Experimental and theoretical evidences for an intermediate $\sigma$-dressed dibaryon in the $NN$ interaction

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This paper is dedicated to the memory of Lev Landau in occasion of his centenary

Abstract

Numerous theoretical and experimental arguments are presented in favor of the generation of intermediate $\sigma$-dressed dibaryon in $NN$ interaction at intermediate and short distances. We argue that this intermediate dibaryon can be responsible for the strong intermediate-range attraction and the short-range repulsion in the $NN$ interaction, and also for the short-range correlations in nuclei. The suggested mechanism for the $\sigma$-dressing of the dibaryon is identical to that which explains the Roper resonance structure, its dominant decay modes and its extraordinary low mass. A similar transformation mechanism from the glue to the scalar field was discovered in $J/\Psi$ decays. The new experimental data on $2\pi$-production in the scalar-isoscalar channel produced in $pn$- and $pd$-collisions and in particular the very recent data on $\gamma\gamma$ correlations in $pC$ and $dC$ scattering in the GeV region seems to corroborate the existence of the $\sigma$-dressed dibaryon in two- and three nucleon interactions.

Key words: nucleon-nucleon interaction, quark model, dibaryon, quarks, meson cloud, ABC puzzle.
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1 Introduction

It is well known now that the conventional one-boson-exchange (OBE) concept of the $NN$ interaction suggested long ago in the classical work by Yukawa describes very well the peripheral part of $NN$ interaction at distances $r_{NN} \gtrsim 1.4$ fm. However this accepted mechanism meets quite serious problems on the fundamental level in the description of phenomena depending on the short-range behavior of the interaction when two nucleons are overlapping. To give examples, we point out the difficulties with the extra-large short-range cutoff parameters $\Lambda_{\pi}$ or $\Lambda_\rho$, with high values for $\omega NN$-coupling constant $g_{\omega NN}$, and with the ratio for the tensor-to-vector $\rho NN$ coupling $\kappa_\rho$. Because of these problems the short-range part of the $NN$ interaction is treated in modern $NN$-potential models and in numerous effective-field-theory (EFT) approaches mainly on a purely phenomenological basis. Very recently, however new serious problems with the basic scalar $NN$ force at intermediate ranges have arisen. Using completely different approaches, a few groups have revisited the scalar-isoscalar part of $2\pi$-exchange force which has previously been considered as basic mechanism for the strong intermediate-range $NN$ attraction in conventional OBE-models. Now this part of the interaction was treated more consistently than before, and as a result, the correlated $2\pi$-exchange has lead to a strong short-range repulsion and only very moderate weak peripheral $NN$ attraction. The authors of Ref. summarize their findings as: “Contrary to common belief these processes (i.e. the correlated $2\pi$-exchange at $r_{NN} \sim 1$ fm) lead to negligibly small and repulsive corrections to the $NN$ potential”. With the above new findings (see especially refs.), thus the conventional $t$-channel $2\pi$-meson exchange mechanism cannot provide the strong intermediate-range attraction between two nucleons.

Furthermore, the predictions of the most accurate few-body calculations based on conventional force models disagree in quite numerous cases with the precise experimental data for the few-nucleon systems. One of the most indicative examples is the very strong disagreement between the results of the recent NIKHEF and JLab experiments on the $^3He$ high-energy disintegration into the three-nucleon channel, viz. the $^3He(e, e'pp)$ and the $^3He(\gamma, pn)p$ reaction at $E_\gamma = 0.35-1.55$ GeV and the only existing Laget’s model.

In order to avoid these serious problems at short and intermediate ranges, a few of the present authors have developed some time ago a new model for this part of the $NN$ interaction. The new approach assumes that when two nucleons are approaching very closely to each other for distances $r_{NN} \lesssim 1$ fm,
their quark cores overlap and a new intermediate state, the dressed dibaryon, appears. The respective interaction model has been developed jointly by two groups (in Moscow and Tübingen), initially as interesting and quite successful alternative concept to the conventional $t$-channel meson-exchange mechanism at short ranges. Although this concept was a plausible conjecture it was able to explain consistently the character of short-range $NN$ correlations. However recently very convincing new direct experimental data appeared which, on the authors opinion, can be interpreted as direct evidence of appearance of the dressed dibaryon in the $NN$ system and thus the generation of the dressed six-quark bag looked for in $NN$ system a long time \cite{15,16,17}. After a short description of the dibaryon concept for the $NN$ interaction, we recapitulate in this letter all the new experimental data and give their qualitative interpretation in terms of the dibaryon concept.

2 Concept of the dressed dibaryon in $NN$ interaction

There was a very high activity in 80ies around dibaryons and their experimental manifestation (see e.g. the comprehensive reviews \cite{18,19}). However in all this activity dibaryons (no matter, they are narrow or broad) were considered as some multi-quark exotic mode. In sharp contrast to this previous activity, we treat the intermediate dibaryon as a basic carrier of short-range $NN$ interaction, i.e. as a regular d.o.f.

Thus, in our approach the $NN$ system is described formally as a two- (or multi-) component system including at least two independent channels \cite{11,12,20}. The external ($NN$) channel describes the motion of two nucleons interacting with each other by a conventional $t$-channel one- or two-meson exchange with the appropriate cut-offs at short distances. However, when two nucleons are approaching each other, the system changes to the inner – dibaryon (DB) – channel in which there are no individual nucleons present at all and a new phase emerges which consists of the intermediate dibaryon dressed with strong meson fields, e.g. $\sigma$, $\rho$ and $\pi$. Note, that the main contribution is coming from the scalar $\sigma$-field surrounding six-quark core in a space symmetric state. Formally, it may be interpreted in a way that the standard $t$-channel $\sigma$-exchange between two nucleons at $r_{NN} \lesssim 1$ fm is replaced in our approach by the respective $s$-channel $\sigma$-exchange associated with the intermediate dibaryon production (see Fig. 1). It is important to stress that all channels are defined in our approach in a whole space.

In general, the model includes a Fock-column with different components: $NN$, $6q+\sigma$, $6q+\pi$, etc. \cite{20}. The main problem in this approach is finding the coupling between the external $NN$ channel and the internal $DB$ channels, i.e. the transition vertex $NN \rightarrow DB + \sigma$. 
Fig. 1. The graphs are illustrating the generation of the intermediate s-channel dibaryon dressed with $\sigma$, $\pi$ and $\rho$ meson fields. The contraction of the two bare dibaryon propagators in the left graph leads to the contracted graph shown in the right.

**In the non-relativistic treatment**, we tested two different ways for this coupling: fully microscopic \[12\] and semi-microscopic \[20\]. Within microscopic six-quark model the $\sigma$-dressing mechanism was shown \[11\] to come from specific mixed-symmetry six-quark configurations $|s^4p^2[42]_X[51]_{FS}\rangle$ dominating in the overlap region of two nucleons \[21\]. Thus, the scalar $\sigma$-field can be easily generated in the transition $|s^4p^2[42]_X[51]_{FS}\rangle \rightarrow |s^6[6]_X + \sigma\rangle$ in which two $p$-shell quarks jump down to the $s$-shell with emission of two strongly correlated $S$-wave pions. These two pions produce quite naturally a scalar $\sigma$-meson \[11\] in the field of a six-quark core.

This treatment leads to a very simple and transparent model for interaction in the external $NN$ channel:

$$ V_{NN} = V_{OPE} + V_{TPE} + V_{NDN} + V_{orth} $$

where $V_{OPE}(V_{TPE})$ are the peripheral one-(two-) pion exchange interactions smoothly cutoff at $r \sim 1$ fm. The intermediate- and short-range term $V_{NDN}$ is a nonlocal potential of separable type coming from intermediate $s$-channel dressed dibaryons (cf. Fig. 1), which in the simplest case at low and intermediate ($E_p \lesssim 1$ GeV) energies takes the form:

$$ V_{NDN} = \sum_{JLL'} \varphi_L^J(r) \lambda_{LL'}^J(E) \varphi_{L'}^*(r') $$

where $\varphi_L^J(r)$ are the $2s$ (or $2d$) or $3p$ (or $3f$) h.o. functions for the interaction in the $L^{th}$ partial wave. The energy-dependent coupling constant $\lambda_{LL'}^J(E)$ is expressed in terms of the loop integral (cf. Fig. 1) taking the form

$$ \lambda_{LL'}^J(E) = \int_0^\infty dk \frac{B_L^J(k, E) \cdot B_{L'}^J(k, E)}{E - E_{DB} - k^2/2m_{\sigma}} $$

where $m_{\sigma}$ is the reduced mass in the $6q + \sigma$ channel, $k^2/2m_{\sigma}$ is the kinetic energy of the $\sigma$-meson, $E_{DB}$ is the difference of the bare mass of the dibaryon and sum of nucleon masses. $B_L^J$ and $B_{L'}^J$ are the vertex functions for the $DB + \sigma$ interaction.
couplings which can be calculated microscopically [12]. In the semi-microscopic
variant of the model the explicit consideration of multi-quark dynamics was
replaced by a simple parametrization of the vertex functions [20]. The results
of the microscopic and semi-microscopic variants occurred to be quite near to
each other.

$V_{\text{orth}}$ is a pseudo-potential providing the orthogonality condition between the
excited $2\hbar\omega$ and the non-excited $0\hbar\omega$ 6q-states expressed through the variables
of the $NN$ channel. The potential in the $S$-wave takes the form $V_{\text{orth}} = \mu \langle \mathbf{r} | \varphi_0 \rangle \langle \varphi_0 | \mathbf{r}' \rangle$. Here $\varphi_0(\mathbf{r})$ is the $0s$ h.o. wave function and the constant $\mu$ should be taken
positive and sufficiently large to eliminate the contribution of the $s^6$ bag-like
configuration from the initial $NN$ channel [12,13]. Similar constructions for
$V_{\text{orth}}$ are found also for the $P$-waves. It should be noted, that in our approach
the traditional mechanism for the short-range $NN$ repulsion induced by the
vector (i.e. $\omega$- and $\rho$-) meson exchange is replaced mainly by a nonlocal repul-
sion coming from the $V_{\text{orth}}$ term in Eq. (1) and also from the nodal character
of all $NN$ wave functions in the low partial waves [11,21,22] with stationary
inner nodes.

Moreover, the inner node positions have been found to almost coincide with the
repulsive core radii in traditional $NN$-potential models. The conventional
t-channel $\omega$- and $\rho$-exchanges can also be included into the model with proper
coupling constants but the main part of short-range $NN$ repulsion will come
just from dibaryon mechanism. Thus, in our approach the $\omega NN$ and $\rho NN$
coupling constants can be taken in full agreement with $SU(3)$ prescription.

**In a fully relativistic treatment** [2,13] we start with a time ordered two-
point Green function for the transition chain $NN \rightarrow D(CC) \rightarrow NN$

$$M_{fi} = -\frac{i}{2!} \int d^4x_1 d^4x_2 d^4x_3 d^4x_4$$
$$\langle 4, 3 | T \{ \mathcal{L}_{ND}(x_3, x_4) \times \mathcal{L}_{ND}(x_1, x_2) \} | 2, 1 \rangle$$  (4)

where $D(CC)$ means the confined (on color) dibaryon state and $T$ means a
chronological ordering operator whereas the states $| 2, 1 \rangle$ and $| 4, 3 \rangle$ correspond
to the initial and final nucleons with 4-momenta $p_2, p_1$ and $p_4, p_3$ respectively.
The (nonlocal) Lagrangian density is chosen as

$$\mathcal{L}_{ND}(x_1, x_2) = \tilde{N}(x_2) \{ \Psi(x_1, x_2) V_0(x_1 - x_2)$$
$$+ \gamma_5 \gamma_\mu \Psi_\mu(x_1, x_2) V_1(x_1 - x_2) \} N(x_1) + h.c.$$  (5)

where function $\Psi(x_1, x_2)$ describes the dibaryon with spin $S = 0$ whereas
$\Psi_\mu(x_1, x_2)$ corresponds to the $S = 1$ dibaryon. In the two cases the isospin $I$
is taken zero, $I = 0$. For the $I = 1$ dibaryon an evident replacement $\Psi \rightarrow \tau \bar{\Psi}$
should be done. After a lengthy calculation (for details see Refs. [2,13]) one gets a relativistic dibaryon-induced $NN$ potential which gives in the nonrelativistic reduction a separable potential similar to Eqs. (2) and (3).

In the simplest case, the above model [14,20] has two components only, the external $NN$ part and the inner $\sigma$-dressed dibaryon part. With this two-component model we were able to fit excellently the lower partial wave $NN$ phase shifts up to 1000 MeV [2,11,12], using only a few basic parameters (mass and radius of the intermediate dibaryon, and the cutoff parameters for $V_{OPE}$ and $V_{TPE}$). The quantitative estimates for the mass of the dressed dibaryon still require the accurate consideration of the chiral symmetry restoration effects and thus we postpone such cumbersome calculations to a future. However we found that the $NN$ phase shifts can be nicely fitted until the energy $E_{Lab} \simeq 1$ GeV at the dibaryon mass $m_{DB} = 2.2 \div 2.3$ GeV (for $^1S_0$ and $^3S_1 - ^3D_1$ partial waves).

Using two-component model one can calculate accurately the weight $W_D$ of the dressed dibaryon in the deuteron and also in the $NN$ scattering states. For the deuteron we found $W_D \approx 0.025$ [12,20]. Despite this rather small admixture of the dressed dibaryon component, it provides (jointly with the OPE-tensor force and some very moderate peripheral attraction coming from TPE) a sufficient intermediate-range attraction to fit the $NN$ phase shifts up to 1 GeV and to bind the deuteron.

On the other hand, the qualitative picture of the intermediate dibaryon can also be confronted with the earlier dibaryon models [23,24] which have used the different mechanisms for stabilization of intermediate six-quark bag (e.g. delocalization of single-quark orbits [23] or the matching to external $NN$ channel on some surface [24]. However, these previous models were operating only with inner single-quark (and external $NN$) degrees of freedom without explicit scalar field which plays a crucial role in our approach (see below) and is seen clearly in experiments. The other alternative dibaryon model [25] was built on a string-like picture, where the dibaryon was modeled as $4q + 2q$ quark clusters connected by a color string. However, the string in such models was in its ground state regarding its radial excitation and there were also no meson fields present. In terms of the color string between two quark clusters at its ends, our picture corresponds to the generation of a $2\hbar\omega$-excited string configuration between two colored quark clusters in the initial state (because the six-quark configuration $s^4p^2[42]_X$ includes two quanta of gluonic excitation) [2,12]. Consequently, when the string deexcites with the emission of two gluons the latter can transform their energy to the scalar $\sigma$-field and eventually to two final pions. The energy transformation can be easily understood if the $\sigma$-meson contains some glue component in form of light glueball admixture. This picture of the $\sigma$-generation from the string deexcitation in the intermediate dibaryon is in nice agreement with recent approaches [26,27] to
the $\sigma$-meson emission in $pp$ collisions at high energies. The authors suggested to estimate the one- and two $\sigma$-meson emission from the intermediate string by assuming a hybrid nature of the light scalar meson which has both glueball ($0^{++}$) and $\pi^0\pi^0$ ($\pi^+\pi^-$) components. From this point of view, production of the intermediate $\sigma$-dressed dibaryon can be viewed as $s$-channel version of the $\sigma$-emission mechanism (proposed by Kisslinger et al. for Pomeron exchange at high energies [27]) in case of low and intermediate energies.

3 Application to the Roper resonance structure and decay

The above dibaryon model combined with the specific mechanism for the strong scalar field generation in the quark bag gives unique predictions for several hadronic processes and for many properties of the few-body systems. In particular, the non-conventional picture for the strong scalar field generation described above was confirmed very nicely in recent studies of the Roper-resonance structure [28] and its decay [29,30,31] and also in other new experiments with high-energy deuterons [32]. In fact, the quark structure of the Roper resonance (corresponding also to the $2\hbar\omega$ monopole excitation of the initial nucleon) should include the excited $3q$-configurations $|(0s)(1p)^2[3]_X + (0s)^2(2s)[3]_X\rangle$, i.e. this Roper state includes also two $p$-shell quarks (or a single quark in the $2s$-excited state). Hence quite similar to our dibaryon, one has for the Roper-resonance a generation mechanism for the scalar field: $|sp^2[3]_X\rangle \rightarrow |s^3[3]_X + \sigma\rangle$. This means that the dominating configuration for the Roper resonance might be $|s^3[3]_X + \sigma\rangle$, i.e. the $\sigma$-dressed three-quark bag in a space symmetrical $3q$-state $|s^3\rangle$ which is equivalent – in the $3q$-dynamics – to our intermediate dibaryon production mechanism in the $6q$-dynamics. Actually, the large admixture of such a $\sigma$-field configuration to the $3q$-state $(0s)^3$ was found both in theoretical [28] and experimental [29,30,31] studies. Moreover, two independent studies [33,34], both done on basis of QCD sum rules, have found that the Roper resonance state has a large admixture for the $\sigma$-field while the nucleon ground state has a negligible amount of $\sigma$-meson admixture.

These conclusions have been well confirmed in a recent dedicated experiment [29,31] where the $\sigma$-meson channel was found to be strongly dominating in the Roper-resonance decay with a branching ratio $\Gamma(R \rightarrow N + \sigma)/\Gamma(R \rightarrow \Delta + \pi)$ of $\sim 4:1$. Thus, the high admixture of the scalar field in the Roper wave function should be one of the main reasons for the strong shift downwards of the Roper-resonance mass to anomalously low mass value $m_R \approx 1370$ $MeV$ [31]). A very similar shift downwards of the $\sigma$-dressed dibaryon mass enhances significantly the $NN$ intermediate-range attraction via the mechanism shown in Fig. 1.
The dressed dibaryon concept is very tightly related to the idea about partial chiral symmetry restoration (CSR) in dense hadronic matter [35]. As is well known, the $\sigma$-meson mass in such a symmetry restoration process decreases drastically and this leads to a strong stabilization of the most symmetrical $6q$-configuration $|s^6[6]X\rangle$ embedded into this scalar field. Simultaneously the mass of the intermediate dressed dibaryon comes also down and as a result of all these highly non-linear effects there appears a strong effective attractive force between two nucleons at intermediate distances $r_{NN} \sim 1$ fm. In the conventional quantum-mechanical language this strong intermediate-range attraction in $NN$ channel can be interpreted in terms of coupled-channel phenomena, i.e. as a result of strong coupling between the external $NN$ channel and inner dibaryon channel with symmetry $|s^6[6]X\rangle$ dressed with $\sigma$-field. This picture should be compared with result of pure $6q$-model [22], i.e. that without any scalar fields where $qq$ force (originating from the Goldstone-boson-exchange (GBE) mechanism) are fitted very nicely to reproduce the spectra of excited baryons (in the normal and strange sectors) [36]. However, the effective two-nucleon force resulting from the GBE $qq$ force was found [22] to be purely repulsive and strong in the nucleon overlap region. Thus, the $qq$ force which fits very well the baryon spectra (octets, decuplets et.) should be supplemented in the $NN$ system with an additional strong scalar force (either on the $qq$- or directly on the $NN$ level) to fit the deuteron properties and the $NN$ scattering data. We conjecture, the dibaryon mechanism considered here is very well suited to be origin for this strong scalar force.

Furthermore, in combination with recent ideas about chiral symmetry restoration [35,37], the dibaryon model predicts the strong enhancement for the $\sigma$-meson production in $NN$ collisions in the energy region $E_{lab}^{\pi\pi} \approx 1.1 - 1.2$ GeV. This property follows straightforwardly from untiing the $\sigma$ loop of the dressed bag propagator (cf. Fig. 1) at energies above the threshold of $\sigma$-meson production.

As a clear signal for such a chiral symmetry restoration (CSR) effect one considers usually parity doublets in the baryon spectra at high excitation [37]. The first (rather approximate) parity doublet is suggested [38] to be the Roper $P_{11}(1440)$ ($J^P = 1/2^+$) and $S_{11}(1535)$ ($J^P = 1/2^-$) isobars. Thus, from this point of view, the $2\hbar\omega$-excitation of the dressed dibaryon is very similar to the $2\hbar\omega$-excitation of the Roper-resonance. So, the scalar-isoscalar enhancement near the $2\pi$-threshold, associated with the intermediate $\sigma$-meson in case of CSR in the excited multiquark bag, should be seen in experiments on two-pion $(\pi^0\pi^0$ or $(\pi^+\pi^-)_{00}$ production in $NN$, $Nd$ etc. collisions. Fortunately, such experiments have been done numerously in 60ies [39] and the authors found very clear and strong enhancement in the $2\pi$-production near the thresholds.
in \( p + d \to ^3\text{He} + (\pi\pi)_{00} \), \( d + d \to ^4\text{He} + (\pi\pi)_{00} \) reactions. These experimental results shown as missing mass distributions are well known nowadays as the famous ABC-puzzle [39][40].

This (partial) symmetry restoration effects have been confirmed by two independent groups of authors: first, this restoration was found [35] in large hadronic systems at high temperature or density, and second, this effect was demonstrated to happen even in a single hadron at high excitations [37,38]. There are also quite general arguments in favor of the \( \sigma \)-mass renormalization [35,37] at sufficiently high excitation energy in both cases mentioned above.

5 New experimental evidence for the \( \sigma \)-dressed dibaryon

Very recently two types of new experimental data appeared [30,31,32,40] which have given the direct and unambiguous evidence for the intermediate \( \sigma \)-dressed dibaryon production with strongly renormalized \( \sigma \)-meson mass. The first type of experiments [30,40] is in essence an improvement of the old classical ABC experiments with modern exclusive setting and detailed measurements of energy and angular correlations of two emitted pions in the reactions \( p + d \to ^3\text{He} + \pi^0\pi^0 \) (or \( \pi^+\pi^- \)) and \( p + n \to d + \pi^0\pi^0 \) at incident proton energies \( E_{\text{lab}}^p \sim 1.1 - 1.2 \text{ GeV} \) specific for the manifestation of the ABC phenomenon.

The new experimental data of the CELSIUS-WASA collaboration [29,30,31,40] together with those from earlier measurements have demonstrated (Fig. 2) that the rather narrow and strong peak observed in the \( p + n \to d + (\pi\pi)_{00} \) cross section cannot be explained by the conventional \( \Delta\Delta \) model [41] (dotted line in Fig. 2), and the data require a near threshold \( \Delta\Delta \) bound state (long dashed line). In fact, a few \( \Delta\Delta \) bound states have been predicted in some recent six-quark calculations [23,42,43]. However, in all these calculations the r.m.s. radius \( r_{\Delta\Delta} \) of matter in such \( \Delta\Delta \) bound states was found to not exceed 0.9 fm [42], or to range even at 0.72 – 0.82 fm [43]. Thus, two deltas in such bound states are strongly overlapping and therefore the assumed \( \Delta\Delta \) bound states are nothing else but the intermediate dibaryon components. Another important result of these experiments is that the authors found (similarly to the ABC-group) a strong enhancement in \( (\pi\pi)_{00} \)-production near threshold at \( M_{\pi\pi} \sim 320 - 330 \text{ MeV} \) with clear \( S \)-wave \( \pi\pi \)-correlation. Hence, in this case, the ABC puzzle can be considered as an indicator for partial chiral symmetry restoration in the excited six-quark system generated from collision of two nucleons at energies \( E_{\text{lab}}^p \sim 1.1 - 1.2 \text{ GeV} \). In such a specific generation process, all the kinetic energy of the two-nucleon relative motion (\( \approx 0.6 \text{ GeV} \)) transforms into a \( 2\hbar\omega \) string excitation near the \( \Delta\Delta \) threshold with subsequent
Fig. 2. The excitation functions for the reactions $pn \rightarrow d\pi^0\pi^0 \cdot 2$ and $pn \rightarrow d\pi^+\pi^-$. Predictions of the conventional $\Delta\Delta$ model\[41\] are shown with dotted line while the long dashed line corresponds to the fit with the near-threshold $\Delta\Delta$-bound state (for detail, see refs. [30]).

$\sigma$-meson emission.

Another very clear signal for the $\sigma$-meson associated with the renormalized-mass $\sigma$-dressed dibaryon in the deuteron has been found in experiments $p + C \rightarrow X + \gamma\gamma$ and $d + C \rightarrow X + \gamma\gamma$ at incident energies 2.5 - 5 GeV/N at Dubna [32]. In the $d+C$ experiment (see Fig. 3a) the authors have found three clear peaks in the $\gamma\gamma$-mass ($M_{\gamma\gamma}$) distribution: the low-energy peak for $M_{\gamma\gamma} \approx 140$ MeV associated with the $\pi^0$-decay mode was suppressed in the analysis by cuts (and so not seen in Fig. 3), a high-energy peak at $M_{\gamma\gamma} \approx 540$ MeV associated with the $\eta$-production and a strong enhancement at $M_{\gamma\gamma} \approx 355$ MeV exhibiting a width $\Gamma_{\gamma\gamma} \approx 49$ MeV; the latter could not be interpreted by the authors [32] in terms of well known mesons despite the comprehensive and detailed modeling.

A similar peak at $M_{\gamma\gamma} \approx 300 - 320$ MeV has been found by the CELSIUS-WASA collaboration [44] in $pp \rightarrow pp\gamma\gamma$ experiments. This peak has been interpreted by the authors as a signal of the intermediate $\sigma$-meson with renormalized mass in the process $pp \rightarrow pp\sigma \rightarrow pp\gamma\gamma$. However, the authors [44] have interpreted two gammas emitted from the reaction as emerging from the intermediate $\pi\pi$ bremsstrahlung. Contrary to this, the new data of the Dubna group have a quite unambiguous interpretation just through the $\sigma$-dressed dibaryon component in the incident deuteron because the signal is seen very clearly in $d+C$ collisions and is not seen in $p+C$ collisions (cf. Fig 3a and 3b).
Fig. 3. Invariant mass distributions for pairs of $\gamma$-quanta (a) in the reaction $d + C \rightarrow \gamma + \gamma + X$ at a momentum of incident deuterons 2.75 GeV/c per nucleon and (b) in the reaction $p + C \rightarrow \gamma + \gamma + X$ at momentum of 5.5 GeV/c, after background subtraction [32].

In the first case the $\sigma$-cloud of the dressed dibaryon component in the incident deuteron is picked-off of six-quark core through the interaction with the carbon target producing a $\gamma\gamma$ signal ($\sigma \rightarrow \gamma\gamma$) with a well known branching ratio $\Gamma_\sigma(\gamma\gamma)/\Gamma_\sigma(\pi\pi) \sim 10^{-5} - 10^{-6}$. Our first estimates for the $\gamma\gamma$-yield in the $d+C$ process are in an approximate agreement with the measured number of the $\gamma\gamma$ events.

The suggested common mechanism for the generation of a light scalar field in the Roper resonance and in dressed dibaryon dynamics was observed actually
also in the $J/\Psi$ decays studied by the BES collaboration \cite{45}, the Crystal Barrel group \cite{46,47} and by the Fermilab E760 experiment \cite{48}. Here the $J/\Psi$-mesons are produced often in the states with radial excitations of $c\bar{c}$ string. The authors \cite{46,47} have found the decay of the excited $0^{++}$ states (after $\gamma$-emission from excited $J/\Psi$ states) to proceed with dominating emission of double $\sigma$-mesons. These specific transitions of $c\bar{c}$ excited strings give a good independent evidence for the discussed mechanism of the scalar field generation and thus in a way for the $\sigma$-dressed intermediate dibaryon in the $NN$ system.

Summarizing all these completely independent experimental findings one can conclude that there should be a common mechanism for the enhanced $\sigma$-meson emission from the Roper resonance decay, from the $2\hbar\omega$-excited intermediate dibaryons, from high-energy $dC$ collisions, and also from deexcitation of $c\bar{c}$ strings. This common mechanism can be further confirmed with many theoretical arguments presented here about the $\sigma$-meson hybrid nature and chiral symmetry restoration in excited hadrons. So that the concept of $\sigma$-field dressing of the intermediate dibaryon in $NN$ system (or alternatively $2\hbar\omega$ string deexcitation mechanism into an enhanced scalar $\sigma$-field) looks to be quite convincing one. Simultaneously, it seems prove the generation of the intermediate $6q$ bag in deuteron and $NN$ system predicted long ago \cite{15,16,17} on the basis of general arguments of quark model and some experimental data. Thus, the above dibaryon concept seems to open a door to the QCD-based description for nuclear phenomena.

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