle of \(\Theta=21^\circ\). The nuclei \(^9\text{Be}\) \([5]\), \(^{12}\text{C}\) \([3]\), \(^{28}\text{Si}\)
Background level

Figure 2: Momentum distribution in the inclusive reaction $^{12}\text{C}(p,p')X$ at a scattering angle $\Theta = 21^\circ$ [3].

$^{40}\text{Ca}$ [3], $^{56}\text{Fe}$ [4], and $^{90}\text{Zr}$ [5] were investigated. The structure in these experimental data was observed that possibly related to quasi-elastic scattering in the momentum intervals II, III, and IV on two-nucleon ($^2\text{H}$), three-nucleon ($^3\text{He}, ^3\text{H}$), and four-nucleon ($^4\text{He}$) correlations, respectively [9, 10].

Recently the momentum distributions of the secondary protons in the $(p,p')$ reaction with nuclei $^{9}\text{Be}$, $^{12}\text{C}$, and $^{40}\text{Ca}$ were measured at the scattering angle of $\Theta = 24.5^\circ$. The measurements were done in the range of high momenta of the scattered proton only.

2 Analysis of experimental data

The measured momentum distribution of the secondary proton produced in the reaction $^{9}\text{Be}(p,p')X$ at the angle of $\Theta = 21^\circ$ with the momentum $K$ and its polarization are presented in Fig. 3 and Fig. 4, respectively [3].

In Fig. 3, there is a wide peak in the momentum distribution with energy $\omega \equiv \omega_2 = 26$ MeV transferred into the nucleus. What is the nature of this peak? Each momentum interval II, III, and IV (Fig. 4) is related to the dominance of quasi-elastic scattering $^{9}\text{Be}(p,p' \text{NC})X$ ($X$ is a residual nucleus of the reaction) on a certain low-nucleon correlation (NC). These reactions are: $^{9}\text{Be}(p,p' \text{H})^7\text{Li}$ for the interval II; $^{9}\text{Be}(p,p' \text{He})^6\text{He}$ and $^{9}\text{Be}(p,p' \text{H})^6\text{Li}$ for the interval III;
In Fig. 3, there is a second rather wide peak in the momentum distribution with energy $\omega = \omega_1 = 9.7$ MeV transferred into the $^9$Be nucleus. The kinematic calculation shows that this peak possibly corresponds to quasi-elastic scattering on a $^8$Be - like nucleon cluster in the momentum interval VIII. The detection of this peak supports a theoretical model of the $^9$Be nucleus, within which the nucleus consists of a solid nucleon core ($^8$Be - like nucleon cluster) and an external neutron weakly bound to this core. A value of the measured polarization of the secondary protons produced at the scattering angle $\Theta = 21^\circ$ in the momentum interval VIII is given in Fig. 4.

The measured momentum distribution of the secondary protons produced in the reaction $^9$Be($p, p'$)$X$ at the scattering angle $\Theta = 24.5^\circ$ is shown in Fig. 5.
Figure 4: Polarization $P$ of the protons scattered at an angle $\Theta = 21^\circ$ (black squares) in the inclusive reaction $^9\text{Be}(p, p')X$ versus the secondary proton momentum $K$. The empty square corresponds to the polarization in the elastic $p - ^4\text{He}$ scattering \[12\]. The dotted lines cover the $K$ intervals II, III, and IV corresponding to quasi-elastic scattering on two-nucleon ($^2\text{H}$), three-nucleon ($^3\text{He}, ^3\text{H}$), and four-nucleon ($^4\text{He}$) correlations, respectively. The calculated secondary proton momenta for the maxima of the quasi-elastic peaks in the $^9\text{Be}(p, p'\text{NC})X$ reaction with the corresponding nucleon correlation (NC) are designated as $K_2$, $K_3$, and $K_4$. A narrow momentum interval VIII corresponds to the quasi-elastic proton scattering on a $^8\text{Be}$-like nucleon cluster. Momentum $K_{pN}$ corresponds to the maximum of the quasi-elastic peak in the proton scattering off nuclear nucleons.
Figure 5: Momentum distribution of the protons scattered at an angle $\Theta = 24.5^\circ$ in the inclusive reaction $^9\text{Be}(p, p')X$. $K$ is the secondary proton momentum. A difference of the secondary proton energy calculated for the elastic proton scattering off the nucleus under investigation and measured in the experiment is signified by $\omega$. The momentum interval VIII (IV) corresponds to quasi-elastic scattering on an $^8\text{Be}$ - like (a $^4\text{He}$ - like) nucleon cluster.

This distribution (Fig. 5) is similar to that shown in Fig. 3. There are also two wide peaks corresponding to the transferred energy $\omega = \omega_2 = 35\;\text{MeV}$ and $\omega = \omega_1 = 10.6\;\text{MeV}$. The peak at the $\omega = \omega_1$ is possibly related to quasi-elastic scattering on an $^8\text{Be}$ - like nucleon cluster.

In Fig. 6, the measured momentum distribution of the secondary protons produced in the reaction with carbon nucleus $^{12}\text{C}(p, p')X$ at the scattering angle $\Theta = 21^\circ$ is shown. A stepwise similar drop in the momentum distribution is observed, which corresponds possibly to quasi-elastic scattering on a nucleon cluster (NCL) inside the $^{12}\text{C}$ nucleus ($^9\text{Be}$, $^9\text{B}$, $^{10}\text{B}$, and $^8\text{Be}$) in a reaction $^{12}\text{C}(p, p'\text{NCL})\text{NC}$. Where NC is corresponding few-nucleon correlation ($^3\text{He}$, $^3\text{H}$, $^2\text{H}$, and $^4\text{He}$). This momentum distribution at the $K$ momentum greater than 1640 MeV/c is shown in Fig. 7. According to kinematic calculations, a rather narrow peak at $K = 1658\;\text{MeV/c}$ (at the $\omega_1 = 14.9\;\text{MeV}$) corresponds likely to quasi-elastic scattering $^{12}\text{C}(p, p'\text{^8Be})^4\text{He}$ on an $^8\text{Be}$ - like nucleon cluster inside the carbon nucleus. A value of the measured polarization of the secondary protons in the quasi-elastic scattering on this cluster is given in Fig. 8.
Figure 6: Momentum distribution of the protons scattered at an angle $\Theta = 21^0$ in the inclusive reaction $^{12}\text{C}(p, p')X$. $K$ is the secondary proton momentum. Dashed vertical line at the $K = 1610 \text{ MeV}/c$ indicates the region of large $K$, where effective registration of the secondary protons is carried out. In the upper right corner of the figure, reactions are presented in which the proton scattering by few-nucleon correlations ($^2\text{H}, ^3\text{H}, ^3\text{He},$ and $^4\text{He}$) was studied. Vertical arrows point to the calculated maxima of quasi-elastic peaks in scattering by residual nuclei ($^{8}\text{Be}, ^9\text{Be}, ^9\text{B},$ and $^{10}\text{B}$) in the reactions noted above. A difference of the secondary proton energy calculated for the elastic proton scattering off the nucleus under investigation and measured in the experiment is signified by $\omega$. Moreover $\omega = \omega_0$ and $\omega = \omega_1$ correspond to elastic scattering on the nucleus under study and quasi-elastic scattering on a $^8\text{Be}$-like nucleon cluster inside the $^{12}\text{C}$ nucleus. BL means background level.
Background level

Figure 7: Momentum distribution of the protons scattered at an angle Θ = 21° in the inclusive reaction $^{12}$C($p, p'\)X. $K$ is the secondary proton momentum. A difference of the secondary proton energy calculated for the elastic proton scattering off the nucleus under investigation and measured in the experiment is signified by $\omega$. Moreover $\omega = \omega_0$ and $\omega = \omega_1$ correspond to elastic scattering on the nucleus under study and quasi-elastic scattering on a $^8$Be-like nucleon cluster inside the $^{12}$C nucleus.

The measured momentum distribution of the secondary protons produced in the reaction with carbon nucleus $^{12}$C($p, p'\)X at the scattering angle Θ = 24.5° is presented in Fig. 9. This distribution is similar to the momentum distribution at the scattering angle Θ = 21° (Fig. 6). A stepwise similar drop in the momentum distribution is also observed, which corresponds possibly to quasi-elastic scattering on a nucleon cluster (NCL) inside the $^{12}$C nucleus ($^3$He, $^9$B, $^{10}$B, and $^8$Be) in a reaction $^{12}$C($p, p'\)NCL)NC. Where NC is corresponding few-nucleon correlation ($^3$He, $^3$H, $^2$H, and $^4$He). According to kinematic calculations, a peak at the transferred energy $\omega_1 = 18.4$ MeV to nucleus under investigation corresponds likely to quasi-elastic scattering $^{12}$C($p, p'\)^8$Be)$^4$He on a $^8$Be - like nucleon cluster inside the carbon nucleus.

When studying the ($p, p'$) reaction with $^{40}$Ca nucleus at a scattering angle of 21°, no structure was found in their momentum distribution, that could indicates proton scattering by a $^8$Be-like nucleon cluster inside this nucleus. However, at a scattering angle of 24.5° (Fig. 10), a bump in the momentum distribution is observed, that, according to kinematic calculations, can be associated with scattering by a $^8$Be-like nucleon cluster inside the $^{40}$Ca nucleus. In Fig. 11 corresponding to scattering at an angle of 21° on the Ca nucleus, an estimate of the polarization in quasi-elastic scattering on this cluster is given.
$^{12}\text{C}(p, p')X$ at 1 GeV

\[ \Theta = 21^0 \]

Quasi-elastic scattering on a $^8\text{Be}$-like nucleon cluster

$\omega_1 = 14.9 \text{ MeV}, \ K \sim 1658 \text{ MeV}/c$

Lower estimate of polarization measurement:

$P = 0.384 + - 0.024$

Figure 8: Polarization $P$ of the protons scattered at an angle $\Theta = 21^\circ$ (black squares) in the inclusive reaction $^{12}\text{C}(p, p')X$ versus the secondary proton momentum $K$ [3, 7]. The empty square corresponds to the polarization in the elastic $p-^4\text{He}$ scattering [12]. The dotted lines cover the $K$ intervals II, III, and IV corresponding to quasi-elastic scattering on two-nucleon ($^2\text{H}$), three-nucleon ($^3\text{He}, ^3\text{H}$), and four-nucleon ($^4\text{He}$) correlations, respectively. The calculated secondary proton momenta for the maxima of the quasi-elastic peaks in the $^{12}\text{C}(p, p' \ NC)X$ reaction with the corresponding nucleon correlation (NC) are designated as $K_2$, $K_3$, and $K_4$. Momentum $K_{pN}$ corresponds to the maximum of the quasi-elastic peak in the proton scattering off nuclear nucleons. The dashed curve presents the polarization calculated in the framework of a spin-dependent Distorted Wave Impulse Approximation taking into account the relativistic distortion of the nucleon spinor in nuclear medium (DWIA*) [3]. In this approach the proton scattering off the independent nuclear nucleons was taken into account only. The energy $\omega_1 = 14.9 \text{ MeV}$ transferred to the $^{12}\text{C}$ nucleus (Fig. 7) corresponds to quasi-elastic scattering on a $^8\text{Be}$-like nucleon cluster inside the nucleus.
Figure 9: Momentum distribution of the protons scattered at an angle $\Theta = 24.5^\circ$ in the inclusive reaction $^{12}\text{C}(p, p')X$. $K$ is the secondary proton momentum. Dashed vertical line at the $K = 1610 \text{ MeV/c}$ indicates the region of large $K$, where effective registration of the secondary protons is carried out. In the upper right corner of the figure, reactions are presented in which the proton scattering by few-nucleon correlations ($^2\text{H}, ^3\text{H}, ^3\text{He},$ and $^4\text{He}$) was studied. Vertical arrows point to the calculated maxima of quasi-elastic peaks in scattering by residual nuclei ($^8\text{Be}, ^9\text{Be}, ^9\text{B},$ and $^{10}\text{B}$) in the reactions noted above. A difference of the secondary proton energy calculated for the elastic proton scattering off the nucleus under investigation and measured in the experiment is signified by $\omega$. Moreover $\omega = \omega_0$ and $\omega = \omega_1$ correspond to elastic scattering on the nucleus under study and quasi-elastic scattering on a $^8\text{Be}$-like nucleon cluster inside the $^{12}\text{C}$ nucleus. BL means background level.
Figure 10: Momentum distribution of the protons scattered at an angle Θ = 24.5° in the inclusive reaction $^{40}\text{Ca}(p, p'X)$. $K$ is the secondary proton momentum. Dashed vertical line at the $K = 1610$ MeV/c indicates the region of large $K$, where effective registration of the secondary protons is carried out. Vertical arrow points to the calculated maximum of quasi-elastic peak in the scattering $^{40}\text{Ca}(p, p'\, ^8\text{Be})^{32}\text{S}$ by a $^8\text{Be}$-like nucleon cluster inside the $^{40}\text{Ca}$ nucleus. A difference of the secondary proton energy calculated for the elastic proton scattering off the nucleus under investigation and measured in the experiment is signified by $\omega$. Moreover $\omega = \omega_0$ and $\omega = \omega_1$ correspond to elastic scattering on the $^{40}\text{Ca}$ nucleus and quasi-elastic scattering on the $^8\text{Be}$-like nucleon cluster. BL means background level.
Figure 11: Polarization $P$ of the protons scattered at an angle $\Theta = 21^0$ (black squares) in the inclusive reaction $^{40}\text{Ca}(p,p')X$ versus the secondary proton momentum $K$. The empty square corresponds to the polarization in the elastic $p-^{4}\text{He}$ scattering [12]. The dotted lines cover the $K$ intervals II, III, and IV corresponding to quasi-elastic scattering on two-nucleon ($^2\text{H}$), three-nucleon ($^3\text{He}$, $^3\text{H}$), and four-nucleon ($^4\text{He}$) correlations, respectively. The calculated secondary proton momenta for the maxima of the quasi-elastic peaks in the $^{12}\text{C}(p,p' \text{NC})X$ reaction with the corresponding nucleon correlation (NC) are designated as $K_2$, $K_3$ ($K_3^*$), and $K_4$. Momentum $K_{pN}$ corresponds to the maximum of the quasi-elastic peak in the proton scattering off nuclear nucleons. The dashed curve presents the polarization calculated in the framework of a spin-dependent Distorted Wave Impulse Approximation taking into account the relativistic distortion of the nucleon spinor in nuclear medium (DWIA*) [3]. In this approach the proton scattering off the independent nuclear nucleons was taken into account only. The energy $\omega_1 = 33.7$ MeV transferred to the $^{40}\text{Ca}$ nucleus corresponds to quasi-elastic scattering on a $^8\text{Be}$-like nucleon cluster inside the nucleus.
3 Summary

A kinematic analysis of momentum distributions of the secondary protons in an inclusive \((p, p')\) reaction with \(^9\)Be, \(^{12}\)C, and \(^{40}\)Ca nuclei at an energy of 1 GeV and scattering angles of 21° and 24.5° is carried out. In a range of the high momenta close to the momentum corresponding to the proton elastic scattering off the nucleus under study, the analysis indicates quasi-elastic scattering by a \(^8\)Be-like nucleon cluster inside the nucleus. This observation supports a theoretical model of \(^9\)Be nucleus, within which the nucleus consists of a solid nucleon core and an external neutron weakly bound to this core.

For the scattering angle \(\Theta = 21^\circ\), an estimate of the secondary proton polarization in quasi-elastic scattering on a \(^8\)Be-like nucleon cluster is given for nuclei under investigation.

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