Search for scaling onset in exclusive reactions with the lightest nuclei

Search for scaling onset

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Received: date / Revised version: date

Abstract. The dimensional scaling of the differential cross sections of binary reactions \( \frac{d\sigma}{dt} \sim s^{-(n-2)} \), where \( n \) is given by constituent quark counting rules, was predicted for asymptotically high energies \( \sqrt{s} \gg m_i \) and transferred momenta \( -t \gg m_i \) at \( t/s = \text{const} \) (here \( s \) and \( t \) are the Mandelstam variables and \( m_i \) denotes a hadron mass), but manifested itself at surprisingly moderate energies of few GeV at large fixed cms angles \( \theta_{cm} \sim 90^\circ \). This behaviour is observed not only in reactions with free hadrons, but with the deuteron and \(^3\)He too both for electromagnetic and pure hadronic interactions. One may suppose that observed scaling points out to effective restoration of near-conformal and, probably, chiral symmetry in these processes. A systematical experimental study of the scaling behaviour of the reactions with the deuteron, \(^2\)H, \(^3\)He, and \(^4\)He nuclei is still absent. We consider a possibility to carry out this study in \( dd \) collisions at the JINR Nuclotron.

PACS. 25.10.+s, Nuclear reactions involving few-nucleon systems – 24.85.+p, Quarks, gluons, and QCD in nuclear reactions 25.55.-e, 2H-induced reactions

1 Introduction

The structure of the lightest nuclei at short distances (\( r_{NN} < 0.5 \) fm) or for high relative momenta (\( q > 1/r_{NN} \sim 0.4 \) GeV/c) constitutes fundamental problem in nuclear physics. One of the most important questions is the following: at which values of the Mandelstam variables \( s \) and \( t \) (or, more precisely, relative momenta \( q \) of nucleons in nuclei) does the transition region from the meson-baryon to the quark-gluon picture of nuclei set in? So, the main aim of experiments on deep inelastic nuclear reactions at high transferred momenta in the so-called cumulative region was to search for dense fluctuations of nuclear matter (fluctons). Very interesting features were observed on this way in inclusive spectra which can be interpreted as manifestation of “drops” of the quark phase in nuclei (see for review Ref. [1]). However, a quantitative theory of cumulative effect is not available and, therefore, other independent signals for the transition region are necessary.

A definite signature for transition to the valence quark region is given by the constituent counting rules (CCR) [2,3]. According to the dimensional scaling [2,3] the differential cross section of a binary reaction \( AB \to CD \) at high enough incident energy can be parameterized for a given c.m.s. scattering angle \( \theta_{cm} \) as

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

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 a self-similarity hypothesis [2] and perturbative QCD (pQCD) [3]. The CCR was derived also from the ADS/CFT duality [4].

After short review of existing data in sect. 2 and discussion in sect. 3 a proposal for new measurements is given in sect. 4.

2 Existing data

Existing data at energies about several GeV for many measured hard processes with free hadrons appear to be consistent with the CCR. Among them are reactions of photoproduction of pions, \( \rho \)-mesons, kaons on the proton at the photon beam energy \( E_\gamma = 4 \sim 7.5 \) GeV [5], \( \gamma p \), \( \pi^+ p \), \( K^+ p \) [6], pp-elastic scattering [7] at large scattering angles \( \theta_{cm} \approx 90^\circ \), strangeness production in the reaction \( \pi^- p \to K^0 A \) [8] and others [6].
The CCR properties of the reactions with atomic nuclei were observed first in electromagnetic interactions with the deuteron. So, the deuteron photodisintegration reaction \( \gamma d \rightarrow pn \) follows the \( s^{-11} \) scaling behaviour at photon energies \( E_\gamma = 1 - 4 \) GeV and large scattering angles \( \theta_{cm} \sim 90^\circ \) corresponding to high transversal momenta \( p_T > 1.1 \) GeV/c [9,10,11,12,13,14,15,16]. Meson-exchange models fail to explain the \( \gamma d \rightarrow pn \) data at \( E_\gamma > 1 \) GeV (see, for example, [12]), and therefore several nonperturbative theoretical models were suggested [17-19,20]. Since the pQCD is expected to be valid at much higher transferred momenta [21], the origin of the observed scaling behaviour in the reactions with the deuteron at moderate energies is unclear. Furthermore, the hadron helicity conservation predicted by the pQCD was not confirmed experimentally in the scaling region [13]. 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, \( r_{NN} \sim 1/Q < 0.2 \) fm. Presumably, nucleons lose their separate identity in this overlapping region and form multi-quark configurations. In order to get more insight into the underlying dynamics, new measurements were suggested to study photodisintegration of the diproton in the \( ^3He \) at Jlab [22] and the results compatible with the CCR behaviour given by Eq. (1) were obtained for \( ^3He(\gamma, pp)n \) [23] and recently for \( \gamma ^3He \rightarrow dp \) [24,25].

Before the CCR behaviour was observed in electromagnetic reactions with the \( ^3He \) nucleus in Refs. [23,24], an indication on the scaling onset in a pure hadronic reaction, namely the \( dd \rightarrow ^3He n \) (or \( dd \rightarrow ^3Hp \)), was found in [26] (see Fig. 1). The key point mentioned in Ref. [26] was that in the reaction \( \gamma d \rightarrow pn \) considered within the relativistic impulse approximation the scaling behavior starts at internal momenta between nucleons in the deuteron about \( q_{pn} \sim 1 \) GeV/c. Considering this value as the true scale of the CCR onset, one can find that in the reaction \( dd \rightarrow ^3He n \) studied on the basis of the one-nucleon exchange mechanism (ONE) (see Fig. 2) this magnitude of the momentum \( q_{pn} \) can be...
achieved at beam energies \( T_d \sim 1 \text{ GeV} \) for \( \theta_{cm} \approx 90^\circ \) (see Fig. 3). There are data on this reaction obtained at SAT-URNE in 80’s \[27\] for energies \( T_d = 0.5 - 1.2 \text{ GeV} \) although at lower scattering angles \( \theta_{cm} \leq 60^\circ \). Our analysis of these data \[26\] shows (Fig.1) that in this reaction the CCR behaviour \( \sim s^{-22} \) of the differential cross section \( d\sigma/dt \) takes the place at \( \theta_{cm} = 50^\circ - 60^\circ \) and \( T_d = 0.5 - 1.25 \text{ GeV} \) with \( \chi_{n.d.f.} = 1.18 \) (note that in this reaction \( n = 6 + 6 + 9 + 3 = 24 \)). In terms of the internal momentum \( q_{pn} \) the scaling appears at \( q_{pn} > 0.5 \text{ GeV}/c \) that is twice lower than in the reaction \( \gamma d \rightarrow pn \), where the CCR behaviour starts at \( q_{pn} > 1 \text{ GeV}/c \). At lower scattering angles \( \theta_{cm} < 30^\circ \), i.e. lower internal momenta \( q_{pn} < 0.5 \text{ GeV}/c \), the CCR behaviour is absent as it is expected. Up to now, the reaction \( dd \rightarrow ^3\text{Hen} \) (\(^3\text{Hp}\)) is the only pure hadronic process which involves the deuteron and \(^3\text{He}\) (\(^3\text{H}\)) nuclei and found to follow the CCR.

As shown in \[26\], the cross section of the reaction \( dp \rightarrow dp \) also demonstrates the CCR behaviour \( \sim s^{-16} \) at \( T_d = 2T_p = 1 - 5 \text{ GeV} \) and \( \theta_{cm} = 120^\circ - 130^\circ \). However, the \( \chi^2 \)-value is not good in this case and, perhaps, this is caused by different systematics of the data included into analysis \[24\]. For other reactions with the lightest nuclei as \( pd \rightarrow ^3\text{He}^\pi^+, pd \rightarrow ^3\text{Hen}, d^3\text{He} \rightarrow ^4\text{He}p \), a systematic experimental study at beam energies above 1 GeV and large scattering angles was not done.

3 Discussion

From the point of view of constituent quark model, the observed \( s^{-22} \) behaviour can be considered as a manifestation of the fact that all constituent quarks in the initial and final state are active in the \( dd \rightarrow ^3\text{Hen} \) (\(^3\text{Hp}\)) reaction. On the whole, interpretation of such phenomena involves the quark-hadron duality. So, the most successful description of the \( \gamma d \rightarrow pn \) data was achieved within the Quark-Gluon String model formulated in terms of Reggeon exchange \[19\]. In Ref. \[26\] the Reggeon exchange model of \[19\] with some modifications was also used to describe the \( dd \rightarrow ^3\text{Hen} \) and \( dp \rightarrow dp \) reactions in the region of the observed CCR behaviour.

An exciting feature of existing data on CCR is the following. The scaling behaviour \( s^{-11} \) of the cross section of the reaction \( \gamma d \rightarrow pn \) starts at transversal momenta \( p_T > 1.1 \text{ GeV}/c \) (and \( E_\gamma > 1 \text{ GeV} \)) \[10\], whereas in the reaction \( pp \rightarrow dp^\pi^+ \), measured in Ref. \[23\] at the same \( p_T = 1.0 - 1.4 \text{ GeV}/c \), the expected CCR scaling regime \( s^{-12} \) is not observed \[29\]. Why the reaction with photon differs considerably from the reaction with the pion at almost the same kinematic condition? As far as we know, the answer to this question is absent. An attempt to explain this difference will be done below. Furthermore, in the reaction \( dd \rightarrow ^3\text{Hp} \) the \( s^{-22} \) behaviour is appeared \[26\] at lower transversal momenta \( p_T > 0.6 \text{ GeV}/c \). A similarly low boundary in terms of the beam energy and internal momenta is found for the scaling onset \( \sim s^{-17} \) in the reaction \( \gamma ^3\text{He} \rightarrow pd \) \[23\]. On the other hand, the scaling behaviour \( s^{-11} \) of the diproton photodisintegration in the reaction \( ^3\text{He}(\gamma, pp)n \) starts at photon energy \( E_\gamma \sim 2 \text{ GeV} \) \[23\] that is twice larger than the scaling onset in the reaction \( \gamma d \rightarrow pn \). Thus, search for scaling onset in reactions with different nuclei is the first task in this study.

Empirical success of the CCR at moderate energies and transferred momenta is hardly related to non-perturbative QCD and is considered in current literature as a manifestation of near-conformal symmetry of “the physical QCD” \[20\]. Indeed, classical Lagrangian of QCD has scale (conformal) and chiral invariance in the limit of zero quark masses. Both these symmetries are broken by quantum effects. As a result, the effective coupling constant \( \alpha_s \) depends on transferred momentum squared \( Q^2 \), and due to spontaneously broken chiral symmetry constituent quarks become dynamical masses. There are some arguments, however, that at rather low transferred momenta \( Q^2 < 1 \text{ (GeV)/c}^2 \) the running coupling constant \( \alpha_s (Q^2) \) is large and approximately independent of \( Q^2 \) \[31\]. In this region, in order to get an effective restoration of confor-
nal invariance and explain the CCR onset, one needs a mechanism, which would provide a reduction of constituent quark masses for light flavors. Following the mechanism of effective restoration of chiral symmetry for excited hadrons proposed by Glozman [32], we assume here that for central collisions in nuclear reactions rather high excitations (as compared to $A_{QCD}\sim 200 - 300$ MeV) of hadrons/nuclei are possible in intermediate states. Therefore, intermediate hadronic system follows quasi-classical approximation when quantum effects are irrelevant to internal dynamics of hadrons. In this regime, the dynamical quark masses are reduced [32] that could lead (at $\alpha_s(Q^2)\approx const$) to effective restoration of conformal symmetry, and, as a result, to the CCR behaviour of hard nuclear reactions. In partial restoration of the chiral symmetry means decreasing the $\pi NN$ coupling constant [32], that allows one to explain absence of the CCR behaviour in the $pp\to d\pi^+$ reactions [29]. If chiral symmetry is completely restored in a given excited nucleon it cannot decay into the $\pi N$ channel. On the other hand, this mechanism suggests that in the $pp\to d\rho^+$ reaction the CCR occurs, because the $\rho$-meson is not a Goldstone boson [32]. It is important to check this difference between the $pp\to d\pi^+$ and $pp\to d\rho^+$ in experiment. One should note that a similar result would appeal due to real restoration of conformal symmetry too. Indeed, the nuclear matter density in the short-range configurations with high internal momenta between nucleons $q\sim 1$ GeV/c probed in these reactions, is close to the critical one, $\varepsilon_c\sim 1$GeV/fm$^3$, that corresponds to the phase transition [33].

Therefore, an important task is to search for scaling behaviour of different exclusive reactions with the lightest nuclei at large transversal momenta $p_T > 0.6$ GeV/c. The nearest task is to determine the boundaries of the scaling region of the $dd\to 3He n$ $(dd\to 3Hp)$ reaction which was studied in [27] by completely different motivation and very poor statistics was obtained in that experiment as compared to the $\gamma d\to pn$ reaction in the scaling region [10].

1.4.1 Counting rate estimation

The counting rate at beam energies 1.2–2.2 GeV is estimated using the SATURNE data [24]. Assuming the scaling law $s^{-22}$, the differential cross section at fixed angle $\theta cm$ was extrapolated to higher energies in the laboratory system as

$$\frac{d\sigma}{d\Omega_{lab}} = \frac{J_\pi p_i p_f}{J_0 p_i^0 p_f^0 s_0^{22}} \left(\frac{d\sigma}{dt}\right)_0, \quad (2)$$

where $p_i$ ($p_f$), and $s$ are the initial (final) cms momentum and the invariant mass squared, respectively, at given $T_d$, whereas $p_i^0$ ($p_f^0$) and $s_0$ are the corresponding values at $T_0=1.243$ GeV that is the maximal beam energy in the experiment [27]. The Jacobian of transformation $J$ from the cms to lab-system is given in the Table I. The counting rate for the angular interval $\theta_{lab} = 16^\circ - 17^\circ$ (i.e. $\theta_{cm} = 48^\circ - 50^\circ$) was calculated under assumption that the cms differential cross section at $T_d=1.234$ GeV and $\theta_{cm}=50^\circ$ is equal to $(\frac{d\sigma}{dt})_0 = (0.3 \pm 0.02)$ mb/GeV$^2$ [27].

Therefore, for the solid angle $\Delta\Omega_{lab} = 2\pi \sin \theta_{lab}$ $\Delta\theta_{lab} = 0.03$ rad the number of events expected at $T_d=2.2$ GeV during 24 hours will be equal to $N=108$ at the luminosity $L = 1.35 \times 10^{30}$ cm$^{-2}$ sec$^{-1}$ (see Table I). Note, the acceptance and corrections for registration efficiency were not taken into account in this estimation. In total, in order to measure the $d\sigma/d\Omega_{cm}$ at $\theta_{cm}=50^\circ$, for six energies 1.3, 1.5, 1.6, 1.8, 2.0 and 2.2 GeV with statistical uncertainty $\leq 4\%$ ($N \geq 600$ events) we need two weeks. With increasing beam energy and $\theta_{cm}$ the required beam time is quickly increased.

5 Conclusion

Search for transition region from hadron to quark/gluon degrees of freedom in nuclei is an important task in the QCD treatment of nuclear structure and reactions. Constituent Counting Rules, derived from the perturbative QCD, when being applied for exclusive reactions with lightest nuclei at high $Q^2$, can give a definite signal for transition to the valence quark region. Some of the binary

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1. Of course, this parameter can be determined only within a certain mechanism of the reaction. The ONE mechanism is used here as the most natural one.

4 Proposal for JINR Nuclotron

We propose to measure the cross section of reaction $dd\to 3Hp$ $(or dd\to 3Hen)$ at energies 1 - 2.5 GeV and $\theta_{cm}\leq 50^\circ$ using the BM@N facility at the JINR Nuclotron. The proposed measurement will allow one (i) to check whether the CCR behaviour of the reaction $dd\to 3Hp$ is valid at these kinematical conditions which correspond to high internal momenta $q\geq 0.6$ GeV/c, but were not accessible at SATURNE [27] and (ii) determine the boundaries of this behaviour in terms $\theta_{cm}$, $p_T$ or $q_T$. This measurement was proposed [34] first for WASA-at-COSY [35], however, not performed. We present below the estimations of the counting rate obtained in Ref. [34].
Table 1. Counting rate \( N \) (for 24 hours) expected at \( \theta_{\text{lab}} = 16^\circ - 17^\circ \) for the solid angle \( 2 \pi \sin (17^\circ) \pi/180 = 0.03 \text{rad} \), estimated using data \(^{22}\) for the luminosity \( L = 1.35 \times 10^{30} \text{cm}^{-2} \text{sec}^{-1} \).

| \( T_d, \text{GeV} \) | \( \kappa = \frac{\pi}{m_p p} \) | \( J \) | \( \frac{nn}{pp} \) | \( \frac{T_c}{p^2} \) | \( da/d\Omega_{\text{lab}} \) | \( N \) |
|----------------|-----------------|-------|-----------|-------------|----------------|--------|
| 1.117          | 3.32            | 7.92  | 1         |             | 4320            |        |
| 1.243          | 2.9             | 8.03  | 0.64      | 827         | 2770            |        |
| 1.3            | 2.84            | 8.03  | 0.52      | 675         | 2255            |        |
| 1.4            | 2.64            | 8.09  | 0.36      | 470         | 1570            |        |
| 1.5            | 2.46            | 8.15  | 0.26      | 342         | 1140            |        |
| 1.6            | 2.3             | 8.21  | 0.18      | 239         | 795             |        |
| 1.7            | 2.16            | 8.27  | 0.13      | 174         | 575             |        |
| 1.8            | 2.0             | 8.33  | 0.091     | 122         | 405             |        |
| 1.9            | 1.93            | 8.4   | 0.065     | 88          | 280             |        |
| 2.0            | 1.83            | 8.46  | 0.046     | 63          | 205             |        |
| 2.1            | 1.73            | 8.52  | 0.033     | 45          | 150             |        |
| 2.2            | 1.65            | 8.58  | 0.024     | 33          | 108             |        |

reactions with the deuteron or/and \(^3\)He follow the CCR form of Eq. \(^{11}\) at energies 1 - 2 GeV at large scattering angles.

However, the perturbative QCD, as a basis of CCR, can hardly be valid at these rather low energies and moments. New data on these and other exclusive reactions are required to clarify the underlying CCR dynamics. One of the most important tasks is determination of boundary of scaling domain for different reactions. JINR Nuclotron facility provides an unique possibility to study these properties in \( dd \) and \( pd \) collisions above 1 GeV.

Measurement of energy dependence of the differential cross section of the reaction \( dd \rightarrow 3He \) in the interval \( T_d = 1 - 2.2 \) GeV at fixed cms scattering angles within \( \theta_{\text{cm}} = 30^\circ - 50^\circ \), corresponding to the expected boundary between scaling and non-scaling behaviour for this reaction, is considered here. This proposal can be considered as a first step of a broad experimental program, which will include other exclusive reactions with lightest nuclei: \( dd \rightarrow dd, pd \rightarrow 3H \pi^+, pd \rightarrow 3He \pi, dd \rightarrow 4He \pi, pp \rightarrow dp \pi^+, p^4He \rightarrow p^4He, p^4He \rightarrow d^3He \).

I would like to thank Yu. Petukhov and V. Kurbatov for help in estimation of the counting rate and N.N. Nikolaev for useful discussions.

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