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V.P.Ladygin, N.B.Ladygina

SPIN STRUCTURE OF THE ^{3}He FROM THE $dd \to {}^3\mathrm{He}n$ REACTION

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Ладыгин В.П., Ладыгина Н.Б. E1-95-345

Спиновая структура ^{3}He из реакции $dd \to {}^3$Hen

Рассматриваются поляризационные наблюдаемые реакции $dd \to {}^3$Hen. Показана их высокая чувствительность к волновой функции ^{3}He на малых расстояниях. Использование поляризованной мишени и поляризованного пучка позволяет существенно расширить число возможных экспериментов и отделить структуру ^{3}He от механизмов реакции, используя различные относительные ориентации спинов начальных дейтронов.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Ladygin V.P., Ladygina N.B. E1-95-345

Spin Structure of the ^{3}He from the $dd \to {}^3$Hen Reaction

The polarization observables in the reaction $dd \to {}^3$Hen are considered. Their high sensitivity to the ^{3}He wave function at short distances is shown. Using of both polarized target and beam allows to extend sufficiently the number of possible experiments and to separate ^{3}He structure from the reaction mechanisms using different relative orientations of initial deuterons spins.

The investigation has been performed at the Laboratory of High Energies, JINR.

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1 Introduction

In recent past significant progress in the investigation of the few-body systems, especially of the deuteron and ^3He, have been achieved. Theoretical and experimental study of the light nuclei structure at short distances brings light on the transition regime from traditional soft hadron physics, where pion-nucleon mode of the nuclear matter dominates, to hard processes, where manifestation of quark-gluon degrees of freedom is possible, gives an important information about relativistic bound states, allowing to set a constrain on the different models of description of the nuclear structure.

The studying of the high-momentum component of nuclear wave functions is possible by processes with large momentum transfer to the nucleons of nuclei, both with electromagnetic and hadron probes. In spite of the different nature of electromagnetic and strong interactions combined analysis of these processes provides better understanding of the light nuclei structure and reaction mechanisms.

The nucleon momentum distributions extracted from inclusive $^3He(e,e')X$ [1] and exclusive $^3He(e,ep)d$ and $^3He(e,ep)pn$ data [2] taking into account corrections due to final state interaction (FSI) and meson exchange currents (MEC) [3] and from breakup $A(^3He,p)X$ data at zero angle [4] within Relativistic Impuls Approximation (RIA) [5] are in good accordance. On the other hand, the momentum distributions of spectators obtained from the exclusive measurements of the $^3He(p,2p)d$ and $^3He(p,pd)p$ reactions [6] and inclusive measurements $A(^3He,d)X$ breakup reaction [4], demonstrating a good agreement each with other, show an enhancement of extracted momentum density over calculations performed within RIA using a Faddeev calculation of the ^3He wave function [7] starting from momentum of spectator in the rest frame of ^3He $q > 150 MeV/c$. This discrepancy can be explained as the poor knowledge of ^3He structure at large momenta, as the importance of the reaction mechanisms.

The short-range spin structure of ^3He has not been investigated so widely as the momentum distributions to date. The results of experiment with a polarized ^3He target and polarized protons performed at 290 MeV at TRIUMF [8] indicate that analyzing powers A_{no}, A_{on} and A_{nn} are close to the IA predictions for the $^3\vec{H}e(\vec{p},2p)$ reaction, while for the $^3\vec{H}e(\vec{p},pn)$ there is a strong disagreement with these predictions. Polarized electron scattering on polarized ^3He target $^3\vec{H}e(\vec{e},e')X$ also can be used to study of the different components of the ^3He wave function [9]-[11]. However, to describe of the experimental results [12]-[15] obtained at different relative orientations of electron and ^3He spins it is necessary taking into account

FSI and MEC in addition to IA. Calculations performed for exclusive $^3\vec{H}e(\vec{e},e'p)d$ and $^3\vec{H}e(\vec{e},e'p)pn$ reactions [16] shown the sensitivity as to the various components of the ^3He wave function, as to FSI and MEC at momenta of spectator above $q > 250 MeV/c$ for these reactions.

These difficulties in the interpretation of existing data require to perform of new polarization experiments with ^3He. But the number of possible reactions for this purpose are limited by the absence of the polarized ^3He beam of high intensity and high efficiency polarimeters to measure the ^3He polarization.

In this paper we consider the polarization observables for the $dd \to {}^3Hen$ reaction, which belongs to the same class processes as the deuteron-proton backward elastic scattering $dp \to pd$, extensively studied in the last years [17, 18]. Some of these observables are very sensitive to the ^3He and deuteron wave functions at short distances. Using of both polarized deuteron beam and target with different relative spin orientations gives the opportunity, on the one hand, to increase sufficiently the number of possible experiments, and, on the other hand, to separate ^3He structure from the reaction mechanisms.

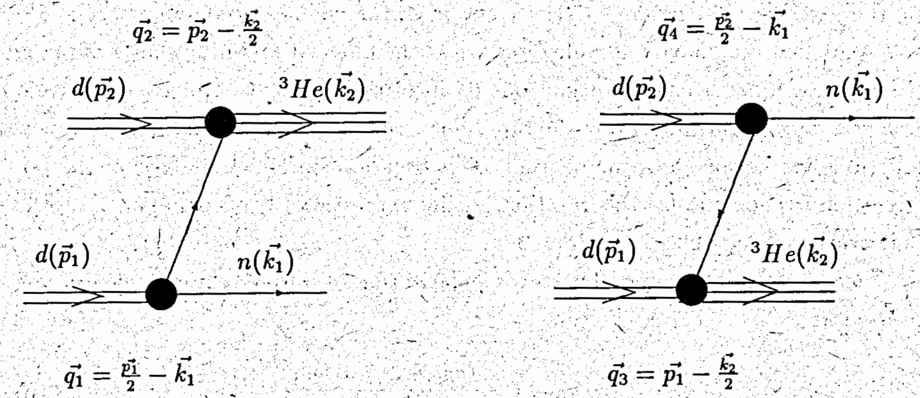
2 Spin effects for $dd \to {}^3Hen$ reaction

In the general case the $dd \to {}^3Hen$ process within framework of One-Nucleon-Exchange (ONE) can be presented as a sum of 2 diagrams (Fig.1). In this paper we propose to study polarization observables for this reaction in the collinear geometry. The corresponding matrix element can be written in the following form:

$$\begin{aligned} M = \psi_n^+\{ & ((\vec{\sigma}\vec{U_1})a_1(q_1) + (\vec{\sigma}\vec{n})(\vec{n}\vec{U_1})b_1(q_1)) \\ & ((\vec{\sigma}\vec{U_2})a_2(q_2) + (\vec{\sigma}\vec{n})(\vec{n}\vec{U_2})b_2(q_2)) + \\ & ((\vec{\sigma}\vec{U_1^*})a_2(q_3) + (\vec{\sigma}\vec{n})(\vec{n}\vec{U_1^*})b_2(q_3)) \\ & ((\vec{\sigma}\vec{U_2^*})a_1(q_4) + (\vec{\sigma}\vec{n})(\vec{n}\vec{U_2^*})b_1(q_4))\}\psi_\tau, \end{aligned} \tag{1}$$

where $\vec{\sigma}$ is the Pauli matrix, ψ_n and ψ_τ are the neutron and ^3He spinors, $\vec{n}$ is the unit vector along the relative momentum of initial particles, $\vec{U_1}$ and $\vec{U_2}$ are the deuterons polarization vectors, $a_1(q_i)$; $b_1(q_i)$, $a_2(q_j)$ and $b_2(q_j)$ are the combinations of the S- and D- waves in the deuteron and ^3He, respectively:

$$a_i(q) = u_i(q) + \frac{1}{\sqrt{2}}w_i(q), \qquad b_i(q) = -\frac{3}{\sqrt{2}}w_i(q) \tag{2}$$



a) b)

Fig.1 The ONE diagrams for $dd \to {}^3Hen$: a) t- channel diagram; b) u- channel diagram.

The relative momenta of the neutron and the proton for $d \to pn$ and the deuteron and the proton for $^3He \to dp$ vertexes are taken as arguments of the deuteron and ^3He wave functions.

We define the general spin observable for $dd \to {}^3Hen$ in terms of Pauli spin matrices σ for ^3He and neutron and a set of spin operators $\hat{S}$ for deuterons as

$$C_{\lambda,\kappa,\alpha,\beta} = \frac{Tr(M\hat{S}_\lambda\hat{S}_\kappa M^+\sigma_\alpha^\tau\sigma_\beta^n)}{Tr(MM^+)}, \tag{3}$$

where indices λ and κ refer to the polarization of the target and beam deuterons and indices α and β to the polarization of the ^3He and the neutron, respectively. We use a righthand coordinate system, where N, L, S are normal, longitudinal and sideways polarization of particles, respectively.

Using expression (1) for amplitude M one can obtain:

$$\begin{aligned} Tr(MM^+) = & (u_1^2(q_1) + w_1^2(q_1))(u_2^2(q_2) + w_2^2(q_2)) + \\ & (u_1^2(q_4) + w_1^2(q_4))(u_2^2(q_3) + w_2^2(q_3)) + \\ & 2(u_1(q_1)u_2(q_3) + w_1(q_1)w_2(q_3)) \\ & (u_1(q_4)u_2(q_2) + w_1(q_4)w_2(q_2)) \end{aligned} \tag{4}$$

Here we discuss the $dd \to {}^3Hen$ reaction in the collinear geometry, when ${}^3He$ and beam deuteron have the same direction of the momentum in the center of mass. Under these kinematical conditions one of diagram (Fig.1b) is strongly suppressed (a few orders of magnitude) by the rapid decreasing of the deuteron and ${}^3He$ wave functions versus spectator momentum. This occasion simplifies analysis of the polarization phenomena for this reaction. Using expression (3) one can calculate the polarization observables.

Tensor analyzing powers due to the polarization of initial deuterons can be expressed as:

$$C_{NN,0,0,0} = \frac{1}{2}\frac{w_1^2 - 2\sqrt{2}u_1 w_1}{u_1^2 + w_1^2} \qquad (5)$$

$$C_{0,NN,0,0} = \frac{1}{2}\frac{w_2^2 - 2\sqrt{2}u_2 w_2}{u_2^2 + w_2^2} \qquad (6)$$

In case of polarized beam(target) tensor analyzing power is mostly defined by the ${}^3He$ (deuteron) wave function. The expression for $C_{0,NN,0,0}$ agree with expression for ρ_{20} of the final deuteron from $A({}^3He, d)X$ breakup reaction [20]. But in case of $dd \to {}^3Hen$ reaction we may study ${}^3He$ spin structure without secondary scattering. Behaviour of tensor analyzing powers are presented in Fig.2. The dashed lines are obtained with presence of only S-wave in ${}^3He$, the full lines are taking into account both S and D waves. Calculations for all observables are performed taking into account both diagrams using ${}^3He$ and deuteron wave function from ref.[7] and ref.[19], respectively.

The expressions for coefficients of polarization transfer depend on the both wave functions:

$$C_{N,0,N,0} = \frac{2}{9}\frac{(u_1^2 - w_1^2 - u_1 w_1/\sqrt{2})}{u_1^2 + w_1^2}\frac{(u_2 - \sqrt{2}w_2)^2}{u_2^2 + w_2^2} \qquad (7)$$

$$C_{0,N,N,0} = \frac{2}{9}\frac{(u_1 - \sqrt{2}w_1)^2}{u_1^2 + w_1^2}\frac{(u_2^2 - w_2^2 - u_2 w_2/\sqrt{2})}{u_2^2 + w_2^2} \qquad (8)$$

$$C_{L,0,L,0} = \frac{2}{9}\frac{(u_1 + w_1/\sqrt{2})^2}{u_1^2 + w_1^2}\frac{(u_2^2 - w_2^2 + 4\sqrt{2}u_2 w_2)}{u_2^2 + w_2^2} \qquad (9)$$

$$C_{0,L,L,0} = \frac{2}{9}\frac{(u_1^2 - w_1^2 + 4\sqrt{2}u_1 w_1)}{u_1^2 + w_1^2}\frac{(u_2 + w_2/\sqrt{2})^2}{u_2^2 + w_2^2} \qquad (10)$$

Results of these calculations are presented in Fig.3 and Fig.4.

The expressions for spin correlations due to vector polarization of initial deuterons have the following form:

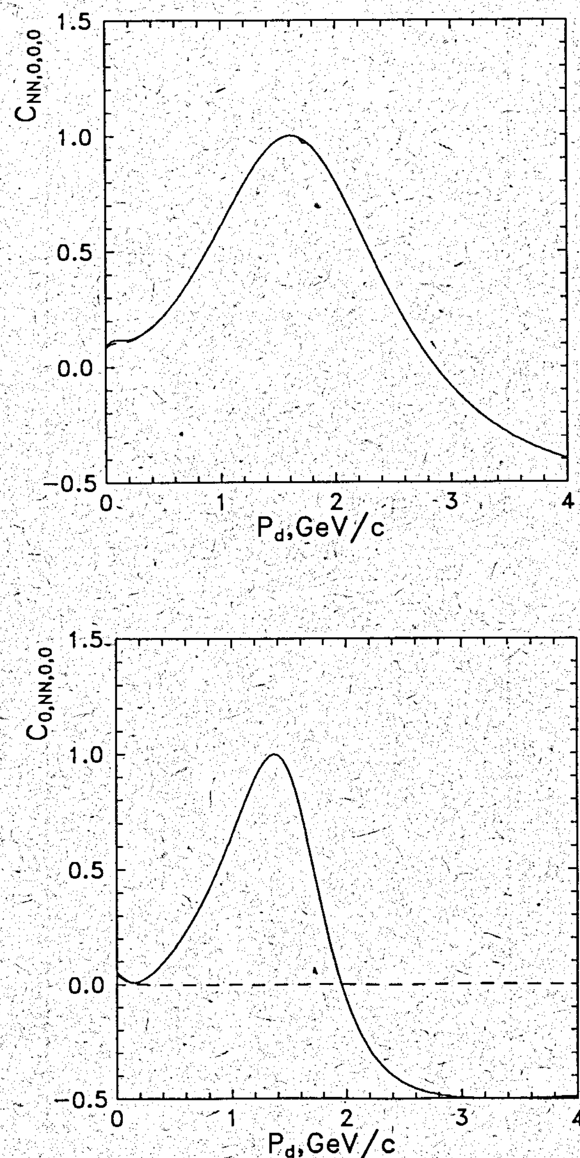


Fig.2 The tensor analyzing powers: a) $C_{NN,0,0,0}$ due to the polarization of the target deuteron; b) $C_{0,NN,0,0}$ due to the polarization of the beam deuteron. Dashed line - without D wave in ${}^3He$, full line - with D-wave.

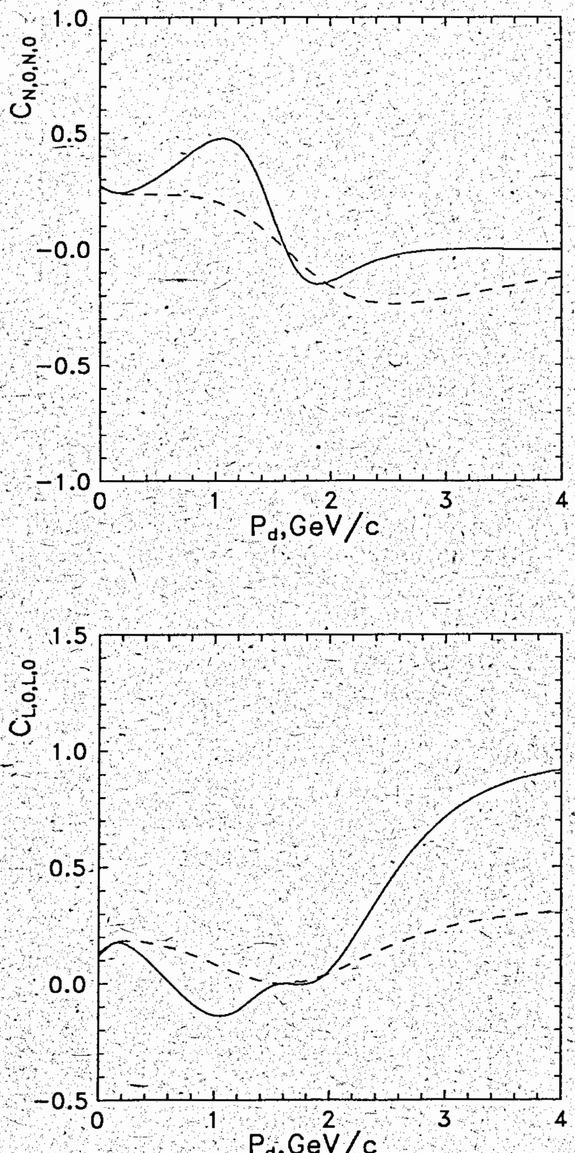


Fig.3 The coefficient of polarization transfer from polarized target deuteron to the ^3He : a) $C_{N,0,N,0}$ due to the transverse polarization of particles; b) $C_{L,0,L,0}$ due to the longitudinal polarization. Lines are as in Fig.2.

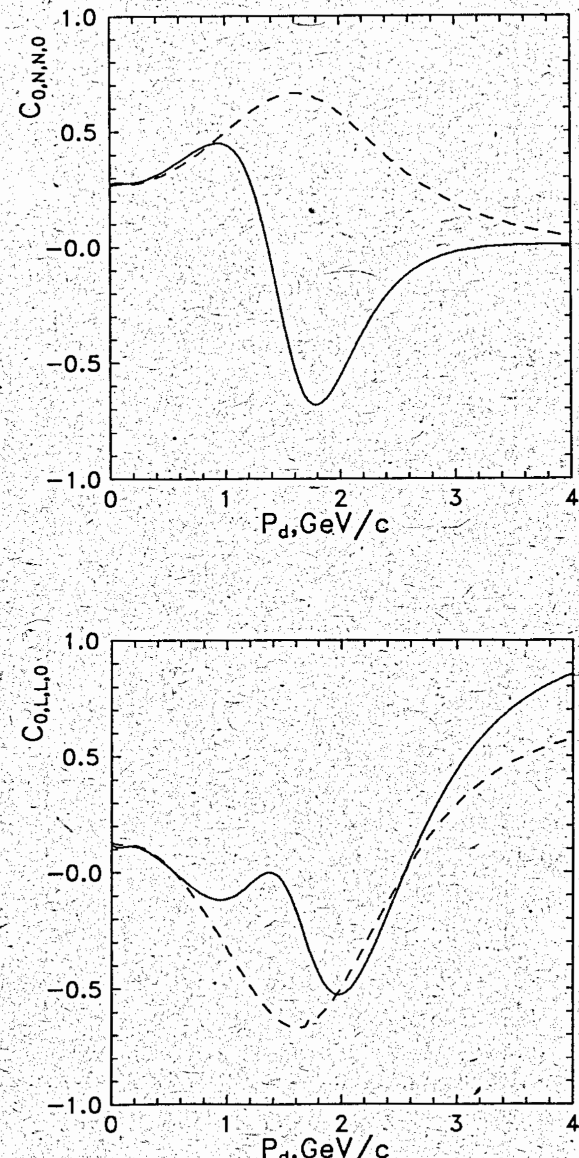
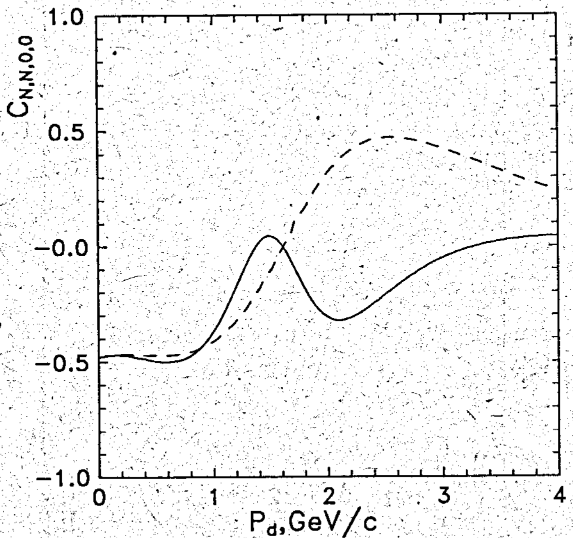


Fig.4 The coefficient of polarization transfer from polarized beam deuteron to ^3He : a) $C_{0,N,N,0}$ due to the transverse polarization of particles; b) $C_{0,L,L,0}$ due to the longitudinal polarization. Lines are as in Fig.2.



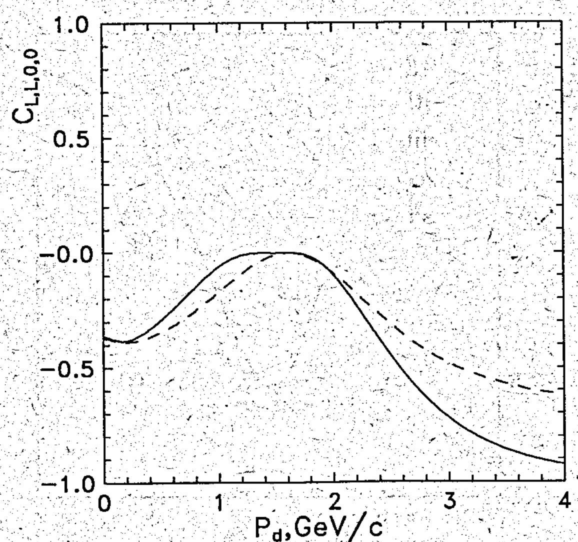


Fig.5 The vector spin correlations for $dd \to {}^3Hen$ reaction: a) $C_{N,N,0,0}$ due to the transverse polarization of both deuterons; b) $C_{L,L,0,0}$ due to the longitudinal polarization. Lines are as in Fig.2.

$$C_{N,N,0,0} = -\frac{4}{9}\frac{(u_1^2 - w_1^2 - u_1 w_1/\sqrt{2})}{u_1^2 + w_1^2}\frac{(u_2^2 - w_2^2 - u_2 w_2/\sqrt{2})}{u_2^2 + w_2^2} \qquad (11)$$

$$C_{L,L,0,0} = -\frac{4}{9}\frac{(u_1 + w_1/\sqrt{2})^2}{u_1^2 + w_1^2}\frac{(u_2 + w_2/\sqrt{2})^2}{u_2^2 + w_2^2} \qquad (12)$$

The sign of these observables is negative at small relative momenta of initial deuterons what is easy to understand. Since two protons in the ^3He must have opposite directions of spins due to the Pauli principle, the maximal yield of ^3He will be in case of opposite orientations of the initial deuterons spins. It should be noted that for processes $dp \to pd$ [21] and $d\,{}^3He \to {}^3Hed$ the spin correlations are positive at small momenta. Spin correlations due to the normal and longitudinal polarization of both deuterons are presented in Fig.5.

We would like to note, that most of considered observables are sensitive to the ^3He structure at initial momenta of deuteron 0.7 - 3.0 GeV/c, that corresponds to high relative momenta of the dp pair in the ^3He. In this range the relativistic effects, as well as non nucleonic degrees of freedom start to be very sufficient and must be taken into account in addition to simple ONE.

All polarization observables considered above are T-even. Note the study of T-odd effects for this reaction is the great importance. Theoretical calculations give the nonzero value of $C_{N,LS,0,0}$ even within framework of ONE. For more complete analysis it is necessary to consider the additional mechanisms, for instance Δ excitation in the intermediate state or 3-body forces [22]. Two deuterons in the initial state for this reaction give a lot of possibilities to study such kind of effects in the first scattering. Spin correlation parameter $C_{N,LS,0,0}$ (or $C_{L,NS,0,0}$) proposed to be measured for $dp \to {}^3He\pi^o$ and $dp \to pd$ reactions [23, 24] also can be measured for this reaction to understand the features of reaction mechanism and to separate it from the ^3He structure.

3 Conclusions

We considered the polarization observables for $dd \to {}^3Hen$ reaction within ONE approximation. It is shown the high sensitivity some of them to the spin structure of ^3He, especially over range 0.7-3.0 GeV/c of initial momenta of deuteron in laboratory.

The most realizable experiments for this reaction in addition to measured cross section [25, 26] are the study of the tensor analyzing power $C_{0,NN,0,0}$ and spin correlation $C_{N,N,0,0}$ due to the transverse polarization of both initial deuterons. Such investigations could be performed at SATURNE, COSY and in Dubna.

The next step is the measurement of the T-odd observables like $C_{N,LS,0,0}$ for this reaction, what could give an important information about reaction mechanisms and allow to correctly extract the spin structure of ^3He. In principle, this experiment could be done using extracted polarized deuteron beam of new superconducting accelerator NUCLOTRON and installed polarized target in Dubna.

Performance of these experiments is also important from the point of view of using polarized ^3He as a polarized neutron target to study the neutron spin structure functions [27] from deep inelastic scattering, as well as to extract the neutron form factors from quasi-elastic electron-^3He scattering.

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