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Experimental and theoretical backgrounds for generation of dibaryons in NN and $3N$ interactions

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Abstract. Numerous experimental and theoretical arguments in favor of the intermediate dibaryon generation in NN and $3N$ interactions are presented. Using some specific mechanism for the scalar field production when the $2\hbar\omega$-excited multi-quark system deexcites to the ground state one formulates a concept for σ-dressed dibaryon as a carrier of intermediate-range attraction and a reason for short-range repulsion in NN-interaction. It is argued that the basic mechanisms responsible for large lowering of the Roper-resonance and the dressed dibaryon masses should be very similar. The modern experimental data of a few groups seem to confirm strongly the dibaryon picture in NN and $3N$-interactions. Some important common features of the dibaryon and pomeron in high-energy NN scattering are discussed.

1 Introduction

General idea of dibaryons, or six-quarks bags, is almost as old as idea of quarks [1,2]. Most of dibaryon activity, both experimental and theoretical, occurred still in 80ies of the last century, and until recent time the dibaryon studies were only weakly reminiscent the previous strong activity in the field. The conventional look at the nature of dibaryons, e.g. those advocated by Jaffe, was the following. Due to some specific structure of multiquark wavefunctions in color, spin and flavor spaces in $SU(6)$ scheme and specific quark-quark interaction via OGE it might be possible that the dibaryon mass in some channels would be less or near to initial two-baryon mass. So, in such channels two baryons should interact so strongly to couple into one dibaryon. The first candidate of such sort suggested still a long ago was $\Lambda\Lambda$ dibaryon [3,4]. However, very long and intensive experimental searches for such di-lambda dibaryon were unsuccessful. Another interesting candidates, now in non-strange sector, were very broad and highly inelastic resonances in different partial waves in NN scattering at intermediate energies $E_N \sim 600 - 800$ MeV [5–7]. However, the nature of such broad intermediate states were rather unclear because almost all of them were seen near $N\Delta$ or $\Delta\Delta$ thresholds and thus might be interpreted as specific threshold singularities. Unfortunately, the predictions of the quark model for these states were rather indefinite (see below). Still the most probable candidate for such non-strange dibaryon was $J^{\pi}I = 3^{+}0$ dibaryon in $\Delta\Delta$ channel near $\Delta\Delta$ threshold [8].

In all these previous studies the dibaryons were considered as some exotic multiquark mode, like pentaquark. And their role was mainly to constraint somehow the quark-quark interaction.

In contrast to this, we suggested the idea of dibaryons as carriers of strong internucleon interaction at intermediate and short distances [9–11], i.e. as fully regular degree of freedom in nuclear physics like pions, Δ-isobars etc. Moreover, in our approach the above dibaryon includes sigma and other mesonic clouds around six-quark core and just this strong scalar field reduces essentially mass of dibaryon making it to be much closer to NN, $N\Delta$ or $\Delta\Delta$ thresholds [12].

In last years new strong indications, both experimental and theoretical, appeared in favor of the dibaryon concept of NN and $3N$ interactions at short and intermediate distances and the present report is devoted to their presentation and discussion of validity.

2 Problems with NN scalar force at intermediate distances.

In the conventional OBE-like models for nuclear force it is assumed that main NN attractive force at intermediate ranges $R_{NN} \sim 0.7 - 1$ fm comes from an effective scalar σ-meson exchange which models t-channel 2π-exchange with a strong $\pi\pi$ interaction [14]. However new studies for 2π-exchange made independently by few groups within different approaches (χPT, $1/N_c$ expansion etc.) have demonstrated very clearly [15–17] that more consistent treatment for such t- channel 2π-exchange leads unavoidably to a strong short-range *repulsion* (of 1 GeV height) and only *very weak peripheral attraction* at $r_{NN} > 1.2$ fm. So in the OBE-like models we have now no strong scalar force which can hold nucleons together in a nucleus (see Fig 1). This scalar force catastrophe has been enhanced even further by recent microscopic quark-model calculations for NN interaction [18] within the framework Goldstone-boson-exchange (GBE) model used for qq interaction. In fact, by

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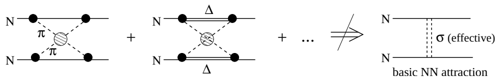

Fig. 1. The failure of traditional view on σ-meson exchange force

using only a few free parameters for the GBE qq interaction it was possible to fit (with rather low χ^2 per d.o.f.) the baryon spectra in all sectors (i.e. octet, decouplet etc.). However, when one employs the same qq force to describe NN interaction within the framework of six-quark model [18] this leads to completely repulsive NN phase shifts and strong repulsive interaction with a core of ca. 1 GeV height [19].

From this very interesting study it becomes evident that those qq interaction (within GBE or OGE models) which fits excellently all spectra of excited baryons (i.e. in 3q sector) cannot fit satisfactorily NN interaction (e.g. phase shifts, deuteron binding, etc.). In other words, there should appear in two-nucleon system being treated as six-quark cluster some additional strong attractive NN interaction which is absent in one-nucleon sector (i.e. in three-quark system). The σ-dressed dibaryon model just leads to such a strong additional attraction – through the s-channel intermediate dibaryon production – the effect which is absent in one nucleon. This fact gives a very good argument in favor of such a dibaryon picture for NN interaction.

3 Generation of the σ-dressed dibaryon in NN interaction

Let us start with a symmetry aspect of NN force in six-quark model which should be only weakly dependent upon the details of quark dynamics. The space (and permutation) symmetry of the three-quark system in nucleon is $|s^3[3]_x\rangle$, so that for two nucleon symmetry one has a product of two irreducible representations:

$$[3]_x \times [3]_x \Longrightarrow \frac{8}{9}[42]_x + \frac{1}{9}[6]_x. \qquad (1)$$

So, for two non-interacting nucleons in S-wave state one has the strong dominating 6q configuration $|s^4p^2[42]_x\rangle$ of mixed symmetry and only a small fraction of fully symmetric configuration $|s^6[6]\rangle$.

For two interacting nucleons was demonstrated a long ago by many authors [20,18,21] this dominating mixed-symmetry configuration was preserved also for any reasonable qq interaction. Moreover, it was found in detailed six-quark studies [20,18] that in a quite realistic six-quark calculations a coherent superposition of $[42]_x$ mixed-symmetry components has a large projection onto NN channel, i.e. this component describes in essence the NN system in the overlap region ($r_{NN} \lesssim 1.2$ fm). On the other hand, the fully symmetric 6q component $|s^6[6]\rangle$ has a rather small projection onto NN channel, while a large projection in color-color channel (i.e. channel with hidden color). So this component can be associated with bag-like structure [18,21].

It was established in previous works performed within the multiquark models that two above basic components of the different nature get mixed noticeably by one-gluon exchange force. In our approach we added there a strong coupling of quarks with scalar field fluctuations of QCD vacuum [11–13]. This coupling leads immediately to the transitions (for S-wave):

$$|s^4p^2[42]_x\rangle \Longleftrightarrow |s^6[6]_x + \sigma\rangle \qquad (2)$$

between two basic 6q components. The transition can be illustrated by the following graphs in Fig. 2.

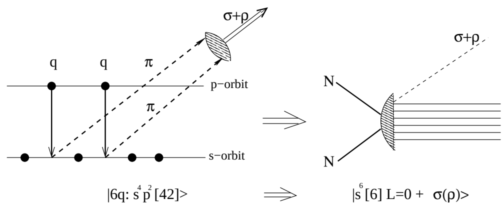

Fig. 2. The schematical picture illustrating the emission of scalar σ-meson in transition of the mixed-symmetry six-quark component $|s^4p^2[42]_x\rangle$ to fully symmetric $|s^6[6]_x\rangle$.

Here in the first stage two separated nucleons when approaching close to each other (at $r_{NN} \lesssim 1.2$ fm) get overlapped in alone (bare) six-quark bag with dominating symmetry $|s^4p^2[42]_x[51]_{FS}\rangle$. This is the 2$\hbar\omega$-excited six-quark configuration which is able to discharge this gluonic excitation by emission light scalar meson (see below) with transition to unexcited six-quark configuration $|s^6[6]_x\rangle$. This emission process leads to generation of σ-meson cloud around the symmetric bag. The this virtual (or real!) σ-meson may be reabsorbed by the quark core giving again the mixed-symmetry 6q configuration. This can be treated on the field-theory language as a σ-meson loop in full 6q propagator. Such dressing process can be treated microscopically as following (see Fig. 2): two p-shell quarks in the mixed-symmetry configuration $|s^4p^2[42]_x\rangle$ jumps down to the s-shell with emission of two s-wave pions.

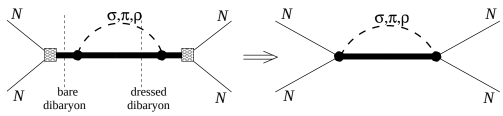

Fig. 3. The graphs are illustrating the generation of the intermediate s-channel dibaryon dressed with σ, π and ρ meson fields. The contraction of the two bare dibaryon propagators in the left graph leads to the contracted graph shown on the right.

These two s-wave pions being interacting in the field of six-quark core can produce a light σ-meson. The emitted σ-meson, in its turn, interacts strongly with six-quark core by attractive force, which leads to an effective reduction of the σ-meson mass from the bare value $m_\sigma^{\rm bare} \simeq 460 \pm 20$ MeV and width $\Gamma_\sigma^{\rm bare} \simeq 450$ MeV to renormalized (reduced) values: $m_\sigma^{\rm eff} \simeq 330 \pm 20$ MeV, $\Gamma_\sigma^{\rm eff} \simeq 60$ MeV. This mass and width renormalization, as will be shown below, is tightly interrelated to the chiral symmetry partial restoration effect in strongly excited hadronic systems [22, 23].

Moreover, just these renormalized mass and width of light scalar meson have been observed in numerous experiments for last 50 years most important among which was an observation of the so called ABC-puzzle by Abashian, Booth and Crowe still in 1960ies [24]. They found a strong enhancement of 2π production near the 2π threshold (with missing mass $m_{2\pi} \simeq 320 \pm 10$ MeV) in reactions $p + d \to {}^3\mathrm{He} + (\pi^+\pi^-)_{00}$ and $d + d \to {}^4\mathrm{He} + (\pi^+\pi^-)_{00}$.

The quite similar mass and width reduction of σ-meson have been observed also in very recent experiments of Tübingen group [25–27] and in Dubna group experiment [28]. In these experiments the enhanced σ-meson emission from resulted multiquark systems (i.e. $6q$, $9q$, $6q + N$ etc.) have been found. However there is very serious puzzle with the σ-meson parameters (mass and width) observed in the experiments of different type (see below), in particular from $\pi\pi$ scattering in free space and from hadronic reactions like $p + d \to {}^3\mathrm{He} + \pi^0\pi^0$. It may be argued that the difference is due to the chiral symmetry restoration (CSR) effect which is one of the main features of QCD. The strong difference between the parameters of the bare σ-meson extracted with a high reliability from the $\pi\pi$ scattering [29] (where there are no CSR effects) and those found from ABC and other numerous experiments with excited multiquark systems (where the CSR effects have been predicted in many refs.) gives a strong and evident argument in favor of the manifestation for the partial chiral symmetry restoration phenomena in the σ-meson production. Some additional convincing arguments in favor of CSR effects in such systems will be discussed below in Sect. 6

The most important consequence of such scalar meson renormalization in NN and $3N$ systems is a reduction of dressed dibaryon mass and related to this the strengthening of the NN attraction at intermediate distances $r_{NN} \sim 0.8 -$ 1 fm induced by this dressed dibaryon.

So, from this point of view, one can say that the origin of the observed strong NN attraction at intermediate distances (which one ascribes conventionally to the t-channel σ-meson exchange) is due to the the strong chiral symmetry restoration effects in the $2\hbar\omega$-excited six-quark system.

The magnitude for the $\hbar\omega$-quantum has been estimated to be around $\simeq$ 300 – 350 MeV [13], so that the $2\hbar\omega$ excitation in dibaryon corresponds to the excitation energy $\Delta E_{\mathrm{exc}} \simeq 600 - 700$ MeV which is rather large. Very similar scalar $2\hbar\omega$-excitation in nucleon leads to an appearance of the Roper resonance $N^*(1440)$ in decay of which the similar σ-mesons with reduced mass and width are found and studied experimentally [30, 31] (see also below).

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

$$V_{NN} = V_{OPE} + V_{TPE} + V_{NDN} + V_{orth} \qquad (3)$$

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

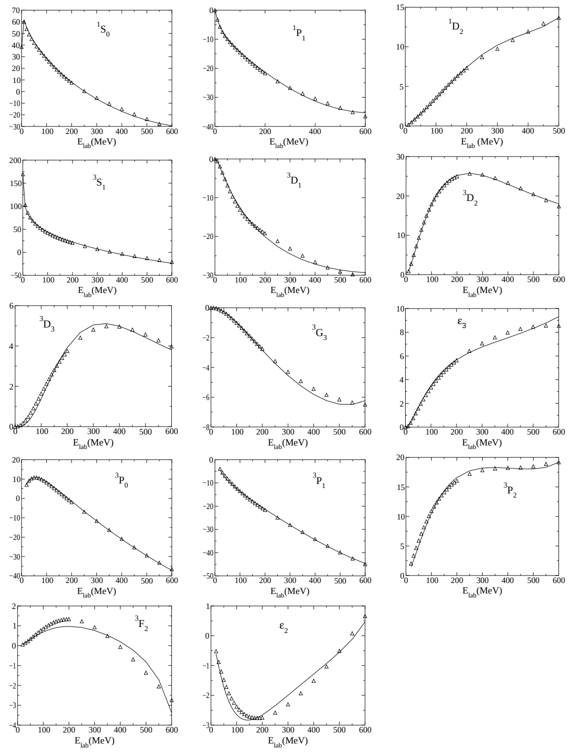

Fig. 4. The description of NN phase shifts in the energy region 0-600 MeV which can be attained with the dibaryon-induced NN potential, see eqs. (3)-(4). The triangles represent the results of PSA.

dressed dibaryons (cf. Fig. 3), which in the simplest case at low and intermediate ($E_p \lesssim 1$ GeV) energies takes the form:

$$V_{NDN} = \sum_{JLL'} \varphi_L^J(\mathbf{r})\, \lambda_{LL'}^J(E)\, \varphi_{L'}^{\star J}(\mathbf{r}') \qquad (4)$$

where $\varphi_L^J(\mathbf{r})$ are the potential form factors which can be chosen in the form of the harmonic oscillator (h.o.): $2s$ (or $2d$) or $3p$ (or $3f$) 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. 3) taking the form [11–13]:

$$\lambda_{LL'}^J(E) = \int_0^\infty d\mathbf{k}\, \frac{B_L^J(\mathbf{k}, E) \cdot B_{L'}^{\star J}(\mathbf{k}, E)}{E - E_{DB} - k^2/2\overline{m}_\sigma} \qquad (5)$$

where $\overline{m}_\sigma$ is the reduced mass in the $6q{+}\sigma$ channel, $k^2/2\overline{m}_\sigma$ is the kinetic energy of the σ-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 $DB + \sigma$ couplings which can be calculated microscopically [11]. 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 [32]. The results of the microscopic and semi-microscopic variants occurred to be quite near to each other.

The V_{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 pseudo-potential in the S-wave takes

Table 1. Deuteron properties in DBM and other current NN models

Model	E_d, MeV	P_D, %	r_m, fm	Q_d, fm^2	μ_d, n.m.	A_S,fm$^{-1/2}$	$\eta(D/S)$
RSC	2.22461	6.47	1.957	0.2796	0.8429	0.8776	0.0262
Moscow 99	2.22452	5.52	1.966	0.2722	0.8483	0.8844	0.0255
Bonn 2001	2.224575	4.85	1.966	0.270	0.8521	0.8846	0.0256
DBM (I) P_{6q} = 3.66%	2.22454	5.22	1.9715	0.2754	0.8548	0.8864	0.02588
DBM (II) P_{6q} = 2.5%	2.22459	5.31	1.970	0.2768	0.8538	0.8866	0.0263
Experiment	2.224575	–	1.971	0.2859	0.8574	0.8846	0.0263

the form $V_{orth} = \mu\ \langle \mathbf{r}|\varphi_0\rangle\langle\varphi_0|\mathbf{r}'\rangle$. Here $\varphi_0(\mathbf{r})$ is the 0s h.o. wave function and the constant μ should be taken positive and sufficiently large to reduce the contribution of the s^6 bag-like configuration from the initial NN channel [11, 12]. Similar constructions for V_{orth} are found also for the P-waves.

We found by varying only a few basic parameters in NN potential in each partial wave (which are the dibaryon mass and radius and cut-off parameters for $V_{\rm TPE}$) that one can fit almost perfectly the all basic NN phase shifts in a large energy range 0-600 MeV (see Fig. 4), or even at larger interval 0-1000 MeV. The deuteron properties derived from this NN potential occurred to be even in a better agreement with experimental data than for Bonn or AV18 potentials.

4 Nature of short-range NN repulsion in dibaryon model

Here it would be important to elucidate the nature of short-range NN repulsion within the framework of the dibaryon model, those repulsion which is ascribed conventionally within the OBE-like models to the t-channel vector-meson exchange. However this conventional explanation is suffered from some serious inconsistencies [33]:

(i) To reproduce NN repulsive core required by the fit to empirical NN phase shifts the ωNN coupling constant $g^2_{\omega NN}/4\pi$ should be taken around the values 11.6-16 while the $SU(3)$ scheme predicts $g^2_{\omega NN}/4\pi \simeq 5$. It should be stressed that $SU(3)$ symmetry is good for all other coupling constants.

(ii) Also the ratio for tensor to vector coupling constants for ρ-mesons $\varkappa_\rho$ is taken in OBE models as $\varkappa_\rho \simeq 6-7$ while an analysis of the data on πN scattering gives much more modest value $\varkappa_\rho \simeq 1-3$.

(iii) There are also a strong disagreement between OBE short-range cut-off parameters employed in the fits of NN phase shifts and fundamental theory.

So, all the above serious disagreements imply that the short-range NN repulsion in conventional OBE model are treated purely on the phenomenological grounds [33]. In contrast to this, the origin of the short-range repulsion in the dibaryon model is tightly related to quark structure and symmetry of the six-quark system and actually this short-range repulsion is a property of symmetry of the six-quark system.

In fact, as was noted above the dominating symmetry of six-quark wave function in the NN overlap region is the mixed symmetry configuration $|s^4p^2[42_x[51]_{FS}\rangle$ with two quanta of inner excitation. If to project this 6q configuration onto NN channel, i.e to examine the overlap function $\chi(r_{NN}) = \frac{1}{\sqrt{N}}\langle\phi_N\phi_N|s^4p^2[42_x[51]_{FS}\rangle$ it turns out that $\chi(r_{NN})$ has an inner stationary node the position of which practically coincides with traditional repulsive core radius [10]. In literature such a core was referred to as a structural core [34]. Such a non-local repulsion is very similar to short-range repulsion in $\alpha-\alpha$, $\alpha-d$ etc. cluster systems where this nodal behaviour of the relative motion wave function is due to Pauli principle, t.e. in the essence is also the sequence of symmetry. In the dibaryon model, such structural core appears mainly in S and P partial waves. This result is in general agreement with empirical NN phase shifts at energies $E \lesssim 400$ MeV.

5 Similarities between the Roper resonance and dibaryon properties

There are striking similarities between properties of dibaryon and Roper resonance. In fact, the Roper resonance is a monopole $2\hbar\omega$-excitation of the nucleon, i.e. of the 3q s-wave state $1/2^+$. So, the quark structure for the Roper should be $|sp^2[3]_x + s^2(2s)[3]_x\rangle$ with two p-shell quarks or with one s-shell quark on 2s-orbit. These two p-shell quarks (or one 2s-shell quark) can transit to the ground nucleon state $|s^3[3]\rangle$ with an emission of σ-meson:

$$|sp^2[3]_x\rangle \Longleftrightarrow |s^3[3]_x + \sigma\rangle. \tag{6}$$

Fully similarly to the dibaryon case the emitted σ-meson in the Roper resonance should interact strongly (with an attractive force) with the 3q core leading to a strong reduction for the Roper mass and width. As a result of this renormalization the Roper resonance mass will shift downward fully similar to the dibaryon case.

Let us estimate roughly this energy shift. If to assume that $1\hbar\omega$ excitation in nucleon (i.e. for the negative parity state S_{11} (1535) etc.) costs ca. 400-500 MeV thus two excitation quanta cost 800-1000 MeV and hence the Roper bare state should have a mass ca. 1700-1900 MeV. But, instead of it, the Roper mass $m_R \simeq 1400$ MeV, so the energy gain due to the virtual σ-meson generation inside nucleon reaches $\Delta E_R \simeq 500-700$ MeV The energy shift for the σ-dressed dibaryon mass should be even larger (because the attraction of σ-meson to six quarks must be stronger than that to three quarks). Thus, the extraordinary low mass of Roper resonance should point at the same time to the abnormal low mass of the σ-dressed dibaryon!

The above similarities manifest much further in decays mode. In fact, as it was found on recent detailed studies for the Roper decay modes [35,30,31], the scalar-isoscalar 2π channel plays a leading role in the Roper decay, contrary to the previous belief about dominance for $R \to \Delta + \pi$ decay mode (we do not discuss here the well known π channel decay into the nucleon ground state). In line with this, the interpretation and explanation for ABC-puzzle should also be related to the dibaryon decay into 2π channel (with σ-meson generation). The Fig. 5 shows the full parallelism in σ-decay of Roper resonance and the dressed dibaryon.

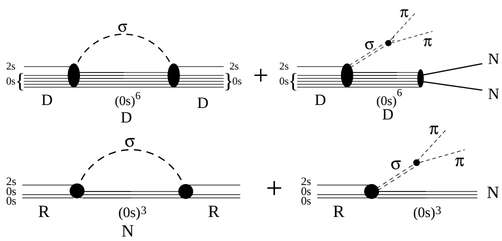

Fig. 5. The graphs illustrating the close analogy between Roper-resonance stabilization by σ-field and its decay to the 2π-channel (bottom part) and the similar stabilization and 2π-decay channel for dressed dibaryon (upper part).

This picture for the σ-meson composition of the nucleon and dibaryon has been nicely confirmed by a few independent calculations [35,37,36] made by various methods. The common result of all these studies can be formulated as follows:

– the σ-meson content of the nucleon is very low while the σ-meson content of the Roper resonance is quite large ($\gtrsim$ 50%). In the other words, the admixture of the σ-mesonic components is small in nucleon case and large in the Roper state.

To summarize this section, the Roper resonance (which is well studied now) has properties very similar to the σ-dressed dibaryon and thus these properties in the Roper case give a strong indications to the properties of the dibaryons which have been predicted in our previous works [11,12].

6 Chiral symmetry restoration in the Roper and dibaryon dynamics

During the last few years it has been realized that the spectra of baryon and mesonic resonances exhibit few remarkable features. First of all it is clustering, or multiplet structure of the experimental spectra, i.e. baryon resonances should not be treated as individual states, but rather as a set of clusters [38]. Another startling feature is the occurrence of the parity doublets in the hadronic spectra. The parity doublet means the (approximate) mass degeneracy of physical resonances with the same J but the opposite P-parities). Later on, in the works of Glozman et al. [22, 23] it was recognized that the parity doublets can indicate chiral symmetry restoration (CSR) phenomenon in spectra of hadrons. Now, after many dedicated works (see the review [39]) the CSR effect seems understood in essence and explained. In particular, the first lowest parity doublet in the baryon spectra is the Roper state (1440) with positive parity and near ($\Delta \sim$ 95 MeV) negative parity resonance $S_{11}(1535)$. Moreover the theoretical studies [40,41] have demonstrated that when the CSR occurs the σ-meson mass also decreases strongly. Thus, from numerous experimental data (on baryon spectra) and recent theoretical studies one can expect that the σ-meson mass (and width) in the Roper resonance and in the $2\hbar\omega$-excited dibaryon should be renormalized. Such a renormalization for the σ-meson mass and width plays the key role in the Roper and dibaryon dynamics and also in the properties of the dense nuclear matter [41]. This CSR effects makes the Roper and dibaryon masses lower and thus – in dibaryon case – it enhances noticeably the effective NN attraction at intermediate distances which is induced by the intermediate dibaryon generation.

7 New experimental evidence for the σ-dressed dibaryon

Very recently new experimental data appeared [25,26,31, 27,30] (see also older data [42][1]) which have given the direct evidence for the intermediate σ-dressed dibaryon production with strongly renormalized σ-meson mass. The first type of experiments [25–27] 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 $p + d \to {}^3\mathrm{He} + \pi^0\pi^0$ (or $\pi^+\pi^-$) and $p + n \to d + \pi^0\pi^0$ at incident proton energies ($E_p^{lab} \sim 1.1 - 1.2$ GeV) specific for the manifestation of the ABC phenomenon.

The experimental data of the CELSIUS-WASA collaboration [30,25,31,27,26] together with those from earlier measurements [42] have demonstrated (see the Fig. 6) that 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 [45] (dotted and dashed lines in Fig. 6), and the data require a near threshold *$\Delta\Delta$ bound state* (solid line). In fact, a few $\Delta\Delta$ bound states have been predicted in some recent six-quark calculations [43,44]. However, in all these calculations the r.m.s. radius $r_{\Delta\Delta}$ of matter in such $\Delta\Delta$ bound states was found not to exceed 0.9 fm [43], or to range even at 0.72 – 0.82 fm [44]. 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 $M_{\pi\pi} \sim 320 - 330$ MeV with

[1] These are the old bubble-chamber experiments done with low statistics.

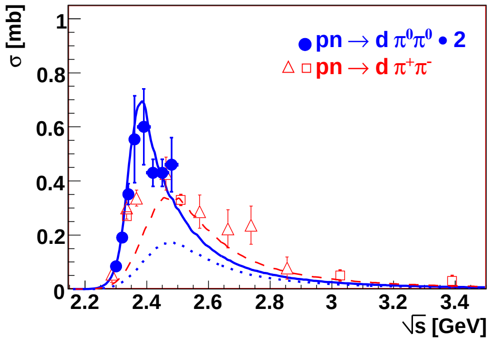

Fig. 6. (Quoted from ref. [26]) Energy dependence of the total cross section for the $pn \to d\pi^+\pi^-$ and $pn \to d\pi^\circ\pi^\circ$ reactions from threshold ($\sqrt{s}$ = 2.15 GeV) up to $\sqrt{s}$ = 3.5 GeV. Experimental data for the $pn \to d\pi^+\pi^-$ are from Refs. [42] (open squares) and [45] (open triangles), for the $\pi^0\pi^0$ channel – scaled by the isospin factor of two – (full circles) are from ref. [26]. Dashed and dotted lines represent the cross sections for $\pi^+\pi^-$ and $\pi^0\pi^0$ channels, respectively, as expected from the isovector $\pi^+\pi^0$ data by isospin relations. The solid curve includes *s*-channel resonance in the $\Delta\Delta$ system adjusted to describe the ABC effect in the $\pi^0\pi^0$ channel [26].

very strong S-wave $\pi\pi$-correlation distinguished from that in the free space $\pi\pi$ scattering. 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 $E_p^{lab} \sim 1.1 - 1.2$ GeV. In such a specific generation process, all the kinetic energy of the two-nucleon relative motion (≈0.6 GeV) transforms into a $2\hbar\omega$ string excitation near the $\Delta\Delta$ threshold with subsequent σ-meson emission. In such a case the structure of intermediate dibaryon (in channels $J^\pi T = 3^+0$ or 1^+0) can be presented by a Fock column:

$$\Psi(3^+) = \begin{pmatrix} |NN\rangle \\ |6q + \sigma\rangle \end{pmatrix}, \qquad (7)$$

where the dressed dibaryon $D = 6q + \sigma$ should be coupled strongly to the hadron $\Delta + \Delta$ and $N + R$ channels due to closeness of the respective thresholds. Then the intermediate Roper resonance decays into $\sigma + N$ or $\Delta + \pi$ channels. It should be stressed here that the $N + R$ and $\Delta + \Delta$ thresholds in NN system are located rather close to each other.

Another signal for existence of the σ-meson associated with the renormalized-mass σ-dressed dibaryon in the deuteron has been found in recent experiments on measurements of the $\gamma\gamma$-correlations in p + C → $X + \gamma\gamma$ and d+C → $X+\gamma\gamma$ reactions at incident energies 2.5 - 5 GeV/N done at Dubna [28].

In p+C collisions the authors found two peaks for $M_{\gamma\gamma}$ mass (see Fig. 7b): the first one at $M_{\gamma\gamma} \simeq 140$ MeV is associated to the π^0 decay, and the second one at $M_{\gamma\gamma} \simeq$ 540 MeV which is associated to the η-meson production (the π^0 peaks were suppressed in the analysis of p+C and d+C events by cuts and thus not seen in Fig. 7). From the general point of view, it would seem that in d+C collisions one should observe the same two peaks for π^0 and η decays if the deuteron can be considered as a weakly bound two-nucleon state. However, the actual situation is different. In the d+C experiment (see Fig. 7a) the authors have found *three* clear peaks in the $\gamma\gamma$-mass ($M_{\gamma\gamma}$) distribution: the low-energy peak for $M_{\gamma\gamma} \simeq 140$ MeV associated with the π^0-decay mode, a high-energy peak at $M_{\gamma\gamma} \sim 540$ MeV associated with the η-production and some extra enhancement at $M_{\gamma\gamma} \sim 355$ MeV exhibiting a width $\Gamma_{\gamma\gamma} \sim 49$ MeV; the latter could not be interpreted by the authors [28] in terms of well known mesons despite the comprehensive and detailed modeling.

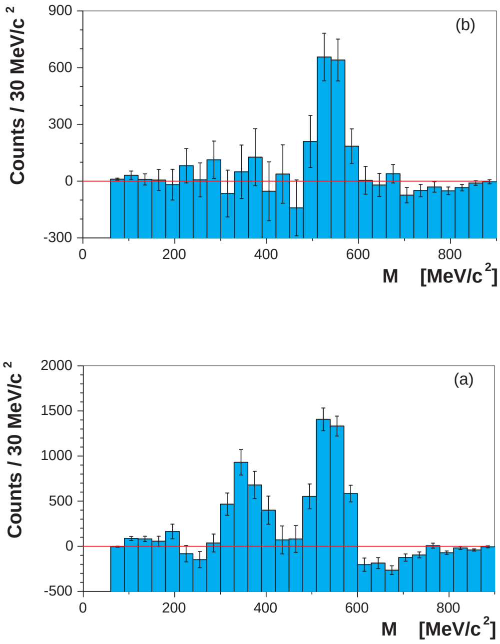

Fig. 7. Invariant mass distributions for pairs of γ-quanta (a) in the reaction $d + \mathrm{C} \to \gamma + \gamma + X$ at a momentum of incident deuterons 2.75 GeV/c per nucleon and (b) in the reaction $p + \mathrm{C} \to \gamma + \gamma + X$ at momentum of 5.5 GeV/c, after background subtraction [28].

A similar peak at $M_{\gamma\gamma} \sim 300 - 320$ MeV has been found also by the CELSIUS-WASA collaboration [46] in $pp \to pp\gamma\gamma$ experiments. This peak has been interpreted by the authors as a signal of the intermediate σ-meson with renormalized mass in the process $pp \to pp\sigma \to pp\gamma\gamma$. However, the authors [46] have interpreted two gammas emitted from the reaction as emerging from the intermediate $\pi\pi$ bremsstrahlung.

In a contrast to this, the new data of the Dubna group may have a quite natural interpretation as coming from the σ-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 7a and 7b). In the first case the σ-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 ($\sigma \to \gamma\gamma$) with a well known branching ratio $\Gamma_\sigma(\gamma\gamma)/\Gamma_\sigma(\pi\pi) \sim 10^{-5} - 10^{-6}$ (see Fig. 8). 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. However, for the derivation of fully reliable conclusions from the latter Dubna experiment one needs still very detailed modeling for the $\gamma\gamma$-yield with incorporation of the dibaryon mechanism.

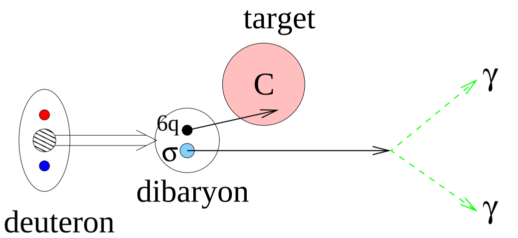

Fig. 8. The graph illustrating 2γ production from the intermediate σ-dressed dibaryon D.

From the point of view of the dibaryon model the strong σ-meson emission should be observed in all (or many) nuclear reactions (above the σ-production threshold) at high momentum transfer. It is explained by fact that in the dibaryon model the deuteron, triton and other nuclei do include explicitly also mesonic components in which the σ-mesons are coupled to the nucleon (or quark) core. And when the fast incindent hadron hits on this core the σ-mesons are "shaked off" and emerged to an external zone. The numerous experiments in 1 GeV region where the ABC-peak has been found can be interpreted just in this spirit [47, 48].

8 The string picture for the dibaryon and Roper. Interrelation to the charmonium decay channels.

It would be interesting to interpret the dibaryon and Roper structures in terms of the color string formation and deexcitation. In fact, the most remarkable feature of the dibaryon and Roper structure, being interpreted in term of color string, is that the string in both cases should be *excited* with $2\hbar\omega$ (i.e. two-gluon) excitation. On the other hand, this excited string corresponds just to the initial bare configurations $|s^4p^2[42]_x\rangle$ and $|sp^2[3]_x\rangle$ in the dibaryon and Roper case respectively. In the subsequent dressing process $|s^4p^2[42]_x\rangle \Rightarrow |s^6[6]_x{+}\sigma\rangle$ and $|sp^2[3]_x\rangle \Rightarrow |s^3[3]_x{+}\sigma\rangle$ these two-gluon excitations are transformed to the scalar field emission, see Fig. 9.

Because the emerged σ-meson decays immediately into two pions in relative S-wave $\sigma \to \pi^+\pi^-$ or $\sigma \to \pi^0{+}\pi^0$ and because two emitted gluons should be in colorless state it is very reasonable to interpret the resulted σ-meson as a hybrid coupled-channel state $\sigma \to (2g + 2\pi)$. Just this hybrid nature for the light scalar meson has been proposed

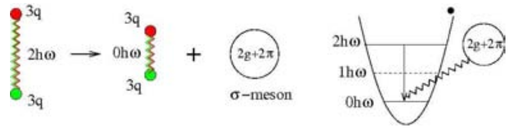

Fig. 9. The deexciotation of the $2\hbar\omega$-excited string inside dibaryon leading to the scalar field emission.

by L. Kisslinger [40] about 10 yeas ago on basis of QCD sum rules. He found the solution of QCD sum rules for the light scalar meson with mass $m_\sigma \sim 500$ MeV. We come to the same conclusion qualitatively on the basis of our dibaryon production mechanism. The above string picture can be confirmed in D-meson and J/Ψ decays as well [49].

The situation here is as follows. The BESII collaboration has observed recently [49] a strong σ-meson emission from the $\Psi(2S)$ decay:

$$\Psi(2S) \Rightarrow J/\Psi^+ + (\pi^+\pi^-)_{00}$$

They established reliably the isotropy in two-pion angular distribution in their c.-m. system and the observed mass of two-pion enhancement to be around $m_{\pi\pi} \sim 450$ MeV with width $\Gamma_{\pi\pi} \sim 470$ MeV. The similar scalar two-pion "resonance" has been found also in $J/\Psi \to \pi^+\pi^-\omega$, $J/\Psi \to \pi^+\pi^-\pi^+\pi^-$ and D-meson decays. These mass and width are very similar to the σ-meson pole parameters extracted by Caprini et al. [29] from the solving of the Ray equation for $\pi\pi$ scattering. So these parameters corresponds to the initial, i.e. bare σ-meson which is generated from the two-gluon deexcitation of $\Psi(2S)$ state of charmonium, and also in $\pi\pi$ scattering in $J^\pi I = 0^+0$-channel. However, when this initial bare σ-meson (emitted from the string in the Roper resonance or in the dibaryon) interacts strongly with near multiquark core its mass and width get renormalized quite noticeably giving the reduced values:

$$m_\sigma^{\rm ren} \simeq 340 \pm 20 \text{ MeV}, \quad \Gamma_\sigma^{\rm ren} \simeq 50 \pm 30 \text{ MeV} \qquad (8)$$

It is very instructive for our understanding that just these σ-meson parameters have been extracted from ABC-type experiments of Bashkanov et al. [26,27]

$$p + n(\text{ from deuteron target}) \to D \to d + \sigma|_{\to\pi^0\pi^0} \qquad (9)$$

and also from the Dubna experiments by Abraamyan et al. [28]

$$d + C \to D \to d + \sigma|_{\to\gamma\gamma} + X. \qquad (10)$$

Thus, from general QCD point of view this strong reduction of the σ-meson parameters can be interpreted as a manifestation for chiral symmetry restoration in excited hadrons [22,23] or in high-density nuclear matter [41].

9 Dibaryons and pomerons

If our general concept for NN interaction at short distances is correct, the concept implies that NN interaction at low and intermediate ($\sim$ 1 GeV) energies is governed by the intermediate dibaryons (in various lowest partial waves and spin-isospin channels) originated essentially from the string formation between multi-quark clusters. On the other hand, the NN at high energies (in multi-GeV region) is governed by the t-channel pomeron exchange which is also associated with two-gluon exchange and the string formation. So, if to assume the tight interrelation between string excitation (deexcitation) and scalar field absorption (emission) found in our studies [13, 55], one can conclude that the pomeron (or double pomeron) exchange should be also accompanied by an enhanced σ-meson emission.

This conclusion would be highly important for our general understanding of the strong interactions. To our fortunate it has been partially confirmed in a few recent studies. On theoretical side, Kisslinger et al. [50] predicted the strong one- and double σ-meson emission at high-energy pp collisions (at 50 GeV) originated from the intermediate pomerons. Experimentally there exists now two very interesting observations [51, 52]. The first one relates to enormous $\pi^0\pi^0$ production in pp central collisions at 450 GeV/c at CERN SPS. The authors found a large and broad peak at $M_{\pi^0\pi^0} \simeq 500$ MeV. This result is in agreement with the previous findings [53, 51] where a large s-wave contribution in the low-mass region of $\pi\pi$ system ($M_{\pi\pi} \sim 500$ MeV) has been found in the central pp collisions. This has been treated either through a large s-dependence of the production amplitude, or by specific ansatz for production amplitude. Then the authors [51] conclude: (a) "there remains the question of the *physical origin* of the s-dependence of the production amplitude" and (b) "the physical character of the s-wave contribution *is obscure*".

Another important result is the observation of Morsch and Zupransky [52] of the large production of the Roper resonance and the near-threshold $\pi\pi$-pairs in the old Brookhaven data for pp scattering at energies 9-30 GeV/c. These authors have found that the Roper resonance production dominates in all baryonic excitations at low momentum transfers $-t \leq 0.1$ (GeV/c)^2. This strange result can be interpreted quite naturally with a unified dibaryon-pomeron concept if to assume that the light scalar meson emitted from the string is reabsorbed immediately by three-quark cluster on its end leading to the Roper resonance.

Therefore one may think that the strong s-channel dibaryon production in combination with one- and double pomeron exchange can give the adequate explanation for the above puzzles with enormous S-wave two-pion production in pp high-energy collisions.

10 Conclusion

The numerous arguments given from both theoretical and experimental sides in favor of the generation of the intermediate σ-dressed dibaryon in NN and $3N$ systems are discussed in the paper. The concept leads to a very serious revision for many aspects of nuclear theory and hadronic processes [54] such as:

– the origin of nuclear binding energy,

– the conditions and new mechanisms for saturation in nuclear matter at normal and high densities,

– novel electromagnetic currents in nuclei, the new three-body forces, both central and spin-orbit intimately related to the presence of strong scalar fields in nuclei,

– an enhanced production of dipion pairs in scalar-isoscalar state in many hadronic processes with high momentum transfer, e.g. in pp and pd central collisions,

– an enhanced production of fast deuterons in fast nucleon-nucleus collisions etc. etc. All the above can be viewed as a wide implantation of QCD into nuclear physics.

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