E2-2004-217

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INDICATION OF ASYMPTOTIC SCALING IN THE REACTIONS $dd \to p^3$H, $dd \to n^3$He AND $pd \to pd$

Submitted to «Pisma ZhETF»

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Указание на асимптотический скейлинг в реакциях
$dd \to p^3$H, $dd \to n^3$He и $pd \to pd$

Показано, что дифференциальное сечение реакций $dd \to n^3$He и $dd \to p^3$H, измеренное при угле рассеяния в с. ц. м. $\theta_{\rm cm} = 60^\circ$ в интервале энергий дейтронного пучка 0,5–1,2 ГэВ, демонстрирует скейлинговое поведение $d\sigma/dt \sim s^{-22}$, которое следует из правил кваркового счета. Найдено также, что дифференциальное сечение упругого рассеяния $dp \to dp$ при углах рассеяния $\theta_{\rm cm} = 125^\circ$–$135^\circ$ демонстрирует скейлинговое поведение $\sim s^{-16}$ при энергиях пучка 0,5–5,0 ГэВ. Эти экспериментальные данные параметризованы с использованием механизма обмена реджеоном.

Работа выполнена в Лаборатории ядерных проблем им. В. П. Джелепова ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна, 2004

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Indication of Asymptotic Scaling in the Reactions
$dd \to p^3$H, $dd \to n^3$He and $pd \to pd$

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

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna, 2004

Nuclei and nuclear reactions at low and intermediate energies (or at long and medium distances between nucleons $r_{NN} > 0.5$ fm) are traditionally 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 apply 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 what values s and t (or, more precisely, internal momenta q between nucleons inside of nuclei) does the transition region from the meson–baryon picture to quark–gluon one 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 for a given scattering angle $\theta_{\rm cm}$ can be parameterized 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 the scattering angle $\theta_{\rm cm}$. 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 are 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 the scaling as $\sqrt{A(Q^2)} \to Q^{-10}$, which 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, $\theta_{\rm cm} \approx 90^\circ$ and Jlab [10] at E_γ = 1–2 GeV for $\theta_{\rm cm} = 89^\circ, 69^\circ$ [11]. At photon energy 3.1 GeV and scattering angle $\theta_{\rm cm} = 36^\circ$ there is no evidence from the data [10] that the s^{-11} scaling has set in. A recently measured nearly-complete angular distribution of the cross section of this reaction 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], and [10] therein). Models based on quark degrees of freedom have recently become quite successful in describing these data. Thus, the observed in Ref. [8, 11] forward–backward asymmetry is described within the Quark–Gluon String (QGS) model [14] using a nonlinear Regge trajectory of the nucleon. Other quark models applied to this reaction are reviewed in Ref. [15].

The dimensional scaling has been derived before the QCD is discovered. The main assumption is 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 have not been reached yet 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 deuteron at moderate transferred momenta [5–12] is unclear and is considered in some papers as a potentially misleading indicator of the success of pQCD [15]. Moreover, the hadron helicity conservation predicted by the pQCD has not been confirmed experimentally in the scaling region (see Ref. [18] and references therein). On the other hand, in these reactions the three-momentum transfer $Q = 1$–5 GeV/c is large enough to probe very short distances between nucleons in nuclei, $r_{NN} \sim 1/Q < 0.3$ fm, where 0.3 fm is a size of the constituent quark [19]. One may expect that nucleons lose their individuality in this overlapping region and, therefore, six-quark (or, in general case, multiquark) 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) also occurs, specifically, at beam energies about 1 GeV if the scattering angle is large enough. In order to estimate at what internal momenta q_{pn} between nucleons in the deuteron one should expect the scaling onset, we consider 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 $d\sigma \sim |\psi_d(q_{pn})|^2$. We find that q_{pn} is larger than 1 GeV/c at the photon energy $E_\gamma > 1$ GeV and $\theta_{\rm cm} = 90^\circ$. Furthermore, assuming for the reaction $dd \to p^3$H (or $dd \to n^3$He) that the ONE mechanism dominates (Fig. 1, *a*–*b*), we get $d\sigma \sim |\psi_d(q_{pn})|^2 \times |\Psi_h(q_{nd})|^2$, 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 ^{3}H(^{3}He). On this basis we find, for example, at $T_d = 0.8$ GeV and $\theta_{\rm cm} = 90^\circ$ the relative momenta $q_{pn} = 0.8$ GeV/c and $q_{nd} = 1.0$ GeV/c. These values are close to those we have got 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, $\theta_{\rm cm} \sim 90^\circ$. In Fig. 2, *a*–*b*, we show the experimental data from Ref. [20] obtained at SATURNE at beam energies 0.3–1.25 GeV for the maximum measured scattering angle $\theta_{\rm cm} = 60^\circ$. On the upper scale, the minimum relative momentum in the deuteron for the ONE diagram is shown. 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. 2, the dashed curve represents the s^{-22} dependence with arbitrary normalization fitted on the data with $\chi^2_{\text{n.d.f.}} = 1.18$. For the ONE diagram in Fig. 1, b, which dominates at $\theta_{\text{cm}} = 60°$, this region corresponds to the internal momenta $q_{pn} = 0.55$–0.85 GeV/c in the deuteron and $q_{pd} = 0.60$–0.94 GeV/c in the ^{3}He (^{3}H) nuclei. Therefore, within this model the probed NN distances in the deuteron are less than $r_{NN} < 1/0.55$ GeV/c = 0.35 fm. This regime, in principle, corresponds to formation of the six-quark configuration in the deuteron. At $\theta_{\text{cm}} = 90°$ the diagrams a and b in Fig. 1 are equivalent and correspond to higher momenta $q_{pn} = 0.7$–1.1 GeV/c and $q_{pd} = 0.80$–1.22 GeV/c for the same beam energies 0.5–1.25 GeV. Therefore, continuation of measurements up to $\theta_{\text{cm}} = 90°$ is very desirable to confirm the observed s^{-22} behaviour.

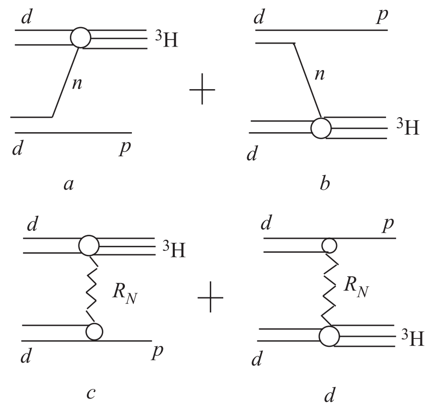

Fig. 1. The mechanisms of the reaction $dd \to p^3$H: one nucleon exchange (a–b), Reggeon exchange (c–d)

In Fig. 2, c–d, the $pd \to pd$ data obtained in different experiments [21–25] at the c.m.s. scattering angle $\theta_{\text{cm}} = 127°$ versus the deuteron beam energy T_d are shown. This scattering angle corresponds to a region of the minimum in the angular dependence of the differential cross section $pd \to pd$, where the contribution of the three-body forces (or non-nucleon degrees of freedom in the deuteron) is expected to be best pronounced [26, 27]. 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 appears to follow the s^{-16} scaling behaviour. (In the $pd \to pd$, one has $n = 3+6+3+6 = 18$). We can show that a similar result is valid at $\theta_{\text{cm}} = 135°$. However, the parameter $\chi^2_{\text{n.d.f.}}$ is rather high for the $pd \to dp$ data, $\chi^2_{\text{n.d.f.}} = 4.3$. Too high $\chi^2_{\text{n.d.f.}}$ value can be, probably, addressed to uncertainties in systematic errors, which are different in various experimental conditions [25] and can hardly be under control. Therefore, new more detailed data, preferably from the same experiment, are requested at energies $T_d = 1$–5 GeV. We notice that the discrepancy observed in [28] between the results of the Faddeev calculations and measured unpolarized cross section of the $pd \to pd$ at $T_p = 0.25$ GeV (i.e. $T_d = 0.5$ GeV) (corresponding to $T_d = 0.5$ GeV in the $dp \to dp$) presumably comes from the deuteron six-quark component, which is

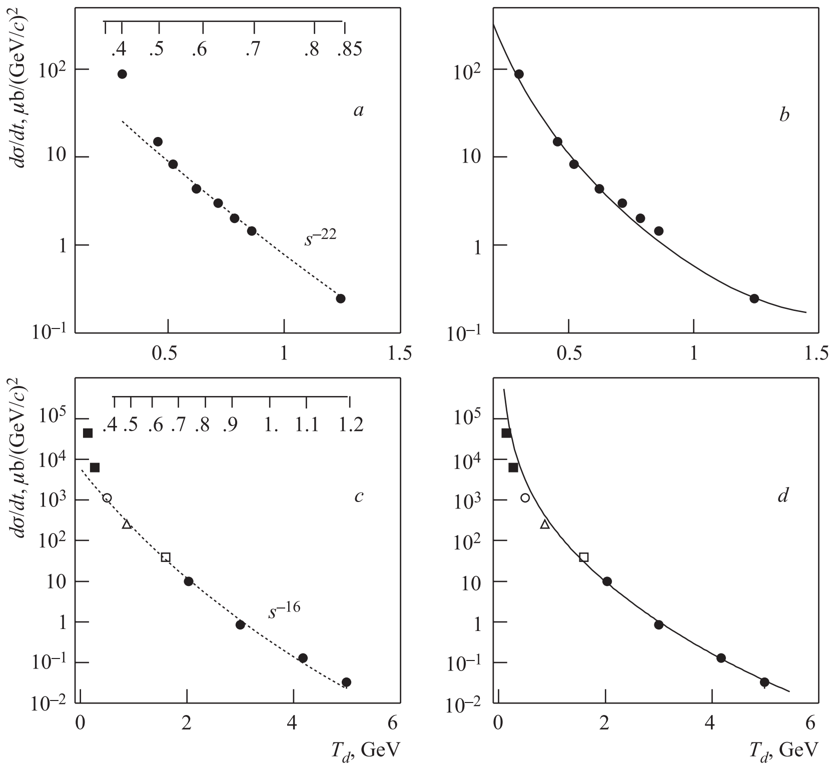

Fig. 2. The differential cross section of the $dd \to n^3$He and $dd \to p^3$H reactions at $\theta_{\rm cm} = 60^\circ$ (a–b) and $dp \to dp$ at $\theta_{\rm cm} = 127^\circ$ (c–d) versus the deuteron beam kinetic energy. Experimental data in (a–b) are taken from [20]. In (c–d), the experimental data (■), (○), (△), (□) and (●) are taken from [21], [22], [23], [24], and [25], respectively. The dashed curves represent 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) — $C_1 = 1.9$ GeV^2, $R_1^2 = 0.2$ GeV^{-2}, $C_2 = 3.5$, $R_2^2 = -0.1$ GeV^{-2}; (d) — $C_1 = 7.2$ GeV^2, $R_1^2 = 0.5$ GeV^{-2}, $C_2 = 1.8$, $R_2^2 = -0.1$ GeV^{-2}. On the upper scales in (a) and (c), the relative momentum g_{pn} (GeV/c) between nucleons in the deuteron for the ONE mechanism is shown

not taken into account in [28], but, as seen from Fig. 2, c, starts playing in the pd elastic scattering at this kinematics.

Due to very high internal momenta $q \sim 1$ GeV/c in the $d \leftrightarrows pn$ and $Nd \leftrightarrows {}^3$H(^{3}He) vertices, calculations with the wave functions of the deuteron and ^{3}He(^{3}H), obtained from the Schrödinger equation with conventional NN

potentials, are likely unrealistic. Since in the reactions $\gamma d \to pn$, $dd \to {}^3\mathrm{H}\,p$ (or $dd \to {}^3\mathrm{He}\,n$) and $pd \to pd$ (in the backward hemisphere) an important contribution comes from the mechanism of a baryon exchange, for numerical estimations we apply here the Reggeon exchange formalism developed earlier for the $pp \to d\pi^+$ reaction at $-t < 1.6$ (GeV/c)^2 [29] 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 $dd \to {}^3\mathrm{He}\,n$ ($dd \to {}^3\mathrm{H}\,p$) and $pd \to pd$ reactions is connected to that in the $\gamma d \to pn$ reaction. The amplitude of the reaction $dd \to {}^3\mathrm{H}\,p$ can be written as

$$T = T(s,t) + T(s,u), \tag{2}$$

where the first (second) term corresponds to the diagram in Fig. 1, *a*–*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:

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

We use here the effective Regge trajectory for the nucleon from [29]: $\alpha_N(t) = \alpha_N(0) + \alpha'_N t + \alpha''_N/2t^2$ with the parameters $\alpha_N(0) = -0.5$, $\alpha'_N = 0.9$ GeV^{-2} and $\alpha''_N = 0.4$ 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 [29]

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

where the first term explicitly takes into account the nucleon pole in the t channel. According to [29], the second term at $R^2 \approx 0$ is important at $|t| > 1$ (GeV$/c$)^2, which indicates presence of structureless configurations in the deuteron (^{3}He, ^{3}H) wave functions at short distances. The results of calculation are shown in Fig. 2, *b* and parameters C and R^2 are given in the caption. One can see fairly good agreement with the data. For the reactions $dd \to n\,{}^3$He and $dd \to p\,{}^3$H, the parameter R_1^2 is lower in comparison with that used in [29] ($R_1^2 = 3$ GeV^2) to fit the $pp \to d\pi^+$. Such a diminishing R_1^2 is likely connected to a much more intensive high-momentum nucleon component of the ^{3}He(^{3}H) wave function as compared with the deuteron [30]. The increasing ratio C_1/C_2 can mean that multiquark configurations in ^{3}He(^{3}H) become more important at a given t as compared with the deuteron. We also performed this analysis for the $pd \to pd$ reaction and obtained good agreement with the data under minor modification of the parameters R_1^2 and C_1/C_2 (see Fig. 2, *d*).

In conclusion, the CCR scaling behaviour is observed in cross sections of hadron–nucleus reactions with the deuteron and ^{3}He (^{3}H) nuclei. This behaviour sets in at energies about 1 GeV and large scattering angles, where high-momentum components of nuclear wave functions are required in a traditional discription. 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.

I am thankful to V. I. Komarov, A. V. Kulikov, and V. V. Kurbatov for stimulating discussions.

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Received on December 29, 2004.

Редактор *Н. С. Скокова*

Подписано в печать 28.02.2005.
Формат $60 \times 90/16$. Бумага офсетная. Печать офсетная.
Усл. печ. л. 0,56. Уч.-изд. л. 0,81. Тираж 415 экз. Заказ № 54809.

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