

Spin structure of the charge-exchange
process $n+p \rightarrow p+n$ at zero angle

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① Isotopic structure of NN-scattering

Operator describing the nucleon-nucleon scattering
(taking into account the isotopic invariance):

$$\hat{f}(\vec{p}, \vec{p}') = \hat{a}(\vec{p}, \vec{p}') + \hat{b}(\vec{p}, \vec{p}') \hat{\tau}^{(1)} \hat{\tau}^{(2)}$$

$\hat{\tau}^{(1)}, \hat{\tau}^{(2)}$ → vector Pauli operators in the isotopic space

$\hat{a}(\vec{p}, \vec{p}')$, $\hat{b}(\vec{p}, \vec{p}')$ → 4-row matrices in the spin space
of two nucleons;

\vec{p}, \vec{p}' → initial and final momenta
in the c.m. frame;

directions of \vec{p}' → defined within the solid angle
in the c.m. frame, corresponding to the front hemisphere.

Process of elastic neutron-proton scattering into the
back hemisphere → interpreted as the charge-exchange
process $n+p \rightarrow p+n$.

Matrices of amplitudes of proton-proton, neutron-neutron and neutron-proton scattering:

$$\underline{\hat{f}_{pp \rightarrow pp}(\vec{p}, \vec{p}') = \hat{f}_{nn \rightarrow nn}(\vec{p}, \vec{p}') = \hat{a}(\vec{p}, \vec{p}') + \hat{b}(\vec{p}, \vec{p}')}$$

$$\underline{\hat{f}_{np \rightarrow np}(\vec{p}, \vec{p}') = \hat{a}(\vec{p}, \vec{p}') - \hat{b}(\vec{p}, \vec{p}')}$$

Matrix of amplitudes of the charge transfer process:

$$\underline{\hat{f}_{np \rightarrow pn}(\vec{p}, \vec{p}') = 2\hat{b}(\vec{p}, \vec{p}') = \hat{f}_{pp \rightarrow pp}(\vec{p}, \vec{p}') - \hat{f}_{np \rightarrow np}(\vec{p}, \vec{p}')}$$

States with total isotopic spins $T=1$ ($\hat{\tau}^{(1)}\hat{\tau}^{(2)}=1$)

and $T=0$ ($\hat{\tau}^{(1)}\hat{\tau}^{(2)}=-3$) \Rightarrow

matrices describing NN-scattering in the states with

$T=1$ and $T=0$:

$$\begin{cases} \hat{f}^{(T=1)}(\vec{p}, \vec{p}') = \hat{a}(\vec{p}, \vec{p}') + \hat{b}(\vec{p}, \vec{p}') \\ \hat{f}^{(T=0)}(\vec{p}, \vec{p}') = \hat{a}(\vec{p}, \vec{p}') - 3\hat{b}(\vec{p}, \vec{p}') \end{cases} \Rightarrow$$

$$\Rightarrow \begin{cases} \hat{a}(\vec{p}, \vec{p}') = \frac{1}{4} (f^{\wedge(\tau=0)}(\vec{p}, \vec{p}') + 3f^{\wedge(\tau=1)}(\vec{p}, \vec{p}')) \\ \hat{b}(\vec{p}, \vec{p}') = \frac{1}{4} (f^{\wedge(\tau=1)}(\vec{p}, \vec{p}') - f^{\wedge(\tau=0)}(\vec{p}, \vec{p}')) \end{cases}$$

\Rightarrow we obtain in this representation:

$$\hat{f}_{pp \rightarrow pp}(\vec{p}, \vec{p}') = \hat{f}_{nn \rightarrow nn}(\vec{p}, \vec{p}') = f^{\wedge(\tau=1)}(\vec{p}, \vec{p}')$$

$$\hat{f}_{np \rightarrow np}(\vec{p}, \vec{p}') = \frac{1}{2} (f^{\wedge(\tau=1)}(\vec{p}, \vec{p}') + f^{\wedge(\tau=0)}(\vec{p}, \vec{p}'))$$

$$\hat{f}_{np \rightarrow pn}(\vec{p}, \vec{p}') = \frac{1}{2} (f^{\wedge(\tau=1)}(\vec{p}, \vec{p}') - f^{\wedge(\tau=0)}(\vec{p}, \vec{p}'))$$

Amplitude of the charge transfer reaction $\hat{f}_{np \rightarrow pn}(\vec{p}, \vec{p}')$
 defined in the front hemisphere $0 \leq \theta \leq \frac{\pi}{2}$, $0 \leq \varphi \leq 2\pi$
 ($\theta \rightarrow$ angle between the momenta of initial neutron and
 final proton, $\varphi \rightarrow$ azimuthal angle) \Rightarrow should be connected
 with the amplitude of neutron-proton scattering
 $\hat{f}_{np \rightarrow np}(\vec{p}, -\vec{p}')$ in the back hemisphere by the angle
 $\tilde{\theta} = \pi - \theta$ at the azimuthal angle $\tilde{\varphi} = \pi + \varphi$ in the c.m. frame.

Relation between $\hat{f}_{np \rightarrow pn}(\vec{p}, \vec{p}')$ and $\hat{f}_{np \rightarrow np}(\vec{p}, -\vec{p}')$,
 following from the antisymmetry of the state of two
 fermions with respect to the total permutation,
 including the permutation of momenta ($\vec{p}' \rightarrow -\vec{p}'$),
 permutation of spin projections and permutation
 of isotopic projections ($p \rightleftharpoons n$): $\hat{f}^{(\pi=1)}(\vec{p}, \vec{p}') = -\hat{P}^{(1,2)\wedge(\pi=1)} \hat{f}(\vec{p}, -\vec{p}')$,
 $\hat{f}^{(\pi=0)}(\vec{p}, \vec{p}') = \hat{P}^{(1,2)\wedge(\pi=0)} \hat{f}(\vec{p}, -\vec{p}')$
 $\rightarrow \hat{f}_{np \rightarrow pn}(\vec{p}, \vec{p}') = -\hat{P}^{(1,2)\wedge} \hat{f}_{np \rightarrow np}(\vec{p}, -\vec{p}')$

where $\hat{P}^{(1,2)}$ \rightarrow Hermitian operator of permutation of
spin projections:

$$\hat{P}^{(1,2)} = \frac{1}{2} \left(\hat{I}^{(1,2)} + \hat{\sigma}^{(1)} \hat{\sigma}^{(2)} \right)$$

$\hat{I}^{(1,2)}$ \rightarrow 4-row
unit matrix
 $\hat{\sigma}^{(1)}, \hat{\sigma}^{(2)}$ \rightarrow vector
Pauli operators

$$\langle m_1' m_2' | \hat{P}^{(1,2)} | m_1 m_2 \rangle = \delta_{m_1' m_1} \delta_{m_2' m_2} \rightarrow \text{matrix elements.}$$

[V. L. Lyuboshitz, M. I. Podgoretsky,
Yadernaya Fizika, 59 (3), 476 (1996)
(Phys. At. Nucl. 59(3), 449 (1996))]

In the case of the amplitude of the charge-exchange reaction $f_{np \rightarrow pn}(\vec{p}, \vec{p}') \rightarrow$ the two-row matrices with the index 1 act between the spin states of the initial neutron with the momentum \vec{p} and the final proton with the momentum \vec{p}' , and the two-row matrices with the index 2 act between the spin states of the initial proton with the momentum $-\vec{p}$ and the final neutron with the momentum $(-\vec{p}')$.

In the case of the amplitude of elastic scattering into the back hemisphere $f_{np \rightarrow np}(\vec{p}, -\vec{p}') \rightarrow$ the matrices with the index 1 act between spin states of the neutrons with the momenta \vec{p} and $(-\vec{p}')$, and the matrices with the index 2 act between spin states of the protons with the momenta $(-\vec{p})$ and \vec{p}' .

$$\hat{p}^{(1,2)} \hat{p}^{(1,2)+} = \hat{p}^{(1,2)+} \hat{p}^{(1,2)} = \hat{I}^{(1,2)}; \text{ hence } \rightarrow \text{the matrix equality}$$

$$\hat{f}_{np \rightarrow pn}^+(\vec{p}, \vec{p}') \hat{f}_{np \rightarrow pn}(\vec{p}, \vec{p}') = \hat{f}_{np \rightarrow np}^+(\vec{p}, -\vec{p}') \hat{f}_{np \rightarrow np}(\vec{p}, -\vec{p}')$$

As a result, at any polarizations of the initial nucleons the differential cross-sections of the exchange reaction $n+p \rightarrow p+n$ and the elastic np -scattering in the corresponding back hemisphere

coincide:

$$\frac{d\sigma_{np \rightarrow pn}}{d\Omega}(\vec{p}, \vec{p}') = \frac{d\sigma_{np \rightarrow np}}{d\Omega}(\vec{p}, -\vec{p}')$$

(just as it should hold)

However, the separation into the spin-dependent and spin-independent parts is different for the amplitudes $\hat{f}_{np \rightarrow pn}(\vec{p}, \vec{p}')$ and $\hat{f}_{np \rightarrow np}(\vec{p}, -\vec{p}')$!

② Nucleon charge-exchange process at zero angle

Spin structure of the amplitude of the nucleon charge-exchange reaction in the "forward" direction in the c.m. frame of the (np)-system:

$$\hat{f}_{np \rightarrow pn}(0) = c_1 \hat{I}^{(1,2)} + c_2 \left[\hat{\sigma}^{(1)} \hat{\sigma}^{(2)} - (\hat{\sigma}^{(1)} \vec{l})(\hat{\sigma}^{(2)} \vec{l}) \right] + c_3 (\hat{\sigma}^{(1)} \vec{l})(\hat{\sigma}^{(2)} \vec{l})$$

(\vec{l} - unit vector along the momentum of incident neutron).

Spin structure of the amplitude of elastic np-scattering in the "backward" direction:

$$\hat{f}_{np \rightarrow np}(\pi) = \tilde{c}_1 \hat{I}^{(1,2)} + \tilde{c}_2 \left[\hat{\sigma}^{(1)} \hat{\sigma}^{(2)} - (\hat{\sigma}^{(1)} \vec{l})(\hat{\sigma}^{(2)} \vec{l}) \right] + \tilde{c}_3 (\hat{\sigma}^{(1)} \vec{l})(\hat{\sigma}^{(2)} \vec{l})$$

Connection between the spin structure

of the amplitudes $\hat{f}_{np \rightarrow pn}(0)$ and $\hat{f}_{np \rightarrow np}(\pi)$:
 $\hat{f}_{np \rightarrow pn}(0) = -\hat{P}^{(1,2)} \hat{f}_{np \rightarrow np}(\pi)$; relations:

$$(\hat{\sigma}^{(1)} \hat{\sigma}^{(2)})(\hat{\sigma}^{(1)} \hat{\sigma}^{(2)}) = 3 \hat{I}^{(1,2)} - 2 \hat{\sigma}^{(1)} \hat{\sigma}^{(2)}$$

$$(\hat{\sigma}^{(1)} \hat{\sigma}^{(2)})(\hat{\sigma}^{(1)} \vec{l})(\hat{\sigma}^{(2)} \vec{l}) = \hat{I}^{(1,2)} \hat{\sigma}^{(1)} \hat{\sigma}^{(2)} + (\hat{\sigma}^{(1)} \vec{l})(\hat{\sigma}^{(2)} \vec{l})$$

As a result:

$$c_1 = -\frac{1}{2}(\tilde{c}_1 + 2\tilde{c}_2 + \tilde{c}_3); \quad c_2 = -\frac{1}{2}(\tilde{c}_1 - \tilde{c}_3); \quad c_3 = -\frac{1}{2}(\tilde{c}_1 - 2\tilde{c}_2 + \tilde{c}_3).$$

Differential cross-sections (for unpolarized nucleons)

$$\frac{d\sigma_{np \rightarrow pn}}{d\Omega}(0) = |c_1|^2 + 2|c_2|^2 + |c_3|^2 = \frac{1}{4}|\tilde{c}_1 + 2\tilde{c}_2 + \tilde{c}_3|^2 +$$

$$+ \frac{1}{2}|\tilde{c}_1 - \tilde{c}_3|^2 + \frac{1}{4}|\tilde{c}_1 - 2\tilde{c}_2 + \tilde{c}_3|^2 = |\tilde{c}_1|^2 + 2|\tilde{c}_2|^2 + |\tilde{c}_3|^2 = \frac{d\sigma_{np \rightarrow np}}{d\Omega}(\pi)$$

Amplitudes of "forward" proton-proton and neutron-proton elastic scattering have the analogous spin structure \Rightarrow due to the isotopic invariance

$$c_1 = c_1^{(pp)} - c_1^{(np)}; \quad c_2 = c_2^{(pp)} - c_2^{(np)}; \quad c_3 = c_3^{(pp)} - c_3^{(np)}$$

According to the optical theorem (using isotopic invariance)

$$\frac{4\pi}{k} \text{Im } c_1 = \frac{4\pi}{k} (\text{Im } c_1^{(pp)} - \text{Im } c_1^{(np)}) = \sigma_{pp} - \sigma_{np} = \sigma_{nn} - \sigma_{np}$$

$\sigma_{pp}, \sigma_{nn}, \sigma_{np} \rightarrow$ total cross-sections of interaction of two unpolarized protons (neutrons) and of an unpolarized neutron with an unpolarized proton, respectively.

$|\vec{p}| = k \rightarrow$ neutron momentum in the c.m. frame of the colliding nucleons.

Differential cross-section of the process $n+p \rightarrow p+n$
in the "forward" direction for unpolarized nucleons:

$$\frac{d\sigma_{np \rightarrow pn}}{d\Omega}(0) = |c_1|^2 + 2|c_2|^2 + |c_3|^2 =$$

$$= \frac{d\sigma_{np \rightarrow pn}^{(si)}}{d\Omega}(0) + \frac{d\sigma_{np \rightarrow pn}^{(sd)}}{d\Omega}(0).$$

Here: $\frac{d\sigma_{np \rightarrow pn}^{(si)}}{d\Omega}(0) = |c_1|^2 = (\text{Im } c_1)^2 + (\text{Re } c_1)^2 =$

$$= \frac{k^2}{16\pi^2} (\sigma_{pp} - \sigma_{np})^2 (1 + \alpha^2) \Rightarrow$$

$\left(\alpha = \frac{\text{Re } c_1}{\text{Im } c_1} \right) \Rightarrow$ spin-independent
part of the cross-section of "forward"
 charge transfer process, determined by the
difference of total cross-sections of unpolarized
proton-proton and neutron-proton interaction.

$$\frac{d\sigma_{np \rightarrow pn}^{(sd)}}{d\Omega}(0) = 2|c_2|^2 + |c_3|^2 \rightarrow$$

spin-dependent
part of the cross-section.

Transition to the differential cross-section $\left. \frac{d\tilde{\sigma}}{dt} \right|_{t=0} \rightarrow$
relativistic invariant $(t = -(p-p')^2 = (\vec{p} - \vec{p}')^2 - (E - E')^2 \rightarrow$
 \rightarrow square of 4-dimensional transferred momentum)

In the c.m. frame:

$$t = 2k^2(1 - \cos\theta); \quad \frac{d\tilde{\sigma}}{d(-\cos\theta)} = 2\pi \frac{d\tilde{\sigma}}{d\Omega}; \quad \frac{d\tilde{\sigma}}{dt} = \frac{1}{2k^2} \frac{d\tilde{\sigma}}{d(-\cos\theta)} = \frac{\pi}{k^2} \frac{d\tilde{\sigma}}{d\Omega}$$

$$\left. \frac{d\tilde{\sigma}_{np \rightarrow pn}}{dt} \right|_{t=0} = \left. \frac{d\tilde{\sigma}_{np \rightarrow pn}^{(si)}}{dt} \right|_{t=0} + \left. \frac{d\tilde{\sigma}_{np \rightarrow pn}^{(sd)}}{dt} \right|_{t=0};$$

$$\left. \frac{d\tilde{\sigma}_{np \rightarrow pn}^{(si)}}{dt} \right|_{t=0} = \frac{\pi}{k^2} |c_1|^2; \quad \left. \frac{d\tilde{\sigma}_{np \rightarrow pn}^{(sd)}}{dt} \right|_{t=0} = \frac{\pi}{k^2} (2|c_2|^2 + |c_3|^2).$$

So, we obtain:

$$\left. \frac{d\tilde{\sigma}_{np \rightarrow pn}}{dt} \right|_{t=0} = \left. \frac{d\tilde{\sigma}_{np \rightarrow pn}^{(sd)}}{dt} \right|_{t=0} + \frac{1}{16\pi} (\sigma_{pp} - \sigma_{np})^2 (1 + \alpha^2)$$

Impulse approach (the velocity of the initial neutron $v \gg \sqrt{\frac{\epsilon_d}{m_d}} \sim \frac{1}{20}$, ϵ_d - deuteron binding energy, m_d - deuteron mass, $\hbar = c = 1$) \Rightarrow

there exists a simple connection between the spin-dependent part of the differential cross-section of the charge-exchange reaction $n+p \rightarrow p+n$ at zero angle

$$\left. \frac{d\sigma_{np \rightarrow pn}^{(sd)}}{dt} \right|_{t=0} \quad (\text{not the "backward" elastic neutron-proton scattering!})$$

and the differential cross-section

of the deuteron charge-exchange breakup $d+p \rightarrow (pp)+n$ in the "forward" direction $\left. \frac{d\sigma_{dp \rightarrow ppn}}{dt} \right|_{t=0}$ at the deuteron

momentum $\vec{k}_d = 2\vec{k}_n$ (\vec{k}_n - initial neutron momentum).

Due to the isotopic invariance \Rightarrow the same connection with the process $p+d \rightarrow n+(pp)$ at the proton momentum $\vec{k}_p = \vec{k}_n$ and with the process $n+d \rightarrow p+(nn)$ at the neutron laboratory momentum \vec{k}_n .

For unpolarized particles we have:

$$\left. \frac{d\sigma_{dp \rightarrow ppn}}{dt} \right|_{t=0} = \frac{2}{3} \left. \frac{d\sigma_{np \rightarrow pn}^{(sd)}}{dt} \right|_{t=0}$$

[N. W. Dean, Phys. Rev. D5, 1661 (1972)

Phys. Rev. D5, 2832 (1972)

V. V. Glagolev, V. L. Lyuboshitz, V. V. Lyuboshitz,

N. M. Piskunov. JINR Communication E1-99-280,
Dubna, 1999.

R. Lednicky, V. L. Lyuboshitz, V. V. Lyuboshitz,

Proceedings of ISHEPP XVI, vol. I,

JINR E1,2-2004-76, Dubna, 2004, p.199

This formula remains valid as well if not only the
deuteron S-wave state, but also the deuteron D-wave
state is taken into account.

[At zero transfer of momentum, two protons produced in the deuteron charge-exchange breakup prove to be in the states with even orbital momentum ($L=0$, or $L=0$ and $L=2$ when taking into account the D-wave) in the deuteron rest frame. It follows from the antisymmetry of the total wave function of two protons that they are in the singlet state (total spin $S=0$) at even orbital momenta \Rightarrow the transition from the triplet state of the neutron and proton in the deuteron, into the singlet state of two protons may take place only due to the spin-dependent terms in the amplitude of the neutron-proton charge-exchange process $np \rightarrow pn$.]

So, finally the differential cross-section of the "forward" nucleon charge-exchange reaction takes the form:

$$\left. \frac{d\sigma_{np \rightarrow pn}}{dt} \right|_{t=0} = \frac{3}{2} \left. \frac{d\sigma_{dp \rightarrow ppn}}{dt} \right|_{t=0} + \frac{1}{16\pi} (\sigma_{pp} - \sigma_{np})^2 (1 + \alpha^2)$$

Thus, in principle, the modulus of the ratio of real and imaginary parts of the spin-independent charge transfer amplitude at zero angle ($|\alpha|$) may be determined using the experimental data on the total cross-sections of interaction of unpolarized nucleons and on the differential cross-sections of the processes $n+p \rightarrow p+n$ and $d+p \rightarrow (pp)+n$ in the "forward" direction.

At present there are no reliable experimental data on the differential cross-section of the deuteron charge-exchange breakup in the "forward" direction. Analysis shows: if we suppose that the real part of the spin-independent amplitude of charge transfer $np \rightarrow pn$ at zero angle is smaller or of the same order as compared with the imaginary part

$$\underline{(\alpha^2 \ll 1)} \Rightarrow$$

then it follows from the available experimental data on the differential charge-exchange cross-section

$$\left. \frac{d\sigma_{np \rightarrow pn}}{dt} \right|_{t=0} \quad \text{and the data on the total cross-sections$$

σ_{pp} and σ_{np} that the main contribution into the cross-sections

$$\left. \frac{d\sigma_{np \rightarrow pn}}{dt} \right|_{t=0} \quad \text{at neutron laboratory kinetic energy } T_n \gtrsim 200 \text{ MeV}$$

is provided namely by the spin-dependent part $\left. \frac{d\sigma_{np \rightarrow pn}^{(sd)}}{dt} \right|_{t=0}$.

P. F. Shepard et al. Phys. Rev. D10, 2735 (1974)

T. J. Delvin et al. Phys. Rev. D8, 136 (1973)

J. L. Friedes et al. Phys. Rev. Lett. 15, 38 (1965)

If the differential cross-section $\frac{d\sigma}{dt}$ is given in $\text{mbn} / \left(\frac{\text{GeV}}{c}\right)^2$ and the total cross-sections are given in mbn \Rightarrow

the spin-independent part of the charge-exchange cross-section

$$\left. \frac{d\sigma_{np \rightarrow pn}^{(si)}}{dt} \right|_{t=0} \approx 0.0512 (\sigma_{pp} - \sigma_{np})^2 (1 + \alpha^2)$$

$$\left(1 \text{ mbn} = 2.576 \left(\frac{\text{GeV}}{c}\right)^{-2} \right)$$

Estimates of the ratio $\frac{d\sigma_{np \rightarrow pn}^{(si)}}{dt} \Big|_{t=0} / \frac{d\sigma_{np \rightarrow pn}}{dt} \Big|_{t=0}$:

① $k_n = 0.7 \frac{\text{GeV}}{c}$; $\frac{d\sigma_{np \rightarrow pn}}{dt} \Big|_{t=0} = 268 \text{ mbn} \left(\frac{\text{GeV}}{c}\right)^{-2}$;

$\sigma_{pp} - \sigma_{np} = -22.6 \text{ mbn} \Rightarrow \frac{d\sigma_{np \rightarrow pn}^{(si)}}{dt} \Big|_{t=0} / \frac{d\sigma_{np \rightarrow pn}}{dt} \Big|_{t=0} \approx 0.1(1+\alpha^2)$

② $k_n = 1.7 \frac{\text{GeV}}{c}$; $\frac{d\sigma_{np \rightarrow pn}}{dt} \Big|_{t=0} \approx 37.6 \text{ mbn} \left(\frac{\text{GeV}}{c}\right)^{-2}$;

$\sigma_{pp} - \sigma_{np} = 10 \text{ mbn} \Rightarrow \frac{d\sigma_{np \rightarrow pn}^{(si)}}{dt} \Big|_{t=0} / \frac{d\sigma_{np \rightarrow pn}}{dt} \Big|_{t=0} \approx 0.136(1+\alpha^2)$

③ $k_n = 2.5 \frac{\text{GeV}}{c}$; $\frac{d\sigma_{np \rightarrow pn}}{dt} \Big|_{t=0} \approx 17.85 \text{ mbn} \left(\frac{\text{GeV}}{c}\right)^{-2}$;

$\sigma_{pp} - \sigma_{np} = 5.5 \text{ mbn} \Rightarrow \frac{d\sigma_{np \rightarrow pn}^{(si)}}{dt} \Big|_{t=0} / \frac{d\sigma_{np \rightarrow pn}}{dt} \Big|_{t=0} \approx 0.085(1+\alpha^2)$

Conclusion about the dominant role of the spin-dependent part of the amplitude of charge transfer $np \rightarrow pn$ at zero angle
 \Rightarrow confirmed also by the preliminary data on the differential cross-section of "forward" deuteron charge-exchange breakup, obtained in Dubna (Laboratory of High Energies, JINR).

4 Summary

1. The structure of the nucleon charge-exchange process $n + p \rightarrow p + n$ is theoretically investigated on the basis of the isotopic invariance of the nucleon-nucleon scattering amplitude.
2. The nucleon charge-exchange reaction at zero angle is analyzed. Due to the optical theorem, the spin-independent part of the differential cross-section of "forward" nucleon charge-exchange reaction for unpolarized particles is connected with the difference of total cross-sections of unpolarized proton-proton and neutron-proton scattering.
3. The spin-dependent part of the differential cross-section of neutron-proton charge-exchange reaction at zero angle is proportional to the differential cross-section of "forward" deuteron charge-exchange breakup.

Analysis of the existing data shows that the main contribution into the differential cross-section of "forward" nucleon charge-exchange reaction is provided namely by the spin-dependent part.