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Indication of asymptotic scaling in the reactions $dd \to p^3$H, $dd \to n^3$He and $pd \to pd$

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It is shown that the differential cross sections of the reactions $dd \to n^3$He and $dd \to p^3$H measured at c.m.s. scattering angle $\theta_{cm} = 60°$ in the interval of the deuteron beam energy 0.5–1.2 GeV demonstrate the scaling behaviour, $d\sigma/dt \sim s^{-22}$, which follows from constituent quark counting rules. It is found also that the differential cross section of the elastic $dp \to dp$ scattering at $\theta_{cm} = 125-135°$ follows the scaling regime $\sim s^{-16}$ at beam energies 0.5–5 GeV. These data are parameterized here using the Reggeon exchange.

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Nuclei and nuclear reactions at low and intermediate energies (or at long and medium distances between nucleons $r_{NN} > 0.5$ Fm) traditionally are described in terms of effective nucleon-nucleon interactions which are mediated by the exchange of mesons. In the limit of very high energies ($s \to \infty$) and transferred four-momenta ($t \to \infty$) the perturbative quantum chromodynamics (pQCD) is expected to be applied to explanation of nuclear reactions in terms of quarks and gluons. At present, one of the most interesting problems in nuclear physics is an interplay between the meson-baryon and quark-gluon pictures of the strong interaction. The main question is the following: at which s and t values (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?

A possible signature for this transition is given by the constituent counting rules (CCR) [1, 2]. According to dimensional scaling [1, 2] and pQCD [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 θ_{cm} as

$$\frac{d\sigma}{dt}(AB \to CD) = \frac{f(t/s)}{s^{n-2}}, \qquad (1)$$

where $n = N_A + N_B + N_C + N_D$ and N_i is the minimum number of point-like constituents in the ith hadron (for a lepton one has $N_l = 1$), $f(s/t)$ is a function of θ_{cm}. Existing data for many measured hard scattering processes with free hadrons appear to be consistent with Eq. (1) [4]. At present, in a nuclei sector only electromagnetic processes on the deuteron were found to be compatible with the CCR. So, the deuteron electromagnetic form factor measured at SLAC [5] and JLab [6] at high momentum transfer $Q^2 > 4$ GeV^2 approaches to the scaling as $\sqrt{A(Q^2)} \to Q^{-10}$ what is in agreement with the CCR. The deuteron two-body photodisintegration cross section $\gamma d \to pn$ demonstrates the s^{-11} scaling behaviour in the data obtained in SLAC [7 – 9] at $E_\gamma > 1$ GeV, $\theta_{cm} \approx 90°$ and Jlab [10] at $E_\gamma = 1-2$ GeV for $\theta_{cm} = 89°, 69°$ [11]. According to the data [10], at photon energy 3.1 GeV and scattering angle $\theta_{cm} = 36°$ there is no evidence for the s^{-11} scaling. A nearly complete angular distribution of the cross section of this reaction recently measured at energies 0.5 – 3.0 GeV [12] demonstrates the s^{-11} behaviour at proton transverse momentum $p_T > 1.1$ GeV/c [13]. Meson-exchange models fail to explain the $\gamma d \to pn$ data at $E_\gamma > 1$ GeV (see, for example, [10] and references [3, 4, 9, 10] therein). Recent models based on quark degrees of freedom have become quite successful in describing this data. Thus, the observed in Ref. [8, 11] forward-backward asymmetry was described within the Quark-Gluon String (QGS) model [14] using a non-linear Regge trajectory of the nucleon. Other quark models applied to this reaction are reviewed in Ref. [15].

The dimensional scaling was derived before the QCD was discovered. The main assumption was an automodellism hypothesis for the amplitude of the binary reaction with point-like constituents in colliding (and outgoing) particles and high enough s and t [1]. The pQCD (and, consequently, the scaling behaviour within the pQCD) is expected to be valid at very high transferred momenta which are not yet reached in existing data for nucleon and deuteron form factors [16, 17]. From this point of view the origin of the scaling behaviour observed in the reactions with the deuteron at moderate transferred momenta [5 – 12] is unclear and consid-

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ered in some papers as a potentially misleading indicator of the success of pQCD [15]. Moreover, the hadron helicity conservation predicted by the pQCD was not confirmed experimentally in the scaling region (see Ref. [18] and references therein). On the other side, in these reactions the 3-momentum transfer $Q = 1{-}5\,\mathrm{GeV}/c$ is large enough to probe very short distances between nucleons in nuclei, $r_{NN} \sim 1/Q < 0.3\,\mathrm{Fm}$, where 0.3 Fm is a size of a constituent quark [19]. One may expect that nucleons lose their separate identity in this overlapping region and, therefore, six-quark (or, in general case, multi-quark) components of a nucleus can be probed in these reactions. In order to get more insight into the underlying dynamics of the scaling behaviour new data are necessary, in particular, for hadron-nuclei interactions.

In the present paper we show that in hadron interactions with participation of the lightest nuclei ^{2}H, ^{3}H and ^{3}He the scaling behaviour given by Eq. (1) is also occurs, specifically, at beam energies around 1 GeV if the scattering angle is large enough. In order to estimate at which internal momenta q_{pn} between nucleons in the deuteron one should expect the scaling onset, we consider here the reaction $\gamma d \to pn$ assuming that the one nucleon exchange (ONE) mechanism dominates. Under this assumption the cross section is proportional to the squared wave function of the deuteron in momentum space $d\sigma \sim |\psi_d(q_{pn})|^2$. Using relativistic kinematics we obtain that q_{pn} is larger than $1\,\mathrm{GeV}/c$ at the photon energy $E_\gamma > 1\,\mathrm{GeV}$ and $\theta_{cm} = 90°$. Furthermore, assuming for the reaction $dd \to p^3$H (or $dd \to n^3$He) that the ONE mechanism dominates (Fig.1a,b), we get

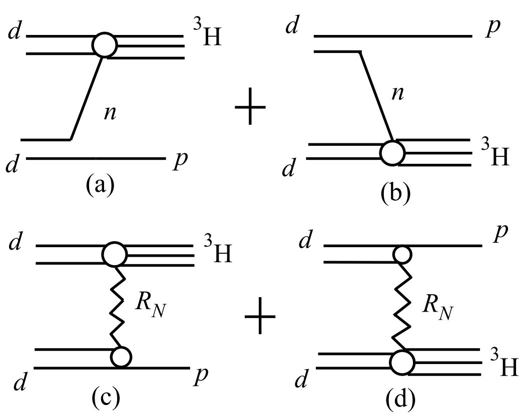

Fig.1. The mechanisms of the reaction $dd \to p^3$H: one nucleon exchange (a-b), Reggeon exchange (c-d)

$d\sigma \sim |\psi_d(q_{pn})|^2 \times |\Psi_h(q_{Nd})|^2$, where $\Psi_h(q_{Nd})$ is the overlap between the ^{3}H(^{3}He) and deuteron wave functions and q_{Nd} is the $N-d$ relative momentum in the ^{3}H(^{3}He). On this basis we obtain, for example, at $T_d = 0.8\,\mathrm{GeV}$ and $\theta_{cm} = 90°$ the relative momenta $q_{pn} = 0.8\,\mathrm{GeV}/c$ and $q_{Nd} = 1.0\,\mathrm{GeV}/c$. This values are close to those we have found for the $\gamma d \to pn$ reaction in the scaling region. Therefore one may expect that the scaling behaviour in the $dd \to n^3$He reaction occurs in the GeV region for large scattering angles, $\theta_{cm} \sim 90°$. In Fig.2a,b we show the experimental data from Ref. [20] obtained at SATURNE at beam energies 0.3–1.25 GeV

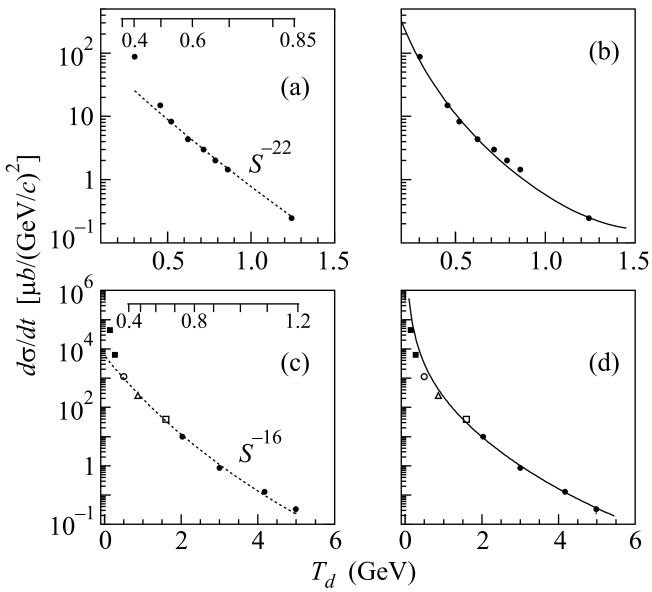

Fig.2. The differential cross section of the $dd \to n^3$He and $dd \to p^3$H reactions at $\theta_{cm} = 60^o$ (a), (b) and $dp \to dp$ at $\theta_{cm} = 127^o$ (c), (d) versus the deuteron beam kinetic energy. Experimental data in (a), (b) are taken from [20]. In (c), (d), the experimental data (black squares),(○), (△), (open square) and (•) are taken from [22 – 26], respectively. The dashed curves give the s^{-22} (a) and s^{-16} (c) behaviour. The full curves show the result of calculations using Regge formalism given by Eqs. (2), (3), (4) with the following parameters: (b) – $C_1 = 1.9\,\mathrm{GeV}^2$, $R_1^2 = 0.2\,\mathrm{GeV}^{-2}$, $C_2 = 3.5$, $R_2^2 = -0.1\,\mathrm{GeV}^{-2}$; (d) – $C_1 = 7.2\,\mathrm{GeV}^2$, $R_1^2 = 0.5\,\mathrm{GeV}^{-2}$, $C_2 = 1.8$, $R_2^2 = -0.1\,\mathrm{GeV}^{-2}$. The upper scales in (a) and (c) show the relative momentum q_{pn} (GeV/c) in the deuteron for the ONE mechanism

for the maximum measured scattering angle $\theta_{cm} = 60°$. Shown on the upper scale is the minimum relative momentum in the deuteron for the ONE diagram. One can see that at beam energies 0.5–1.25 GeV the data perfectly follow the s^{-22} dependence. (In this reaction $n = 6 + 6 + 9 + 3 = 24$). In Fig.2a the dashed curve represents the s^{-22} dependence with arbitrary normalization fitted on the data with $\chi^2_{n.d.f.} = 1.18$. For the ONE diagram in Fig.1b, which dominates at $\theta_{cm} = 60°$, this region corresponds to the internal momenta $q_{pn} = 0.55{-}0.85\,\mathrm{GeV}/c$ in the deuteron and $q_{Nd} = 0.60{-}0.94\,\mathrm{GeV}/c$ in the ^{3}He (^{3}H) nuclei. Therefore, within this model the probed NN-distances in the deuteron are less than $r_{NN} < 1/0.55\,\text{GeV}/c = 0.35\,\text{Fm}$. This regime, in principle, corresponds to formation of a six quark configuration in the deuteron. At $\theta_{cm} = 90°$ the diagrams in Fig.1a and b are equivalent and correspond to higher momenta $q_{pn} = 0.7{-}1.1\,\text{GeV}/c$ and $q_{Nd} = 0.80{-}1.22\,\text{GeV}/c$ for the same beam energies 0.5–1.25 GeV. Therefore, continuation of measurements up to $\theta_{cm} = 90°$ is very desirable to confirm the observed s^{-22} behaviour. One can see in linear scale that the cross section $s^{-22}d\sigma/dt$ demonstrates some oscillations which are similar to those observed in pp-scattering at $\theta^9_{cm}0°$ [21]. However, the number of available experimenatal points is too small in the scaling region (5 or 6) and has to be increased to make a more definite conclusion.

The $dp \to dp$ data obtained in different experiments [22–26] at the c.m.s. scattering angle $\theta_{cm} = 127°$ are shown in Fig.2c,d versus the deuteron beam energy T_d. This scattering angle corresponds to a region of the minimum in the angular dependence of the differential cross section $dp \to dp$, where the contribution of the three-body forces (and non-nucleon degrees of freedom in the deuteron) is expected to be best pronounced [27, 28]. One can see that at low energies (< 0.25 GeV) the cross section falls very fast with increasing T_d, but the slope of the energy dependence is sharply changed at about 0.5 GeV. Above this energy the cross section is appeared to follow the s^{-16} scaling behaviour. (In the $dp \to dp$ one has $n = 3+6+3+6 = 18$). We can show that a similar behaviour is observed at $\theta_{cm} = 135°$. However, the parameter $\chi^2_{n.d.f.}$ is rather high for the $dp \to dp$ data, $\chi^2_{n.d.f.} = 4.3$. The high $\chi^2_{n.d.f.}$ value can be, probably, addressed to uncertainties in systematic errors which are different in various experiments [26]. Therefore, new, more detailed data, are requested preferably from one experiment covering the whole interval of energies $T_d = 1{-}5$ GeV. We notice that the discrepancy observed in [29] between the results of the Faddeev calculations and the measured unpolarized cross section of the $pd \to pd$ at $T_p = 0.25$ GeV (corresponding to $T_d = 0.5$ GeV in the $dp \to dp$), is, presumably, caused by the deuteron six-quark component which is not taken into account in [29] but, as seen from Fig.2c, starts playing in the $pd \to pd$ at this kinematics.

Due to very high internal momenta in the $d \leftrightarrows pn$ and $Nd \leftrightarrows {}^3\text{H}({}^3\text{He})$ vertices, $q \sim 1\,\text{GeV}/c$, calculation with the ${}^3\text{H}({}^3\text{He})$ and deuteron wave functions obtained from the Schrödinger equation with conventional NN-potentials are likely unrealistic. Since in the reactions $\gamma d \to pn$, $dd \to p{}^3\text{H}$ (or $dd \to n{}^3\text{He}$) and $dp \to dp$ (in the backward hemisphere) an important contribution comes from the baryon exchange mechanism, for numerical estimations we apply here the Reggeon exchange formalism developed earlier for the $pp \to d\pi^+$ reaction at $-t < 1.6\,(\text{GeV}/c)^2$ [30] and the $\gamma d \to pn$ at $E_\gamma > 1$ GeV [14]. In this way one may estimate to what extent the observed scaling behaviour in the $dd \to n{}^3\text{He}$ ($dd \to p{}^3\text{H}$) and $dp \to dp$ reactions is connected to that in the $\gamma d \to pn$. The amplitude of the reaction $dd \to p{}^3\text{H}$ can be written as

$$T = T(s,t) + T(s,u), \quad (2)$$

where the first (second) term corresponds to the diagram in Fig.1a,b and the sign plus is chosen due to the Bose-statistics for the deuterons. The amplitude $T(s,t)$ is written in the Regge form:

$$T(s,t) = F(t)\left(\frac{s}{s_0}\right)^{\alpha_N(t)} \exp\left[-\frac{i\pi}{2}\left(\alpha_N(t) - \frac{1}{2}\right)\right]. \quad (3)$$

We use here the effective Regge trajectory for the nucleon from [30]: $\alpha_N(t) = \alpha_N(0) + \alpha'_N\,t + \alpha''_N/2\,t^2$ with the parameters $\alpha_N(0) = -0.5$, $\alpha'_N = 0.9\,\text{GeV}^{-2}$ and $\alpha''_N = 0.4\,\text{GeV}^{-4}$, so $\alpha_N(m_N^2) = \frac{1}{2}$, where m_N is the nucleon mass. The function $F(t)$ is parameterized as [30]

$$F(t) = \frac{C_1 \exp(R_1^2 t)}{m_N^2 - t} + C_2 \exp(R_2^2 t), \quad (4)$$

where the first term explicitely takes into account the nucleon pole in the t channel. According to [30], the second term at $R^2 \approx 0$ is important at $|t| > 1\,\text{GeV}^2$, that indicates to a presence of structureless configurations in the deuteron (^{3}He, ^{3}H) wave functions at short distances. The results of calculation are shown in Fig.2b and parameters C and R^2 are given in the caption. One can see a fairly good agreement with the data. For the reactions $dd \to p{}^3\text{H}$ and $dd \to n{}^3\text{He}$ the parameter R_1^2 is lower in comparison with that used in [30] ($R_1^2 = 3\,\text{GeV}^2$) to fit the $pp \to d\pi^+$ data. Such a diminishing R_1^2 is likely connected to a much more intensive high momentum nucleon component of the ${}^3\text{He}({}^3\text{H})$ wave function as compared with the deuteron [31]. The increasing ratio C_1/C_2 could mean that multiquark configurations in the ${}^3\text{He}({}^3\text{H})$ become more important at given t as compared with the deuteron. We also performed this analysis for the $dp \to dp$ reaction and obtained a good agreement with the data under minor modification of the parameter R_1^2 and C_1/C_2 (see Fig.2d).

In conclusion, the CCR scaling behaviour is observed in cross sections of hadron-nucleus reactions with the deuteron and ${}^3\text{He}({}^3\text{H})$ nuclei. This behaviour sets in at energies around 1 GeV and large scattering angles, where high momentum components of nuclear wave functions are required in the Schrödinger formalism. To confirm this observation, more detailed data are necessary for these and other exclusive reactions in the *pd*, *dd*, p^3He collisions, probably, including meson production.

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