

Signs of Dibaryon Production in $D+D\rightarrow X+D$ Reaction

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Abstract.

The properties of dense nuclear matter under extreme conditions are a subject of the large experimental activities worldwide. Heavy-ion collision experiments are the agenda item at RHIC, LHC, FAIR, and NICA facilities. Meanwhile, a complementary approach to the heavy-ion collision researches devoted to investigation of phase transitions in few-nucleon systems has not been discussed. In this report, we try to fill up the gap. It is shown that signals of the phase transition of deuteron into 6-q bag as well as signs of formation of dibaryons of unknown origin with an equidistant mass spectrum.

Introduction.

High-energy nuclear collisions allow the study of new phases of nuclear matter under extreme conditions, at which the phase transition of nuclear matter to a color-deconfined state was predicted by the fundamental theory of strong interactions, the Quantum Chromodynamics (QCD). The experimental programs at BNL and CERN have already confirmed that the extreme conditions of matter necessary to reach the new phase can be reached in the high-energy nuclear collisions. However, identifying and studying the properties of those phases is a challenging task, mainly because of many-body effects and nonperturbative nature of the processes involved. These challenges stimulate putting forward new experimental and theoretical ideas aimed at search of unambiguous signatures of the phase transition onset.

Recently a proposal of QCD investigation at high density and low temperature complementary to the high-energy nuclear collisions was suggested [1, 2]. The proposal is based on the fact that a large number of nucleons in the interaction region is not necessary for the phase transition to occur, and only a change of the vacuum state should be initiated by some experimental environment. Detection of two- and three-nucleon short range correlations [3] affords an opportunity to use the dense few-nucleon correlated systems of this type (SRC) as targets, which correspond to small fragments of nuclear matter in the dynamically broken chiral symmetry states. Collisions of SRC with bombarding particles can initiate the chiral phase transition, ending in the creation of a multibaryon (MB). Thus, the

observation of MB would be a direct evidence of the chiral condensate disappearance and the chiral symmetry restoration in the interaction area. Separation of a MB mass from the secondary particle background is feasible if the MB decay width is narrow enough. That requires the excitation energy of produced MB to be low. For this purpose, it is reasonable to select only those experimental events in which the MB creation is accompanied with a high momentum particle, taking away an essential part of the energy from the interaction region (a cooling effect). In this paper, we focus on new developments in this direction outlined in [1, 2] and put them in a context with some of older experimental data taken at JINR synchrotron [4, 5, 6, 7].

An experiment [4] was designed for measurement of the cross-sections of elastic pp, ND and DD-scattering at 8.9 GeV momentum of primary protons and deuterons. Particularly, three peaks were observed in the spectrum of the missing masses of the reaction $D+D\rightarrow M_X+D$ at $t = -0.495$ GeV² (see Fig. 1).

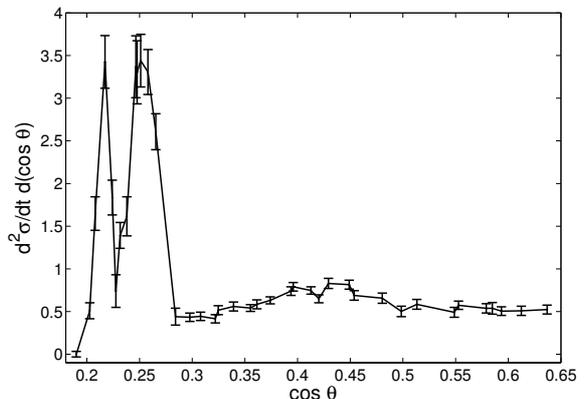


Figure 1: Double differential cross-sections, in $\text{mb}\cdot\text{c}^2/\text{GeV}^2$, of the $D+D\rightarrow M_X+D$ reaction against cosine of the target nucleus scattering angle.

Experimental findings occurred after the paper [4] was written give cause for re-examination of its conclusions. So far as the interpretations of the third peak promise detection of the chiral phase transition, we begin with it. Thereafter problems concerning the first two peaks will be discussed.

Possible transition of deuteron to the 6-q bag.

In Fig. 2, an attempt to explain the experimental data in the range of the third peak by the sum of contributions of reactions $N+D \rightarrow X+D$, where $X=N+\pi$, $\Delta(1232)$, $N(1440)$, and $N(1520)$ are taken into account. Data on baryon resonances are taken from ref. [8]; a contribution of the reaction with $X=N+\pi$ is approximated by the straight line; weights of each of lines are found to obtain the best description of the data, according to a global optimization procedure.

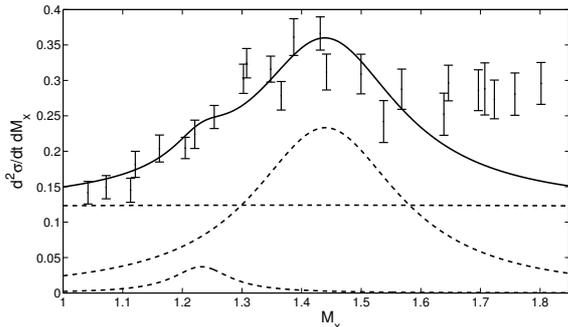


Figure 2: The experimental data in the range of the third peak and their explanation in the frame of the $N+D \rightarrow X+D$ model.

Kinematics reads

$$M_X^2 = M_N^2 + t + \frac{\sqrt{P_1^2 + 4M_N^2 t} + P_1 \sqrt{t(-4M_D^2 + t)} \cos \theta}{M_D} + 1/2, \quad (1)$$

where P_1 is momentum of the primary deuteron, $P_1 = 8.9$, and $M_N = 0.94$, $M_D = 1.8756$ GeV. It is seen that Roper's resonance, $N(1440)$, plays the most important role here, and $N(1520)$ is invisible. Such a description explains a general structure of the third peak, but it does not describe a fine structure at $M_X = 1250 - 1450$ MeV.

The elastic scattering of a constituent quark by the target deuteron may be considered in the framework of a model, in which values of momentum and mass of the projectile quark are taken in the form

$$P_q = xP_1, \quad M_q = xM_D,$$

where x is determined from kinematics of the reaction. The model gives

$$M_q = \frac{-M_D^2 t}{E_1 t + P_1 \sqrt{t(-4M_D^2 + t)} \cos \theta} = 0.311 \text{ GeV}$$

for $\theta = 65^\circ$, in a good agreement with the constituent quark models; see, e.g., ref. [9], in which

$M_q = 0.318$ GeV. Thus, a contribution of this process to the third peak is also admissible.

For the dibaryon production in the reaction $D+D \rightarrow 2B+D$, the isospin conservation leads to $I_{2B} = 0$. The kinematics,

$$M_X^2 = M_D^2 + t + \frac{E_1 t + P_1 \sqrt{t(-4M_D^2 + t)} \cos \theta}{M_D}, \quad (2)$$

states that the fine structure near $\theta = 65^\circ$ is described if one supposes existence of two dibaryons at $M_{2B} \approx 2.4$ and 2.5 GeV. Dibaryons with close masses were predicted in the framework of the MIT bag model in [10]. Similar masses were found in a $pp\pi^+$ system in [7]. Therefore, it is plausible to expect that these hypothetical dibaryons decay into two nucleons and one pion.

The first two peaks' puzzle.

Estimations of the first two peaks' form revealed that they are approximated much better by the Gauss distribution than by the Breit-Wigner function. The Gaussian two-peak approximation results in $\cos \theta_1 = 0.2154$ and $\cos \theta_2 = 0.2539$ for the location of the first two peaks' maxima. It would seem that the experimental errors are dominant in the elastic scattering peaks' form and that an occurrence of resonances are hardly possible in the region. It was very unexpected to find that elastic D-D scattering gives the angle distribution with a maximum at 0.2272 , i.e. between $\cos \theta_1$ and $\cos \theta_2$, see Fig. 3 and formula (2) for $M_X = M_D$.

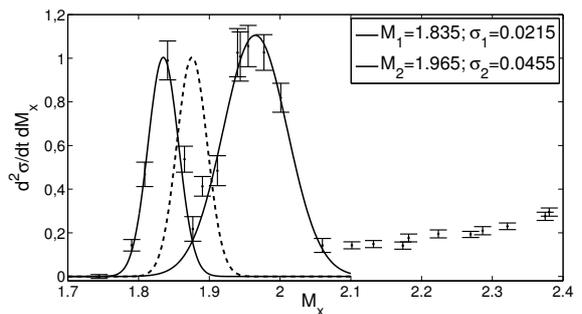


Figure 3: A comparison of the experimental data with the model $D+D \rightarrow D+D$ prediction, shown by the dashed line. A smoothed graph of the experimental mass distributions of M_X from the reactions $D+D \rightarrow X+D$ is shown by the solid lines.

Similarly, elastic N-D scattering described by (1) with $M_X = M_N$ has a maximum at 0.2661 , clearly shifted from the second peak location, see Fig. 4.

Thus, the explanation of the first two peaks by means of contributions of the elastic D-D and N-D scattering fails and their origin remains unclear. At

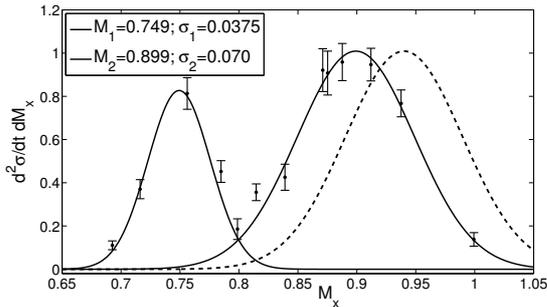


Figure 4: An experimental data comparison with the model $N+D \rightarrow N+D$ prediction, shown by the dashed line. A smoothed graph of the experimental mass distributions of M_X from the reactions $N + D \rightarrow X + D$ is shown by the solid lines.

first glance, the discrepancy may be attributed to systematic errors committed in the experiment, but a subsequent calculations found out that another astonishing explanation is more plausible.

In fact, the Gauss distribution can also arise from superposition of many resonances observed. To explain positions of the first two peaks, different models have been tried out. The models were based on the fact that only the recoil deuteron was unambiguously identified in [4] but masses of all other participants were unknown. Therefore, any transitions $X+Y \rightarrow Z+D$ are allowed to be taken into account. For example, a scattering $X+D$ to $D+D$ explains the first peak location, see Fig. 5, if to assign to

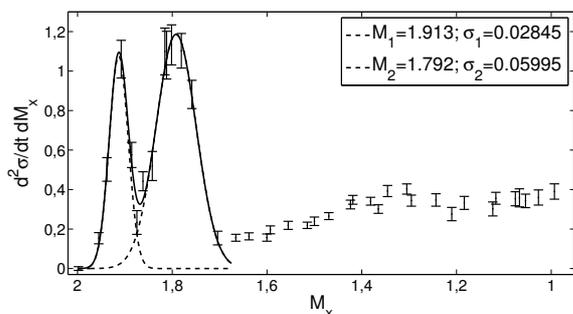


Figure 5: The first peak description in the frame of the $X+D \rightarrow D+D$ model.

X a value of mass of about 1913 MeV, which turns out to be close to 1916 ± 2 MeV, observed in a pp dibaryon spectrum by Yu.A. Troyan [5, 6].

Analysis of other models showed that almost each dibaryon observed in [5, 6] can give a contribution to the first two peaks observed in [4], under an assumption that masses of dibaryons detected in the np-system are 1 MeV less than the corresponding masses in the pp-system. In Table 1, considered reactions are shown in the first column. The sec-

Table 1: Kinematically admissible masses (KAM), which may contribute to the first or second peak in the experiment [4]. Proton-proton dibaryon masses are taken from [5, 6].

Reaction	KAM	pp-dibaryon masses [5, 6]
$X+D \rightarrow D+D$	1913	1916 ± 2
$D+X \rightarrow D+D$	1884	1886 ± 1
$D+X \rightarrow X+D$	1886	1886 ± 1
$X+X \rightarrow X+D$	1884	1886 ± 1
$X+X \rightarrow Y+D$	$1886 \rightarrow 1898$	$1886 \pm 1, 1898 \pm 1$
$X+D \rightarrow Y+D$	$1916 \rightarrow 1884$	$1916 \pm 2, 1886 \pm 1$
	$1965 \rightarrow 1937$	$1965 \pm 2, 1937 \pm 2$
	$1980 \rightarrow 1953$	$1980 \pm 2, 1955 \pm 2$
	$2106 \rightarrow 2086$	$2106 \pm 2, 2087 \pm 3$
$D+D \rightarrow X+D$	1965	1965 ± 2
$X+D \rightarrow Y+D$	$1886 \rightarrow 1966$	$1886 \pm 1, 1965 \pm 2$
	$1898 \rightarrow 1979$	$1898 \pm 1, 1980 \pm 2$
	$1916 \rightarrow 1998$	$1916 \pm 2, 1999 \pm 2$
	$1937 \rightarrow 2020$	$1937 \pm 2, 2017 \pm 3$
	$1999 \rightarrow 2086$	$1999 \pm 2, 2087 \pm 3$
	$2017 \rightarrow 2105$	$2017 \pm 3, 2106 \pm 3$

ond column specifies masses of ingoing or outgoing objects in the deuteron scattering experiment [4]. Dibaryon masses found for the pp-system in refs. [5, 6] are given in the third column. The reactions above the horizontal line explain the first peak and the reactions below it explain the second one. It is possible to verify that the reactions considered for explanation of the data [4] reproduce masses of all dibaryons observed in refs. [5, 6], with the exception of two of them at 2008 ± 3 and 2046 ± 3 MeV/ c^2 .

An equidistant spectrum assumption.

With an assumption that some of dibaryons were unrecognized in the experiments [5, 6], it is possible to approximate the pp-dibaryon mass spectrum within rather small, at 1 – 2 MeV/ c^2 level, experimental errors by the formula

$$M_n = M_{NN} + 10.08 n, \quad (3)$$

where $n = 0, 1, 2, \dots, 40$, all values are taken in MeV/ c^2 , M_{NN} is equal to the value of mass of two protons. A quality of this assumption is seen, e.g., from a fact that only 4 dibaryons might be unrecognized in [5, 6] among the first 14 ones predicted by (3).

To check the suggestion of the similarity of pp- and np-dibaryon mass spectrum, which follows from Table 1, we accepted the relation (3) for np-dibaryons too, only changing M_{NN} with the deuteron value of mass. In Tables 2 and 3, the second column specifies masses of ingoing or outgoing

Table 2: Kinematically admissible masses (KAM), which may contribute to the first peak in $X+D\rightarrow Y+D$ reaction. Dibaryon masses are taken according to the equidistant spectrum assumption.

Reaction	KAM	dibaryon masses, (3)
X+D→Y+D	1916→1884	1916, 1886
	1926→1895	1926, 1896
	1936→1905	1936, 1906
	1946→1916	1946, 1916
	1956→1927	1956, 1926
	1966→1938	1966, 1936
	1976→1948	1976, 1946
	1986→1959	1986, 1956
	2047→2024	2047, 2027
	2057→2034	2057, 2037
	2067→2045	2067, 2047
	2077→2056	2077, 2057
	2087→2066	2087, 2067
	2097→2078	2097, 2077
	2107→2087	2107, 2087
	2118→2099	2118, 2097
	2128→2109	2128, 2107
	2138→2120	2138, 2118
	2148→2131	2148, 2128
	2158→2141	2158, 2138

particles, which are allowed by kinematics,

$$M_Y^2 = M_X^2 + t + M_X P_1 \frac{\sqrt{t(-4M_d^2 + t)}}{M_d^2} \cos \theta + \frac{M_X E_1 t}{M_d^2},$$

of the $X+D\rightarrow Y+D$ reaction. Dibaryon masses for the np-system computed according to (3) are shown in the third column.

One can see that each of dibaryons predicted by (3) in the range from 1886 to 2198 may contribute to the first or second peaks, observed in ref. [4]. Thus, new dibaryons predicted by the equidistant spectrum (3), taken as an assumption on basis of [5, 6], are also confirmed by the data [4]. Moreover, quality of the description definitely improves, since no dibaryon mass calculated using (3) is now lost in the description of the data from [4].

Conclusion.

Our consideration of the data on the hard deuteron-deuteron scattering [4] meets, in some degree, the expectation to observe the transition of nucleon matter into weakly excited quark-gluon plasma using the method of deep cooling, which allows to recognize quasi-resonance peaks in the reaction cross-section. Meanwhile, a further verification of this preliminary conclusion is necessary.

As concerns the dibaryons obeying the equidistant spectrum regularity observed in [4, 5, 6], they

Table 3: Kinematically admissible masses (KAM), which may contribute to the second peak in $X+D\rightarrow Y+D$ reaction. Dibaryon masses are taken according to the equidistant spectrum assumption.

Reaction	KAM	dibaryon masses, (3)
X+D→Y+D	1886→1966	1886, 1966
	1896→1977	1896, 1976
	1916→1998	1916, 1997
	1926→2009	1926, 2007
	1936→2019	1936, 2017
	1946→2030	1946, 2027
	1997→2084	1997, 2087
	2007→2095	2007, 2097
	2017→2105	2017, 2107
	2027→2116	2027, 2118
	2037→2127	2037, 2128
	2047→2137	2047, 2138
	2057→2148	2057, 2148
	2067→2158	2067, 2158
	2077→2169	2077, 2168
	2087→2179	2087, 2178
	2097→2190	2097, 2188
	2107→2200	2107, 2198

hardly can be interpreted in the frame of the 6-q bag model. It is very likely to assign them to the production of pion pairs strongly bound to compressed nucleon matter [11, 12].

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