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RELATIVISTIC IMPULSE APPROXIMATION AND DEUTERON SPIN STRUCTURE

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Introduction

The research of the deuteron structure in the relativistic range is of eminent interest for relativistic nuclear physics in connection with fundamental problems - confinement, spin crisis, vacuum structure, etc. It is known that the deuteron is the most simple bound system consisting of nucleons and therefore it was intensively investigated experimentally as well as theoretically. The existence of relativistic polarized deuteron beams (Dubna, Saclay) opens further possibilities and the hope to receive new information on the high momentum component of the deuteron - the strong-coupling polarized state of the system when its size becomes less than one of the free constituents and in this way forms a droplet of quark matter.

The simplest reaction and the basic one to understand the deuteron structure itself, the peculiarities and mechanisms of hadron-deuteron and nucleus-deuteron interactions is the $p + D \to p' + X$ process in the kinematical region forbidden for single nucleon targets.

The experimental data for the fragmentation cross section of the unpolarized deuteron was presented in Ref. [1-3]. This data was numerically discussed in the framework of relativistic dynamics on the light-front [2-6]. In the analysis were used relativistic wave functions obtained from nonrelativistic ones (Paris, Bonn, Reid). The argument of the latter means the relative nucleon momentum in the center of mass frame of the nucleon pair. The relativistic kinematic was taken into account as well. The analysis of this data shows that the spectator mechanism dominates in the region $q < 0.2$ GeV/c (q is the nucleon momentum in the deuteron rest frame). A shoulder appeared in the region $q = 0.2 - 0.4$ GeV/c and enhances the theoretical calculations based on the impulse approximation with different deuteron wave functions. This enhancement was connected with the resonance pion mechanism due to the Δ-isobar production. At the same time the value of this contribution is strongly depending on the off-mass shell behaviour of the $NN \to \pi X$ vertex. The range of momentum $q > 0.4$ GeV/c up to the kinematic limit is extremely interesting because namely in this range according to theoretical assumptions the transition to the quark level may be possible and the number of final states of the $p + D \to p' + X$ process is strongly restricted.

The experimental results of the fragmentation process for tensor polarized deuterons to protons was presented in Ref. [3,7]. The tensor analyzing power T_{20} was measured at Dubna up to $q = 0.51$ GeV/c and at Saclay up to $q = 0.42$ GeV/c. The theoretical description of T_{20} up to $q = 0.2$ GeV/c including only spectator mechanism is in good agreement with the data. In the intermediate region, contributions from different reaction mechanisms are obvious and their magnitudes are intensively investigated [8,9]. In the deep cumulative range ($q > 0.4$ GeV/c) strong disagreement between the data and standard calculations in the impulse approximation is observed. It was shown in Ref. [11] that the momentum of the incident proton at Dubna and Saclay is not sufficient to transit to the asymptotic regime where mass corrections of the $NN \to \pi X$ vertex and the absence of the cross section factorization must be taken into account. Under these assumptions the calculated momentum dependence of T_{20} on the incident proton momentum is in good agreement with the observed data.

The last experimental data on the vector polarized deuteron fragmentation to polarized protons was presented in Ref. [12,15]. This data was analyzed in Ref. [10] taking the rescattering and absorption mechanisms into account. In Ref. [11] the dependence of vector polarization transfer coefficient (K) on the incident proton momentum and the asymptotic behaviour of this observable were predicted.

In the present paper we consider the fragmentation processes $p + \vec{D} \to p' + X$, $p + \vec{D} \to \vec{p}\,' + X$, $p + D \to p' + X$ of tensor, vector and unpolarized deuterons to protons in the framework of the covariant approach in the light cone variables on the basis of the relativistic deuteron wave function with one nucleon on-mass shell [16-19]. We investigate the dependence of the tensor analyzing power T_{20} and vector polarization transfer coefficient K on the momentum of nucleon-spectator scattering at the angle $\theta_{p'} = 140°, 180°$ and the momentum of the incident proton $k_p = 4.55, 8.9, 50, 10^3$ (GeV/c). Calculation of polarization characteristics for different deuteron and proton spin orientations were made. The obtained results were compared with the asymptotic behaviour of these observables and the experimental data. The experimental verification of the predicted momentum and angular dependencies of the tensor analyzing power and the vector polarization transfer coefficient near the kinematical limit is of great interest.

1. Relativistic Impulse Approximation for the Deuteron

The impulse approximation is based on the assumption of the independent interaction of the incident particle (h) with constituents (N) of

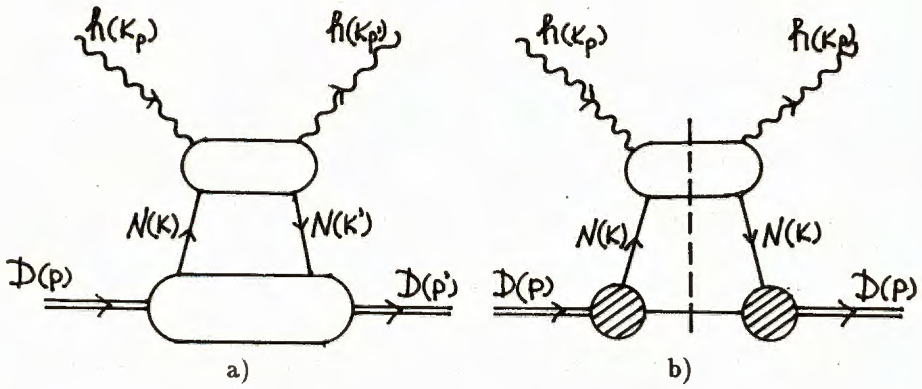


Figure 1: The amplitude of the $h + D \to h' + D'$ process in the IA (a). The imaginary part of the forward amplitude of the $h + D \to h + D$ process in the IA (b).

the deuteron (D). In this approximation the amplitude of the process is described by the Feynman diagram (Fig.1(a)).

Here $k_p(k_{p'})$, $p(p')$, $k(k')$ are momenta of the incident (final) particle, the deuteron and of the deuteron constituent, respectively. The top block is the amplitude of the $h + N \to h' + N'$ process, the bottom one is the amplitude of the $\bar{N} + D \to \bar{N}' + D'$ process.

In the nonrelativistic limit ($k^2 \simeq m^2, k'^2 \simeq m^2$) both nucleons are near mass-shell due to the small binding energy $\epsilon_D \ll m$. The constituents of the deuteron are nucleons. This assumption is proved experimentally. All deuteron models take this fact into account. In this limit according to the optical theorem the imaginary part of the forward scattering amplitude Fig.1(b) is connected with the cross section of the process. The proton deuteron cross section (or other observables) is expressed via the proton constituent cross section and the deuteron wave function. The hypothesis of the amplitude factorization was used as well.

In the RIA the one nucleon approximation is widely used too. The basic object of the investigation is the DNN vertex connected with the relativistic deuteron wave function (RDWF). Different relativistic approaches [4,5,19-21] were used to construct the RDWF. In the framework of covariant approaches in the relativistic region the constituents leave the mass shell and their properties may be different from free ones. Therefore the hypothesis of the amplitude factorization and consequently the cross section factorization may be violated. Note that in these approaches the DNN vertex describes not only the NN component of RDWF (S and D-waves) but also the $N\bar{N}$ pair production component of the RDWF (P-wave). In the relativistic region the contribution of the last mechanism may be considerable and the investigation of it may give the information on the vacuum structure.

2. Tensor Analyzing Power T_{20} of the $p + \vec{D} \to p' + X$ Process in the Relativistic Impulse Approximation

In the RIA the tensor analyzing power T_{20} of the $p+\vec{D} \to p'+X$ process in the framework of the covariant formalism in the light-cone variables with the RDWF [18] is defined by the formula

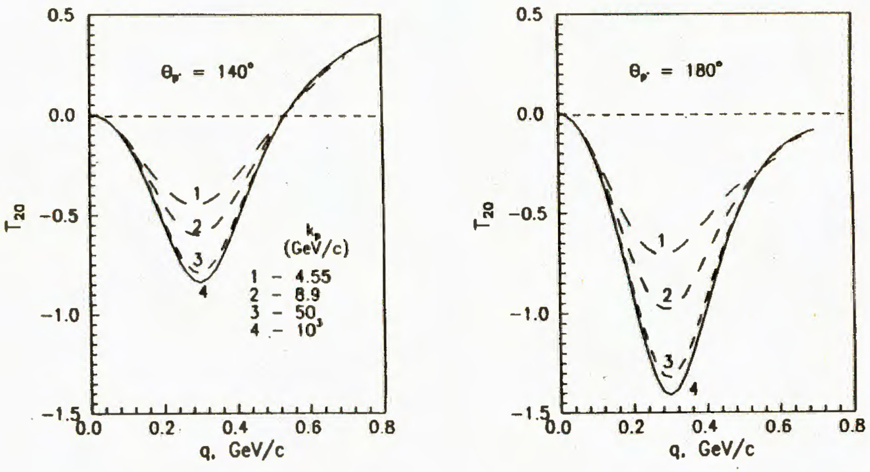
$$T_{20} = \frac{\sqrt{2}}{3} \cdot \frac{Sp\{A^{zz}_{(u)} \cdot \rho^{(T)}_{zz}\}}{Sp\{A^{\alpha\beta}_{(u)} \cdot \rho^{(u)}_{\alpha\beta}\}}.$$

Here $\rho^{(u)}_{\alpha\beta}, \rho^{(T)}_{\alpha\beta}$ are the unpolarized and the tensor polarized parts of the polarization deuteron density matrix. The tensor $A^{(u)}_{\alpha\beta}$ is expressed via the DNN vertex function Γ_α as follows

$$A^{(u)}_{\alpha\beta} = (m + \hat{k})^{-1}\bar{\Gamma}_\alpha(m + \hat{q})\Gamma_\beta(m + \hat{k})^{-1}(\hat{k}_p + \alpha m + \beta\hat{k}).$$

Figure 2 shows calculation results of the dependence of T_{20} on the momentum of the proton-spectator scattered at the angle $\theta_{p'} = 140°, 180°$ for the momenta $k_p = 4.55, 8.9, 50, 10^3$ GeV/c of the incident proton. During the calculation the mass parameters $\alpha = 1.$, $\beta = 0.$ were used. It is seen a noticeable dependence of T_{20} on the momentum k_p. With increasing k_p the T_{20} tends to the asymptotic limit. Note that all curves at $\theta_{p'} = 180°$ do not cross the dashed line, with decreasing $\theta_{p'}$ they move up and cross the dashed line at $q = 0.54$ GeV/c.

Figure 3 shows the comparison of the our results of T_{20} with experimental data [3,7]. Good agreement between theory and experiment can be seen at $k_p = 4.55$ GeV/c. At the low momentum $k_p = 1.75$ GeV/c it is necessary a more detailed calculation of the exclusive $p + D \to p' + p + n$ process to describe the inclusive $p + D \to p' + X$ one. During the calculation parameters $\alpha = 0.5$, $\beta = 0.$ were used. Note that our curves for all



a) b)

Figure 2: Tensor analyzing power T_{20} of the $p + \vec{D} \to p' + X$ process in the RIA: (a) $\theta_{p'} = 140°$, (b) $\theta_{p'} = 180°$.

momenta k_p at $\theta_{p'} = 180°$ don't cross the dashed line in contrary to other results [3,6,7]. The reason of this, in our opinion, is the violation of the amplitude factorization in the relativistic region.

3. Vector Polarization Transfer Coefficient of the $p + \vec{D} \to \vec{p}\,' + X$ Process in the Relativistic Impulse Approximation

The vector polarization transfer coefficient from deuteron to proton is able to give independent information on the deuteron spin structure in the relativistic region. In the RIA this observable in the framework of covariant formalism in the light-cone variables [19] is defined by formula

$$K = \frac{Sp\{A^{\alpha\beta}_{(v)} \cdot \rho^{(v)}_{\alpha\beta}\}}{Sp\{A^{\alpha\beta}_{(u)} \cdot \rho^{(u)}_{\alpha\beta}\}}.$$

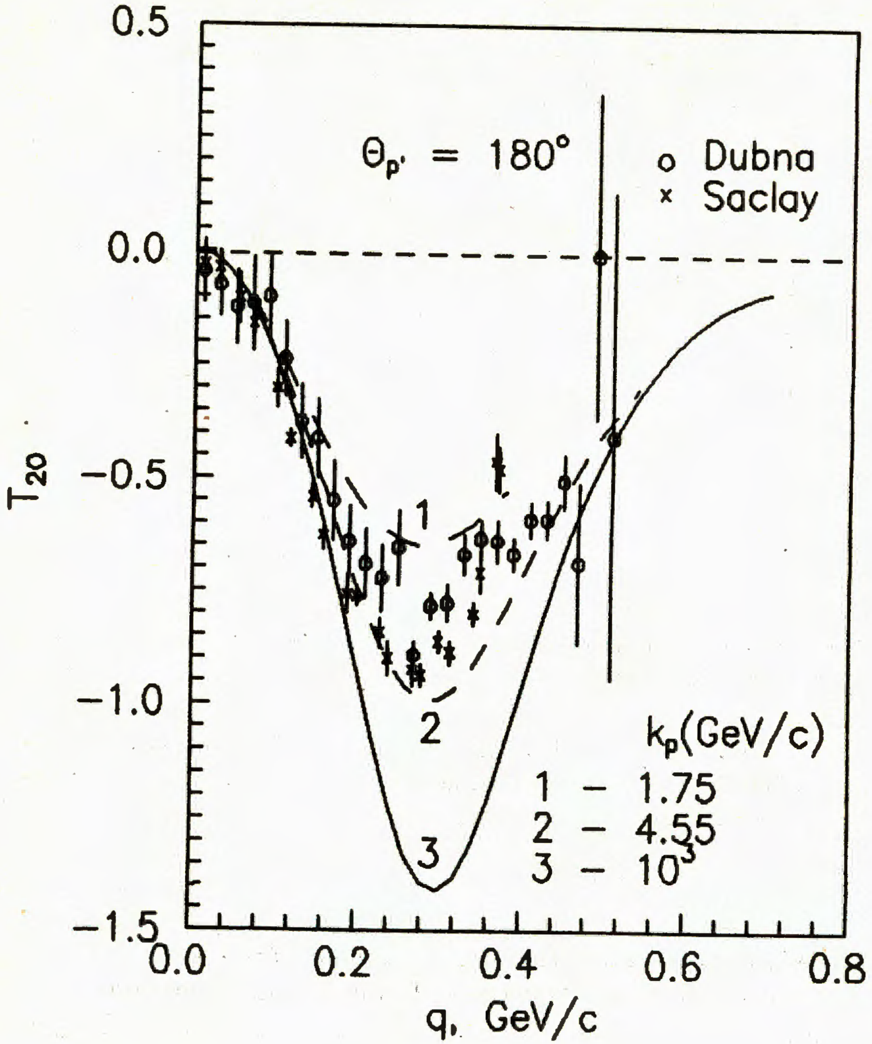


Figure 3: Tensor analyzing power T_{20} of the $p + \vec{D} \to p' + X$ process in the RIA. Experimental data: o - Dubna [7], × - Saclay [3].

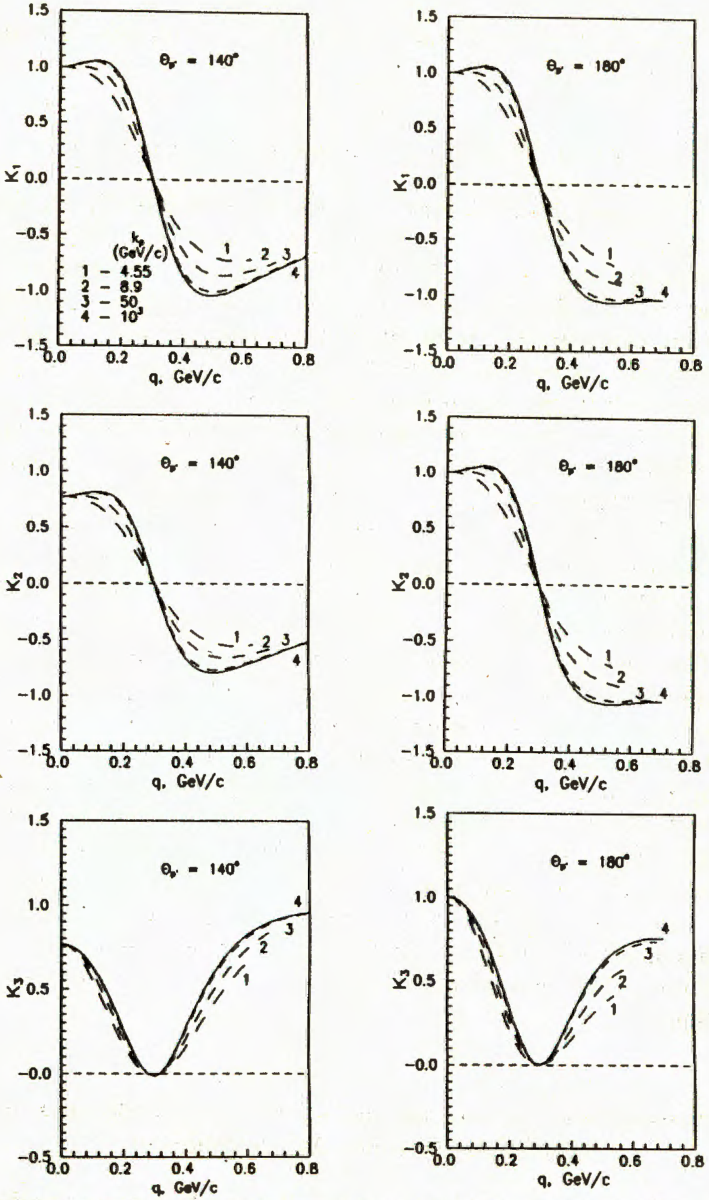


Figure 4: Vector polarization transfer coefficient for the $p + \vec{D} \to \vec{p}\,' + X$ process in RIA. (a) - noncoplanar and (b,c) - coplanar kinematics.

Here $\rho^{(v)}_{\alpha\beta}$ is the vector part of the polarization deuteron density matrix. The tensor $A^{(v)}_{\alpha\beta}$ is expressed as follows

$$A^{(v)}_{\alpha\beta} = (m+\hat{k})^{-1}\bar{\Gamma}_\alpha\gamma_5\hat{s}(m+\hat{q})\Gamma_\beta(m+\hat{k})^{-1}(\hat{k}_p+\alpha m+\beta\hat{k}).$$

Figure 4 shows calculation results of the dependence of K_1, K_2, K_3 on the proton-spectator momentum and the scattering angles $\theta_{p'} = 140°, 180°$ for the momenta $k_p = 4.55, 8.9, 50, 10^3$ GeV/c of the incident proton. The parameters $\alpha = 1.$, $\beta = 0.$ were used. Also various kinematics (noncoplanar - (a) and coplanar - (b,c)) for different deuteron and proton-spectator spin orientations are considered. In the first kinematic (a) spin vectors of the deuteron and the proton-spectator are perpendicular to the scattering plane. In the other cases their spin vectors lie on the scattering plane. They are perpendicular (b) or parallel (c) to momenta of the incident proton and the proton-spectator, respectively.

In Fig.4(a),(b) it is shown that the curves for $\theta_{p'} = 180°$ do not differ from each other. But with decreasing $\theta_{p'}$ these curves have different behaviour. They are tending to the asymptotic behavior with increasing k_p and have a node near the momentum $q = 0.3$ GeV/c. Curves in Fig.4(c) have different qualitative behaviour from the above ones and a strong angular dependence both at small $q < 0.1$ GeV/c and large $q > 0.4$ GeV/c.

Figure 5 shows our calculation results and experimental data [12-15] on the vector polarization transfer coefficient in the first kinematic. Dubna data [15] is preliminary. Good agreement between theory and experiment is observed. During the calculation the mass parameters $\alpha = 0.5$, $\beta = 0.$ were used. The comparison of Saclay and Dubna data shows a similar dependence on the incident proton momentum. Such a dependence was predicted in Ref. [11]. The continuation of the measurement of K_1 to the region $q = 0.5 - 0.6$ GeV/c is of great interest for the understanding of the deuteron spin structure and the comparision with other theoretical calculations.

4. Inclusive Cross Section for the $p + D \to p' + X$ Process in the Relativistic Impulse Approximation

Now we present the calculation results of the inclusive cross section for

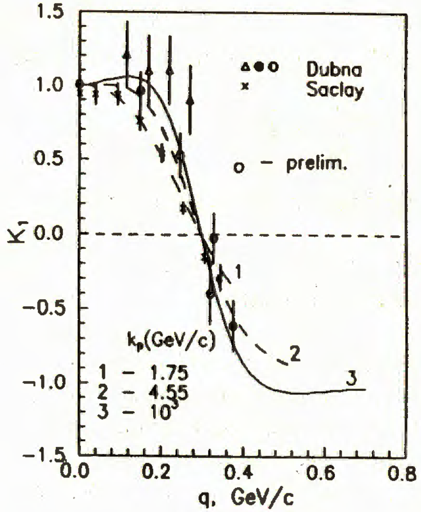


Figure 5: Vector polarization transfer coefficient K_1 for the $p + \vec{D} \to \vec{p}\,' + X$ process in RIA. Experimental data: $\triangle$ - [13], $\times$ - [12], $\bullet$ - [14], $\circ$ - [15].

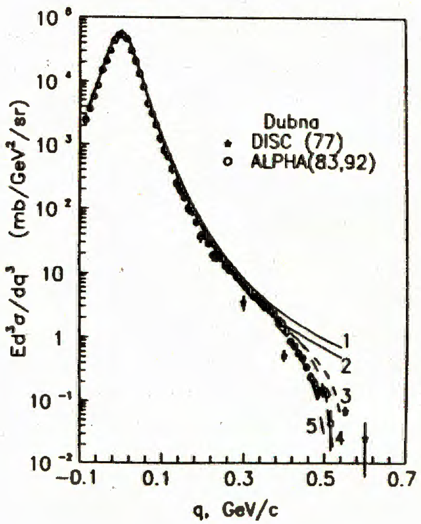


Figure 6: Inclusive cross section for the $p + D \to p' + X$ process in the RIA. Experimental data: $\star$ - [1], $\circ$ - [2].

this process. In the RIA it is defined by the expression

$$E\frac{d^3\sigma}{dq^3} = \mathbf{K} \cdot A^{(u)}_{\alpha\beta} \cdot \rho^{\alpha\beta}_{(u)} \cdot \sigma^{tot}_{pN},$$

where $\mathbf{K}$ is a kinematical factor, σ^{tot}_{pN} is the total cross section of the $p+N \to X$ process.

We have investigated the momentum dependence of the cross section on the mass parameter α and the restriction due to the kinematical boundary of the reaction.

Figure 6 shows the results of our calculation of the cross section with RDWF [18]. Curves 1,2 are calculated for $k_p = 4.55, 10^3$ GeV/c without taking into account the kinematical boundary of the reaction. Curves 3,4,5 include this restriction by the model kind and show ambiguities near the kinematical limit. During the calculation the mass parameters $\alpha = 0.5$, $\beta = 0.$ were used. It is seen that far from the kinematical boundary curves 1,2 lie above the data [2] and curves 3,4,5 agree with them. Our results show that the contribution of the RIA to the cross section is very important for the estimation of other mechanisms. Note that there is a difference between the data at $k_p = 4.55$ GeV/c and at $k_p = 8.9$ GeV/c where the mass correction may give a considerable contribution. In our opinion, that means that at these momenta the asymptotic regime is still not reached. It is necessary to go to higher energies to verify the prediction of the dependence on the incident proton momentum.

Conclusion

The relativistic impulse approximation in the framework of the covariant approach is a nontrivial mechanism of the interaction of incident particles with the deuteron constituents. In the relativistic region it takes into account the nucleon off-shell effect, $N\bar{N}$ pair production and in the deep cumulative region (near the kinematical limit) possibly the vacuum structure itself. The RIA is a powerful theoretical instrument for the development not only of the deuteron theory but generally of the relativistic discription of many body systems.

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Токарев М.В. E2-92-264
Релятивистское импульсное приближение
и спиновая структура дейтрона

Рассмотрены процессы фрагментации тензорно и векторно поляризованных дейтронов в протоны в рамках ковариантного подхода в переменных светового конуса в терминах релятивистской волновой функции дейтрона с одним нуклоном на массовой оболочке. Исследуется зависимость тензорной анализирующей способности, векторного коэффициента передачи поляризации и инклюзивного сечения этого процесса от импульса протона-спектатора, вылетающего в заднюю полусферу ($\theta_{p'}$ = 140°, 180°), и импульса налетающего протона. Проведены расчеты наблюдаемых величин для трех геометрий, отличающихся ориентацией спинов дейтрона и протона-спектатора по отношению к плоскости рассеяния. Полученные результаты сравниваются с асимптотическим поведением этих величин и имеющимися экспериментальными данными. Экспериментальная проверка предсказанных импульсных и угловых зависимостей тензорной анализирующей способности и векторного коэффициента передачи поляризации представляет интерес для изучения импульсных и спиновых распределений конституентов высокоимпульсной компоненты дейтрона.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Tokarev M.V. E2-92-264
Relativistic Impulse Approximation
and Deuteron Spin Structure

The fragmentation processes were considered of tensor- and vector-polarized deuterons to protons in the framework of the covariant approach in the light cone variables on the basis of the relativistic deuteron wave function with one nucleon on-mass shell. In the relativistic impulse approximation the dependence of the tensor analyzing power T_{20} and vector polarization transfer coefficient K on the momentum of the nucleon-spectator backward scattering and the momentum of the incident proton for different deuteron and proton spin orientations were investigated. The obtained results were compared with the asymptotic behaviour of these observables and the experimental data. The experimental verification of predicted dependences of T_{20} and K is of interest for the research of the momentum and spin distributions of high momentum deuteron constituents.

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

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