SCALING BEHAVIOUR OF EXCLUSIVE REACTIONS WITH THE DEUTERON AND $^3$He AT HIGH $p_T$ IN THE GEV REGION

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Abstract

The scaling behaviour $s^{-11}$ of the cross section of the reaction $\gamma d \rightarrow pn$ observed at SLAC and Jlab at energies $E_\gamma = 1 - 4$ GeV and large $p_T$ most likely displays quark degrees of freedom in the deuteron. We show that the cross sections of the $dd \rightarrow ^3Hp$ and $pd \rightarrow ^3Hen$ reactions measured at SATURNE follow the scaling regime $s^{-22}$ at $T_d = 0.5 - 1.2$ GeV and $\theta_{cm} = 50^\circ - 60^\circ$. A necessity to get new data on this and other exclusive reactions is argued.

1 Introduction

Search for transition region from hadron to quark-gluon degrees of freedom in nuclear structure at short distances between nucleons ($r_{NN} < 0.5$ fm) is an important problem of particle and nuclear physics. This transition is expected to occur in processes at high transferred momenta allowing to probe dense fluctuations of nuclear matter (fluctons) in nuclear structure [1, 2]. So, very interesting scaling features were found in inclusive spectra of deep inelastic nuclear reactions in cumulative region. In review [3] these features are interpreted as a manifestation of “drops” of the quark phase in nuclei.

Another possible signature for this transition is related with the constituent counting rules (CCR) [4]. According to dimensional scaling [4] the differential cross section of a binary reaction $AB \rightarrow CD$ at high enough incident energy can be parameterized for a given c.m.s. scattering angle $\theta_{cm}$ as

$$\frac{d\sigma}{dt}(AB \rightarrow CD) = \frac{f(t/s)}{s^{n-2}},$$

where $n = N_A + N_B + N_C + N_D$ and $N_i$ is the minimum number of point-like constituents in the $i$-th hadron (for a lepton and photon one has $N_i = 1$), $f(s/t)$ is a function of $\theta_{cm}$. The CCR follows from perturbative QCD (pQCD). Recently the similar scaling behaviour was found within nonperturbative theories which are dual to QCD [5]. Existing high energy data for many measured hard processes with free hadrons appear to be consistent with the CCR [6].

2 The CCR behaviour in exclusive nuclear reactions

Few exclusive nuclear reactions were found to be compatible with the CCR. So, the deuteron photodisintegration reaction $\gamma d \rightarrow pn$ follows the $s^{-11}$ scaling behaviour at photon energies $E_\gamma = 1 - 4$ GeV and high transversal momenta $p_T > 1.1$ GeV/c corresponding
to large scattering angles $\theta_{cm} \sim 90^\circ$ [7] - [10] (see Fig.1). Meson-exchange models fail to explain the $\gamma d \rightarrow pn$ data at $E_{\gamma} > 1$ GeV (see, for example, [8]), and therefore several nonperturbative theoretical models were suggested [11]-[13],[14]. Since the pQCD is expected to be valid at very high transferred momenta [15], the origin of the observed scaling behaviour in the reactions with the deuteron at moderate energies is unclear. On the other hand, in these reactions the 3-momentum transfer $Q > 1$ GeV/c is large enough to probe very short distances between the nucleons in nuclei, $r_{NN} \sim 1/Q < 0.3$ fm. Most likely, nucleons could lose their separate identity in this overlapping region and form multi-quark configurations. In order to get more insight into the underlying dynamics of the CCR behaviour, new data with the lightest nuclei are necessary.

Very recently was shown [17] that the cross section of the reaction $dd \rightarrow \(^3\)He(n)$ (and $dd \rightarrow \(^3\)Hp$), measured at SATURNE in 80’s [18], also perfectly follows the scaling behaviour at transversal momenta $p_T \sim 0.6 - 0.9$ GeV/c (Fig.2). In this reaction one has $n = 6 + 6 + 9 + 3 = 24$. At the beam energy $T_d = 0.5 - 1.25$ GeV the differential cross section $d\sigma/dt$ demonstrates the $s^{-22}$ dependence for the maximum measured scattering angles $\theta_{cm} = 50^\circ$ ($x_{n,d,f.}^2 = 0.97$ for $T_d = 0.62 - 1.24$ GeV) and $\theta_{cm} = 60^\circ$ ($x_{n,d,f.}^2 = 1.18$ at $T_d = 0.5 - 1.24$ MeV). Up to now, the reaction $dd \rightarrow \(^3\)He(\(^3\)Hp)$ is the only pure hadronic process which involves the deuteron and $\(^3\)He(\(^3\)H)$ nuclei and found to follow the CCR. As shown in [17], the cross section of the reaction $dp \rightarrow dp$ also demonstrates the CCR behaviour $\sim s^{-16}$ at $T_d = 1 - 5$ GeV and $\theta_{cm} = 120^\circ - 130^\circ$ (Fig.3), however the $\chi^2$-value is not good in this case, perhaps, due to different sets of the data included into analysis [17]. For other reactions with the lightest nuclei experimental data in the GeV region and large scattering angles are either noncomplete, as for $d^3He \rightarrow ^4He p$ and $pd \rightarrow ^3H \pi^+$, or were obtained in different set of experiments, what could lead to systematic uncertainties.

In Ref. [3] the reaction $dd \rightarrow ^3He(n)$ at high $p_T$ is considered as a double cumulative process with nucleon cumulations involved in both initial deuterons. From the point of view...
Figure 2: The differential cross section of the \(dd \rightarrow ^3He\) and \(dd \rightarrow ^3H\) reactions multiplied by \(s^{22}\) versus the deuteron beam energy at different scattering angles: \(a - \theta_{c.m.} = 60^\circ; b - 50^\circ - 52^\circ; c - 33^\circ - 35^\circ; d - 28^\circ\). On the upper scale is shown the minimal relative momentum between nucleons in the deuteron for the ONE mechanism. The data are taken from Ref. [18]. At lower scattering angles the plateau is not visible in this data, maybe, except for \(\theta_{c.m.} = 33^\circ - 35^\circ\).

In view of constituent quark model the observed \(s^{-22}\) behaviour implies that all constituent quarks in the initial and final state are active in the \(dd \rightarrow ^3He\) (\(^3H\)) reaction. One should note that the nuclear matter density in the short-range configurations with high internal momenta between nucleons \(q \sim 1\text{GeV/c}\) probed in this reaction, is close to the critical one, \(\varepsilon_c \sim 1\text{GeV/fm}^3\), that corresponds to the phase transition in cold baryon matter [19]. On the whole, interpretation of such phenomena can be associated with the quark-hadron duality. In Ref. [17] the reggeon exchange model [13] was applied to the \(dd \rightarrow ^3He\) reaction to clarify a possible relation to the \(\gamma d \rightarrow pn\) data. One can see from Fig.3 this model allows one to describe the data on the \(dd \rightarrow ^3H\) and \(dp \rightarrow dp\) reactions at high \(p_T\).

\(^1\) Of course, if the equilibrium thermodynamical state is formatted on the intermediate step of this reaction, then its temperature is rather small at beam energies \(T_d \sim 1\text{ GeV}; kT_B \approx 50\text{ MeV}\) for baryon matter, and \(kT_q \approx 5\text{ MeV}\) for constituent quark matter. This is much smaller than the critical temperature \(kT_c = 150 - 170\text{ MeV}\) expected for transition to quark-gluon plasma [19].
Figure 3: The differential cross section of the \( dd \to ^3He \) and \( dd \to ^3H \) reactions at \( \theta_{c.m.} = 60^\circ \) (a – b) and \( dp \to dp \) at \( \theta_{c.m.} = 127^\circ \) (c – d) versus the deuteron beam kinetic energy. Experimental data in (a – b) (●) are taken from [18]. In (c – d), the experimental data (black squares), (○), (△), (open square) and (●) are taken from [20]–[24], respectively. The dashed curves give the \( s^{-22} \) (a) and \( s^{-16} \) (c) behaviour. The full curves show the result of calculations obtained in Ref. [17] using the Regge formalism. On the upper scales in (a) and (c) is shown the minimum relative momentum (GeV/c) between nucleons in the deuteron for the ONE mechanism.

An important task addressed to experiment is a search for similar behaviour in other exclusive reactions with the lightest nuclei at large \( p_T > 0.6 \) GeV/c. This task becomes more important in view of the fact that in the reaction \( pp \to d\pi^+ \), measured at the beam kinetic energy 2.2 - 4.0 GeV and large angles of the pion production \( \theta_{cm} = 40^\circ - 90^\circ \) [25], the CCR behaviour was not observed (see Fig.4). This is in contrast with the behaviour of the \( \gamma d \to pn \) data [7]–[10], although the transversal momenta at these conditions in the inverse reaction \( \pi^+d \to pp \) are almost the same \( p_T > 1 \) GeV/c as in the \( \gamma d \to pn \) reaction in the observed CCR region. Therefore, it would be interesting to check whether the reaction \( pp \to dp^+ \), which can be related to the \( pn \to d\gamma \) by the vector meson dominance, follows the CCR.
Figure 4: The cross section of the reaction \( pp \to d\pi^+ \frac{d\sigma}{dt} \) at \( \theta_{cm} = 89.5^\circ \) taken from Ref.\[25\] multiplied by \( s^{12} \) in arbitrary units as a function of beam energy. On the upper scale is shown the transversal momentum \( p_T \). The scaling behaviour \( s^{-12} \) is not observed.

\[\text{3 Conclusion}\]

The scaling behaviour \( s^{-11} \) of the cross section of the reaction \( \gamma d \to pn \) starts at \( p_T > 1.1 \) GeV/c and \( E_\gamma > 1 \) GeV \[10\], whereas in the reaction \( pp \to d\pi^+ \) the expected scaling regime \( s^{-12} \) is not observed at the same \( p_T \) \[25\]. On the other hand, in the reaction \( dd \to {^3}Hp \) the \( s^{-22} \) behaviour is observed in the data of Ref.\[18\] at lower transversal momenta \( p_T > 0.6 \) GeV/c for \( T_d > 0.5 - 1.2 \) GeV. Therefore, new data are required to get more insight on the origin of this scaling.

Thus, boundaries of the scaling region for the \( dd \to {^3}Hp \) reaction are not yet determined. As it seen from Fig.\[2\] within the ONE mechanism the CCR behaviour in the reaction \( dd \to {^3}Hp \) starts at internal momenta in the deuteron \( q > 0.5 \) GeV/c \[2\]. It is important to verify this observation at other kinematical conditions, i.e. at higher beam energies and lower angles or at lower energies and higher angles. Furthermore, new data are necessary to check whether the CCR behaviour is valid in the reaction \( dd \to {^3}Hp \) at higher energies \( T_d > 1.2 \) GeV and larger scattering angles \( \theta_{cm} = 60^\circ - 90^\circ \), corresponding to large relative momenta in the deuteron \( q_{pn} > 0.8 \) GeV/c. On the whole, one has to know what is a true parameter for the scaling regime – either internal nucleon momentum \( q \), or the transversal momentum \( p_T \). Experimental data on other exclusive reactions with the lightest nuclei where the baryon exchange mechanism are required: \( dd \to dd, \ pp \to \{ pp\}_s \gamma, \ pd \to {^3}H\pi^+, \ pd \to {^3}He\eta, \ dd \to {^4}He\eta, \ pp \to dp^+, \ d^3He \to {^4}He\ p. \)

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\[\text{2In the } dp \to dp \text{ process the } s^{-16} \text{ behaviour also starts at } q > 0.5 \text{ GeV, as it seen from Fig.}[3]\]
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