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ANALYSIS OF THE SPECTATOR NUCLEON DISTRIBUTIONS IN THE DEUTERON BREAK-UP IN THE "LIGHT FRONT" FORMALISM FOR COMPOSITE SYSTEMS

Dubna - Warsaw Collaboration

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Анализ распределений нуклонов-спектаторов в процессе прямого развала дейтрона в формализме "светового фронта"

Проведен релятивистский анализ распределений нуклонов-спектаторов в реакции прямого развала дейтрона $dp \to ppn$ при импульсе падающих дейтронов P_d = 3,3 ГэВ/с. В качестве переменных выбраны поперечный импульс спектаторного нуклона $p_\perp^{sp}$ и "продольное отношение" $x^{sp} = (p_z^{sp} + E^{sp})/(m_N + P_d + E_d)$. Экспериментальные данные сравниваются с теоретической моделью, в которой "продольное движение" составляющих дейтрон нуклонов параметризовано масштабно-инвариантным образом. Наблюдается разумное согласие с экспериментом.

Работа выполнена в Лаборатории высоких энергий ОИЯИ.

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Analysis of the Spectator Nucleon Distributions in the Deuteron Break-Up in the "Light Front" Formalism for Composite Systems

A relativistic analysis of spectator nucleons in the deuteron break-up $dp \to ppn$ at P_d =3.3 GeV/c has been performed in terms of transverse momentum p $p_\perp^{sp}$ and "longitudinal ratio" $x^{sp} = (p_z^{sp} + E^{sp})/(m_N + P_d + E_d)$ distributions. Experimental data are compared with a theoretical model in which the "longitudinal motion" of nucleons inside the relativistic deuteron is parametrized in the scale-invariant manner. A reasonable agreement with experiment is observed.

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

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1. INTRODUCTION

Due to violation of the usual Bjorken scaling in lepton-hadron interactions, interest has recently arisen to search for such variables in terms of which the observable quantities keep their scaling properties. In this connection the ξ -variable, which is a complicated combination of the kinematic variables of deep inelastic lepton-hadron interactions, is discussed (see, e.g.,[1-4] and references therein). As shown in ref. [5], this variable is related to the parton momentum inside the hadron in the following simple way:

$$\xi = (p_0^{part} + p_3^{part}) / (P_0^{hadr} + P_3^{hadr}) , \qquad (1)$$

where p_μ^{part} and P_μ^{hadr} (μ=0,1,2,3) are parton and hadron 4-momenta, respectively.

On the other hand, scale-invariant regularities have been observed in the interactions of high energy nuclei (see, e.g., ref. [6-11] and references therein). These experiments stimulate theoretical studies in which nuclei are treated as relativistic composite systems. We do not describe here the advantages and shortcomings of various approaches to this problem (some of them can be found, e.g., in ref.[12-16]). It should be only noted that our theoretical analysis will be based on the approach to the interactions of relativistic nuclei put forward in refs.[15,16]

2. BASIC THEORETICAL NOTIONS

The approach to processes involving relativistic nuclei, developed in refs. [15,16], is based on the "light front" form [17,-19] of quasipotential dynamics in quantum field theory[20,21]. The characteristic property of this scheme is the fact that the "longitudinal motion" of constituents inside the relativistic composite system is parametruzed by means of the scale-invariant variables

$$x^{(i)} = (p_0^{(i)} + p_3^{(i)})/(P_0 + P_3)$$

(compare with (1)). Assuming that nucleons are rather good quasiparticles to describe the properties of atomic nuclei, we ascribe the subscript (i) to individual nucleons in the nucleus. Quantities $x^{(i)}$ are the ratios of the "light front" variables [22]. Wave functions of composite systems in terms of these variables reflect, in particular, a dependence of the internal motion of constituents on the total momentum of the relativistic composite system.

In order to understand the dynamics of relativistic nuclei, experiments with hydrogen target seem to be very suitable since here the effects are absent connected with target break-up. Observation of fragmentation products of the incident nucleus allows information on the character of its internal motion to be obtained. The selection of spectator fragments permits one to get direct information on the nuclear functions.

Let us consider the interaction process of relativistic deuteron with hydrogen target in which a spectator-nucleon and a system of hadrons X_N are created

$$d + p \to p_s(n_s) + X_N .$$

Assuming that the spectator-nucleon does not interact with a target at all, the following spectator nucleon distribution in the target rest frame has been obtained:

$$E^{sp}\frac{d\sigma}{d\vec{p}^{\,sp}} \sim \frac{\lambda^{1/2}(s_{NN}, m_N^2, m_N^2)}{\lambda^{1/2}(s, m_d^2, m_N^2)}\,\sigma_N(s_{NN}) \times$$

$$\times \left|\frac{\phi(x, \vec{p}_\perp^{\,sp})}{1-(1+m_N/(P_d+E_d))\,x^{sp}}\right|^2 , \qquad (2)$$

where

$$x^{sp} = \frac{p_z^{sp} + E^{sp}}{m_N + P_d + E_d} ; \ \lambda(x, y, z) = (x-y-z)^2 - 4yz ,$$

$$s_{NN} = s(1-x^{sp}) + m_N^2 - \frac{\vec{p}_\perp^{\,sp2} + m_N^2}{x^{sp}} ,$$

$$x = (1 + m_N/(P_d + E_d))\,x^{sp} , \qquad (3)$$

P_d, E_d and p^{sp}, E^{sp} are the momenta and energies of the incident deuteron and the spectator-nucleon, respectively, m_N is the nucleon mass, m_d is the deuteron mass, $\phi(x, \vec{p}_\perp)$ is the relativistic wave function of the incident deuteron (the meaning of this quantity in the field theory approach can be found in refs. [17-19]), $\sigma_N(s_{NN})$ is the interaction cross section of the active nucleon from the deuteron with a proton target leading to the creation of a system of hadrons X_N.

It is interesting to note that in the high energy limit the spectator distribution, summed over the hadron systems X_N, takes the form

$$\frac{1}{\sigma_{tot}(\infty)}\,\frac{d\sigma}{d\vec{p}^{\,sp}/E^{sp}} \sim \frac{|\phi(x^{sp}, \vec{p}_\perp^{\,sp})|^2}{1-x^{sp}} , \qquad (4)$$

which is vely close to the prediction of the limiting fragmentation hypothesis [23] and those of the parton model [24] and of the automodelity principle for strong interactions [25]. In this connection an experimental study of processes with deuteron means of various energies is of great interest.

3. COMPARISON WITH EXPERIMENT

From experimental point of view quite comprehensive data are available on a direct break-up $dp \to ppn$ channel. In this case $\sigma_N(s_{NN})$ in formula (2) is to be replaced by the total elastic cross section $\sigma_{e\ell}(s_{NN})$ of the nucleon-nucleon interaction. Later on we shall restrict ourselves to the neutron-spectator case since there are much more experimental data on $\sigma^{pp}_{e\ell}$ than on $\sigma^{np}_{e\ell}$ (see, e.g., ref. [26]). It should be noted that in the experiment [27] with a beam of 3.3 *GeV/c* deuterons, which is the subject of the present analysis, s_{pp} varies in the interval, where $\sigma_{e\ell}(s_{pp})$ is almost constant and equal to 24 *mb*.

The experimental distributions $d\sigma/dx^{sp}$ and $d\sigma/dp^{sp}_{\perp}$ are analyzed. They are related to the invariant differential cross section as follows:

$$\frac{d\sigma}{dx^{sp}} = \int_{p^{sp}_{\perp,\,min}}^{p^{sp}_{\perp,\,max}} \frac{d\sigma}{dx^{sp}\,dp^{sp}_{\perp}}\, dp^{sp}_{\perp}, \tag{4a}$$

$$\frac{d\sigma}{dp^{sp}_{\perp}} = \int_{x^{sp}_{min}}^{x^{sp}_{max}} \frac{d\sigma}{dx^{sp}\,dp^{sp}_{\perp}}\, dp^{sp}_{\perp}, \tag{4b}$$

$$\frac{d\sigma}{dx^{sp}dp^{sp}_{\perp}} = 2\pi\left(\frac{p^{sp}_{\perp}}{x^{sp}}\right)\frac{d\sigma}{d\vec{p}^{\,sp}/E^{sp}}. \tag{5}$$

The experimental distributions $d\sigma/dx^{sp}$ ($d\sigma/dp^{sp}_{\perp}$) integrated in three various intervals of $p^{sp}_{\perp}$ (x^{sp}) are compared with the results of the theoretical scheme described here. For the deuteron relativistic wave function $\phi(x,\vec{p}_{\perp})$ we choose the relativistic analogue

$$\phi(x,\vec{p}_{\perp}) = \left(\frac{m^2_N+\vec{p}^{\,2}_{\perp}}{x(1-x)} - \alpha\right)^{-1}\left(\frac{m^2_N+\vec{p}^{\,2}_{\perp}}{x(1-x)} - \beta\right)^{-1} \tag{6}$$

of the well-known nonrelativistic Hulten functions with adjustable parameters α and β. Results of the analysis are given in *Figs. 1-6* and *Tables 1-4*. The theoretical curves in *Figs. 1-6* refer to the values of parameters α and β taken from the second lines of *Tables 3* and *4*.

Table 1

Results of analysis of the $d\sigma/dx^{sp}$ distribution in various intervals of $p^{sp}_{\perp}$

Intervals in $p^{sp}_{\perp}$, (GeV/c)	α, (GeV/c)^2	β, (GeV/c)^2	A	χ^2/N_p
0.01–0.04	3.5156–fixed	3.4711±0.0046	0.0066±0.0011	93/50
0.04–0.07	" "	3.4446±0.0087	0.0113±0.0021	56/50
0.07–0.1	" "	3.3990±0.0225	0.0198±0.0056	65/50

Table 2

Results of analysis of the $d\sigma/dp^{sp}_{\perp}$ distribution in various intervals of x^{sp}

Intervals in x^{sp}	α, (GeV/c)^2	β, (GeV/c)^2	A	χ^2/N_p
0.40–0.43	3.5156–fixed	3.4308±0.0089	0.0129±0.0020	62/50
0.43–0.46	" "	3.4677±0.0037	0.0072±0.0007	109/50
0.46–0.49	" "	3.4490±0.0087	0.0127±0.019	70/50

Table 3

Results of joint analysis of the $d\sigma/dx^{sp}$ distribution in three various intervals of $p_\perp^{sp}$ given in *Table 1*

α, $(GeV/c)^2$	β, $(GeV/c)^2$	A	χ^2/N_p
3.5213±0.0010	3.3926±0.0249	0.0173±0.0043	222/150
3.5156-fixed	3.4572±0.0005	0.009-fixed	232/150
3.5179±0.0009	3.4502±0.0031	" "	228/150

Table 4

Results of joint analysis of the $d\sigma/dp_\perp^{sp}$ distribution in three various intervals of x^{sp} given in *Table 2*

α, $(GeV/c)^2$	β, $(GeV/c)^2$	A	χ^2/N_p
3.5230±0.0006	3.3385±0.0230	0.0273±0.0048	264/150
3.5156-fixed	3.4579±0.0005	0.009-fixed	311/150
3.5182±0.0004	3.4498±0.0020	" "	307/150

Table 5

P_d, (GeV/c)	α, $(GeV/c)^2$	β, $(GeV/c)^2$
3.46	3.5156 - fixed	3.5241±0.0004
4.46	" "	3.5223±0.0007
7.66	" "	3.5209±0.0009
10.20	" "	3.5170±0.0021

Table 1(2) shows the results of a separate analysis of the $d\sigma/dx^{sp}$ ($d\sigma/dp_\perp^{sp}$) distribution in various intervals of $p_\perp^{sp}$(x^{sp}). *Table 3(4)* contains the results of the joint fit of the $d\sigma/dx^{sp}$ ($d\sigma/dp_\perp^{sp}$) distribution for three intervals of $p_\perp^{sp}$(x^{sp}). The quantity A is the proportionality factor in formula (2), N_p is the number of experimental points. Quite a reasonable agreement between the model and the experiment is observed. The maximum position in the x^{sp}-distributions does not depend on $p_\perp^{sp}$ and, according to the prediction [15]:

$$\bar{x}^{sp} = \frac{1}{2(1+m_N/(P_d+E_d))}, \qquad (7)$$

is located at $\bar{x}^{sp} \simeq 0.44$. According to the presented version of the model, a nucleon is assumed to be a spinless object. However, we consider such an analysis as a useful step in the development of relativistic approach in the theory of nuclear reactions.

Note that in ref. [28] an analysis of neutron spectators has been performed in the deuteron break-up using an Al target [29] at four various energies of incident deuterons. However, only the neutrons in the forward direction have been detected. The values of parameters α and β of the wave function $\phi(x,\vec{p}_\perp)$ are listed in *Table 5*. As is seen, in the region considered the parameters are almost independent of the incident deuteron energy. This can be thought as an indication of the fact that the relativistic deuteron is rather well described by the wave function with scale-invariant parametrization of the "longitudinal motion" in terms of the "light front" variables.

4. DISCUSSION

This paper is the first attempt to present experimental data on the interactions of high energy nuclei in terms of the x and $p_\perp$-distributions of the final products. (In ref. [28] only the x^{sp}-distributions are given since only the forward moving spectator-neutrons have been detected). We also compare these distributions with the theoretical model into which the $(x,\vec{p}_\perp)$ variables naturally enter.

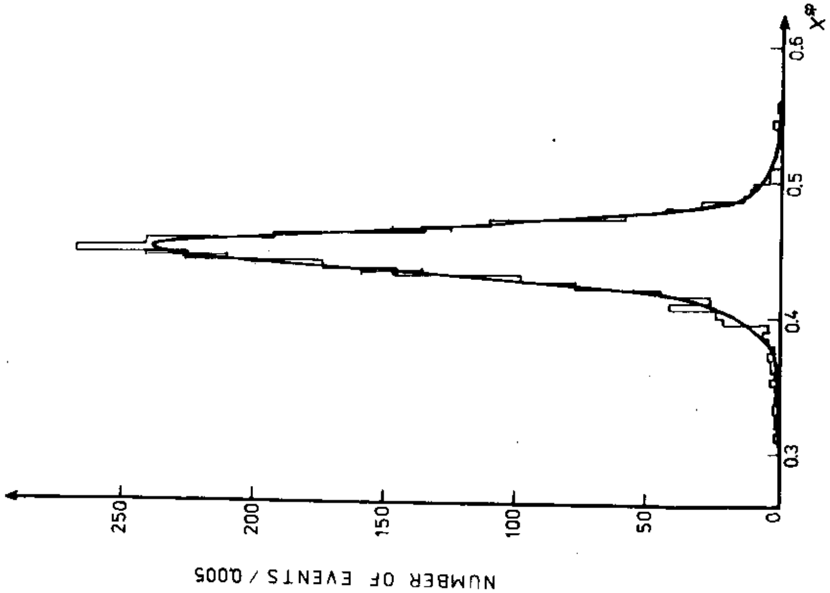


Fig. 1. $d\sigma/dx^{sp}$ *in the interval 0,01 GeV/c* $< p_{\perp}^{sp} <$ *0.04 GeV/c.*

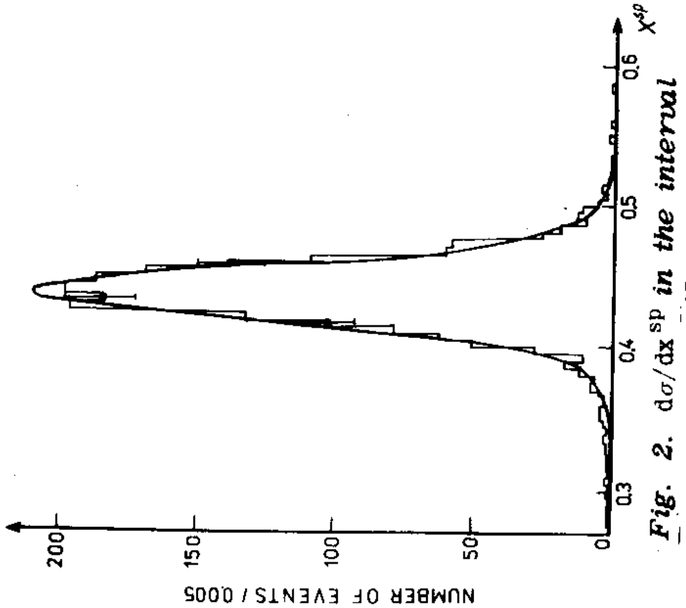


Fig. 2. $d\sigma/dx^{sp}$ *in the interval 0.04 GeV/c* $< p_{\perp}^{sp} <$ *0.07 GeV/c.*

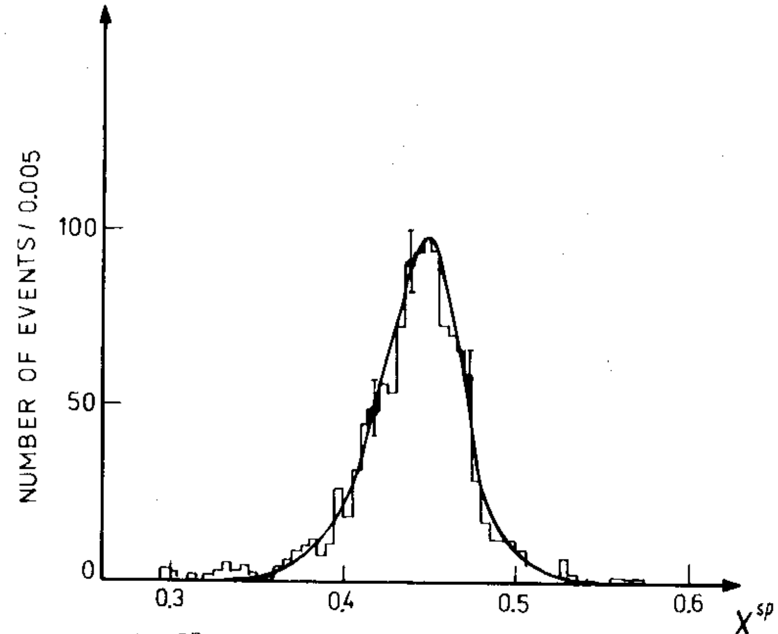


Fig. 3. $d\sigma/dx^{sp}$ *in the interval 0.07 GeV/c* $< p_{\perp}^{sp} <$ *0.1 GeV/c.*

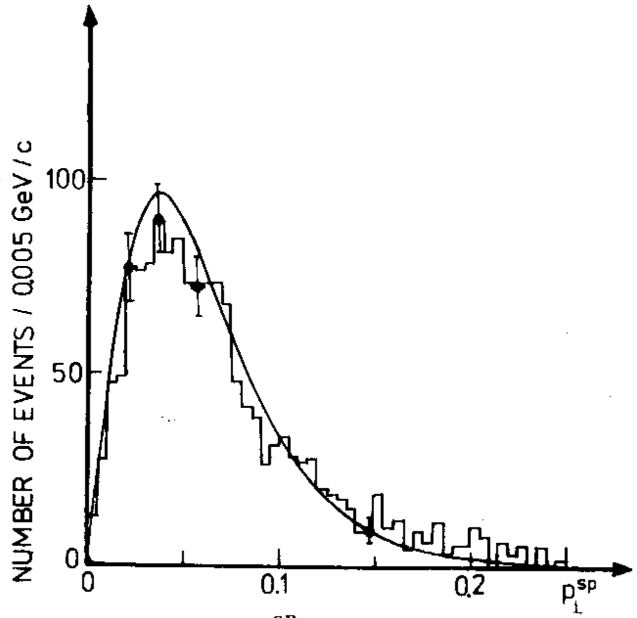
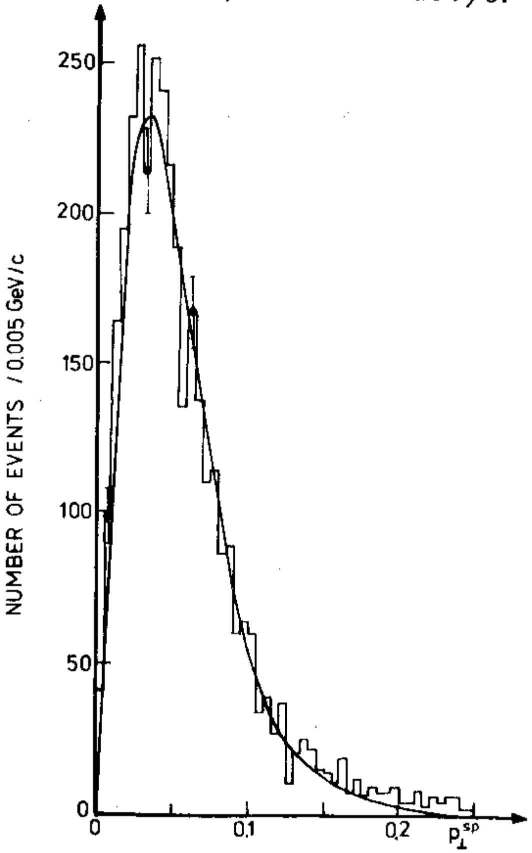


Fig. 4. $d\sigma/dp_{\perp}^{sp}$ *in the interval 0.40 GeV/c* $< x^{sp} <$ *0.43 GeV/c.*

Fig. 5. $d\sigma/dp_{\perp}^{sp}$ *in the interval* *0.43 GeV/c* $< x^{sp} <$ *0.46 GeV/c.*



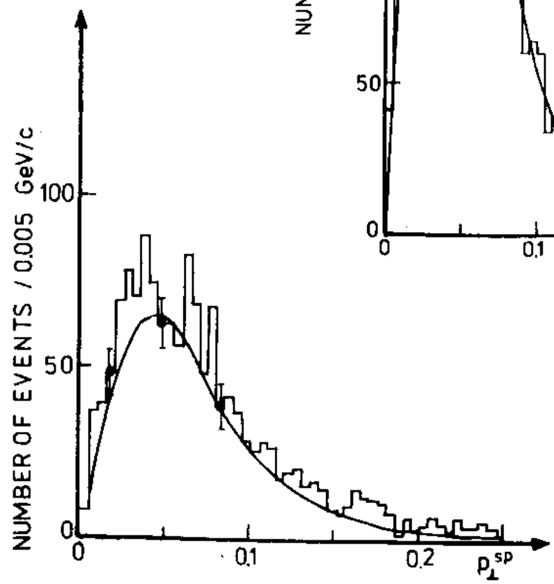


Fig. 6. $d\sigma/dp_{\perp}^{sp}$ *in the interval* *0.46 GeV/c* $< x^{sp} <$ *0.49 GeV/c.*

The authors understand that the analysis performed without taking into account nucleon spins and other possible reaction mechenisms in quantitative in nature. This fact is reflected by the χ^2/N_p values given in the *Tables*. But we consider this analysis as a useful step in the development of relativistic nuclear reaction theory.

It is interesting to apply an analysis of this type to other possible channels in the interactions of relativistic nuclei. A study of spectator distributions in a wave range of energies allows one to answer the question whether the scale-invariant parametrization of the "longitudinal motion" of constituents inside relativistic nuclei holds.

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