ABC EFFECT AS A SIGNAL OF CHIRAL SYMMETRY RESTORATION IN HADRONIC COLLISIONS

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A new nonconventional mechanism for the basic 2π-fusion reaction $pn \rightarrow d + (\pi\pi)_0$ in the energy region $T_\pi = 1.0$–1.4 GeV is suggested. The mechanism is aimed at providing a consistent explanation for the comprehensive experimental studies of this reaction in exclusive setting done recently by the WASA-at-COSY Collaboration. The basic assumption of the model proposed is the production of the $I(J^P) = 0(3^+)$ dibaryon resonance $D_{03}$ in the $pn$ collision. The interference of two decay channels of this resonance: $D_{03} \rightarrow d + \sigma \rightarrow d + (\pi\pi)_0$ and $D_{03} \rightarrow D_{12} + \pi \rightarrow d + (\pi\pi)_0$ is shown to give a strong near-threshold enhancement in the $\pi\pi$ invariant mass spectrum, which is well known as the ABC effect. The $\sigma$-meson parameters found to reproduce the ABC enhancement are in a general agreement with models which predict the chiral symmetry restoration at high excitation energy and/or high density of matter, although they are essentially less than those accepted for the free $\sigma$ meson. So, this result might be considered as an indication of partial chiral symmetry restoration in dense and excited quark matter.

The famous Abashian-Booth-Crowe (ABC) effect discovered more than 50 years ago [1] is observed in double-pionic fusion reactions [2, 3] as a pronounced spectral enhancement of isoscalar nature just above the $\pi\pi$-production threshold. The effect was initially interpreted [1] as being due to strong $\pi\pi$-rescattering in the scalar-isoscalar channel, associated naturally with the $\sigma$ meson. However later on the interpretation was left since no narrow resonance with an appropriate mass ($m \simeq 300$ MeV) was found in $\pi\pi$ scattering at low energies. At the same time, an other interpretation [4] for the ABC effect, based on a generation of two $\Delta$ isobars via the $t$-channel meson exchange and their subsequent decays with pion emission, was commonly accepted. Although the “$t$-channel $\Delta\Delta$” mechanism did not provide quantitative description of the data, it allowed to reproduce the shape of differential cross sections found in the numerous inclusive experiments on double-pionic fusion [4, 5].

The situation has changed dramatically quite recently, after publication of the results of the first exclusive and kinematically complete experiments for the basic $2\pi$-fusion reaction $pn \rightarrow d + \pi^0\pi^0$ done by the CELSIUS/WASA [6] and then by the WASA-at-COSY Collaborations [7]. The comparison of the new experimental data with theoretical predictions has demonstrated clearly that the above $t$-channel $\Delta\Delta$ model cannot reproduce even the qualitative behaviour of the experimental energy and angular distributions, giving just a low background in the considered energy region ($T_\pi = 1.0$–1.4 GeV). At the same time, the most intriguing discovery of these exclusive experiments was an observation of a pronounced resonance structure in the total $2\pi$-production cross section. This fact has been interpreted as a generation of the dibaryon resonance $D_{03}$ in the $pn$ collision, with quantum numbers $I(J^P) = 0(3^+)$, the mass $m_{D_{03}} \simeq 2.37$ GeV and the total width $\Gamma_{D_{03}} \simeq 70$ MeV [7]. Such a resonance state has been predicted already in 1964 by Dyson and Xuong [8] and since then studied in numerous works, both theoretical [9–12] and experimental [13]. From the new exclusive experiments [7], the direct interrelation between the production and decay of the $D_{03}$ resonance and the ABC effect has been clearly established. Having considered the $D_{03}$ as the $\Delta\Delta$ bound state, Adlarson et al. [12] performed microscopic calculations based on the mechanism $pn \rightarrow D_{03} \rightarrow \Delta\Delta \rightarrow d + \pi^0\pi^0$. With such an “$s$-channel $\Delta\Delta$” model they succeeded in a very good description of the numerous energy and angular distributions observed in the reaction $pn \rightarrow d + \pi^0\pi^0$. However, a reasonable agreement with the experimental data at low $\pi\pi$-invariant masses (in the region of the ABC peak) could be reached in their work [12] only when using a very soft form factor $f_{\Delta\Delta}$ for the $D_{03} \rightarrow \Delta\Delta$ vertex with the cutoff parameter $\Lambda_{\Delta\Delta} = 0.15$ GeV/c. Such a low value of $\Lambda_{\Delta\Delta}$ means the characteristic radius of the $D_{03}$ state to be even larger than that of the deuteron. This is incompatible with the observed strong $\Delta–\Delta$ binding in the $D_{03}$ state, $\epsilon_B(D_{03}) \simeq 90$ MeV, and also with the results of the various microscopic quark model calculations (see, e.g., [10, 11]), which all predict the radius for the $0(3^+)\Delta\Delta$ bound state $r(D_{03}) \simeq 0.7–0.9$ fm, i.e. of the order of the nucleon one. Hence, the $D_{03}$ resonance appears to be the truly dibaryon state which arises in a situation when the quark cores of two $\Delta$'s are almost fully overlapped with each other. Moreover, the large width of the free $\Delta$ isobar, $\Gamma_\Delta \simeq 120$ MeV, would not allow for two $\Delta$'s to go away to far distance, so the $D_{03}$ system, even after the pion emission, is likely to stay in a dibaryon state with a small radius. So, this picture contradicts essentially to the concept of the bound state of two isolated quasi-free $\Delta$ isobars, which therefore looks to be rather inconsistent. As will be shown below, a reasonable explanation of the ABC effect in the basic $2\pi$-fusion reaction may be found
within an alternative model, involving the $\sigma$-meson emission from the $D_{03}$ dibaryon and tightly connected to the idea of chiral symmetry restoration in dense and excited hadronic systems.

In constructing such a model, we start from the dibaryon concept for short-range nuclear force [14]. In this concept, the conventional $t$-channel $\sigma$-meson exchange between two isolated nucleons is replaced by the $s$-channel $\sigma$ exchange with the $\sigma$ field surrounding the whole 6$q$ bag, which appears in the overlap region of two nucleons. An emission of a light scalar meson occurs within a virtual transition of the 6$q$ bag from the initial $2\hbar\omega$-excited quark configuration $|s^4p^2[42]\rangle$ to its ground state $|s^6[6]\rangle$. Then, a strong attraction of the $\sigma$ field to the multi-quark core effectively induces a strong $NN$ attraction at intermediate distances $r_{NN} \simeq 0.7$–0.8 fm. The predictions of the model for the empirical $NN$-scattering phase shifts as well as for the lightest nucleon in which the $3q$ core is dressed with a pionic cloud. Thus, analogously to the excited states of the nucleon, one can examine the excited states of the dibaryon, particularly in the reaction $p p \rightarrow d + \pi\pi$ still keeping quite moderate values for short-range cutoff parameters ($\Lambda_{N,NN}$, etc.), which are compatible with the QCD and quark model estimations (for the details, see [14,15] and references therein to the earlier works).

According to the dibaryon model, the deuteron wavefunction, besides the conventional $NN$ component, has also a second, quark-meson component, which becomes dominant at short $NN$ distances, i.e., when two nucleons are essentially overlapped with each other [16]. The second component of the deuteron has the structure $D_{01} \sim s^6 + \sigma$ ($l_\sigma = 0, 2$) (a compact 6$q$ bag dressed with a $\sigma$ field), so it is similar in some sense to the picture of the physical nucleon in which the $3q$ core is dressed with a pionic cloud. Thus, analogously to the excited states of the nucleon, one can examine the excited states of the dibaryon $D_{03}$ and classify them on their total angular momentum, isospin and parity. In this way, the experimentally observed $D_{03}$ can be considered as a rotationally excited state of the $D_{01}$, with the quark-meson structure $s^6 + \sigma$ ($l_\sigma = 2, 4$).

In fact, almost all dibaryon states lie in the vicinity of two-baryon thresholds, e.g., $NN, N\Delta, \Delta\Delta$, etc., and are coupled strongly to the respective two-baryon channels. In our case, it is relevant to consider the following chain of dibaryon states with rising angular momenta: $D_{01} \sim NN, D_{12} \sim N\Delta, D_{03} \sim \Delta\Delta$, etc. Here the $D_{12}$ is the isovector dibaryon resonance with quantum numbers $I(J^P) = 1(2^+)$ and the mass $m_{D_{12}} \simeq 2.15$ GeV, discovered in the analysis of $pp$ scattering in the $^1D_2$ partial wave [14,15]. The production of the $D_{12}$ resonance was later confirmed in $\pi^+d$ elastic scattering [19,20] and particularly in the reaction $\pi^+d \rightarrow pp$ [21], where the total cross section at the energies $T_\pi \lesssim 200$ MeV is dominated by the $D_{12}$-excitation process. Although the $D_{03}$ is a deeply bound state in the $\Delta\Delta$ channel, it is a resonance in the $p+n$ (as was observed in [11]) and $D_{12}+\pi$ systems. It becomes a resonance also in the $d(D_{01}) + \sigma$ system, if the $\sigma$ mass is less than 500 MeV. So, there are two basic possibilities for the decay of the $D_{03}$ resonance into the deuteron (i.e., into its quark-meson component $D_{01}$) and two pions:

(i) by an emission of the $\sigma$ meson (mainly in the $d$ wave relative to the $6q$ core due to the angular momentum conservation) which then decays into two pions;

(ii) by a sequential emission of two pions (each in the $p$ wave) through an intermediate isovector dibaryon $D_{12}$.

It is indicative that the above two interfering mechanisms for the excited dibaryon decay $D_{03} \rightarrow d + \pi\pi$ can be confronted with the quite similar two mechanisms for the Roper resonance (excited nucleon) decay $N^*(1440) \rightarrow N + \pi\pi$ [22]: $N^*(1440) \rightarrow N + (\pi\pi)f_{\text{wave}}(\sigma)$ and $N^*(1440) \rightarrow \Delta + \pi$. It should be stressed that the model [23] based on an excitation of the Roper resonance and its subsequent decay via these two channels was quite successfully applied to the reactions $NN \rightarrow d + \pi\pi$ and $NN \rightarrow NN + \pi\pi$ at the energies $T_N < 1$ GeV.

Thus, we consider the following resonance mechanisms related to the above $D_{03}$ decay channels (i) and (ii) as the basic contributions to the reaction $pn \rightarrow d + (\pi\pi)_0$ in the ABC region ($T_p = 1.0$–1.4 GeV):

(a) $pn \rightarrow D_{03} \rightarrow d + \sigma, \sigma \rightarrow (\pi\pi)_0$;

(b) $pn \rightarrow D_{03} \rightarrow D_{12} + \pi, D_{12} \rightarrow d + \pi$.

The diagrams for these processes are shown in Fig. 1.

FIG. 1: The leading mechanisms for the reaction $pn \rightarrow d + (\pi\pi)_0$ in the ABC region. The 3-momenta in the c.m. of two particles are indicated between the respective lines.

The amplitude for the emission of two neutral pions in the reaction $pn \rightarrow d + \pi^0\pi^0$ at the c.m. energy $E = \sqrt{s}$ is then given by a sum of two terms:

$$M_{\mu_1\mu_2} = M_{\mu_1}^{(D_{03})} \left( M_{\mu_1\mu_2}^{(s)} + M_{\mu_1\mu_2}^{(D_{12})} \right),$$

where

$$M_{\mu_1}^{(D_{03})} = \frac{m_{D_{03}}^2 \Gamma_{D_{03}\pi\pi}^{(2)} / \Gamma_{D_{03}\pi\pi}^{(0)}}{E^2 - m_{D_{03}}^2 + \im \Gamma_{D_{03}}^{(0)} \mathcal{J}_{\mu_1\mu_2}(\hat{p})},$$

$$M_{\mu_1\mu_2}^{(s)} = \frac{m_\sigma \sqrt{\Gamma_{D_{03}\sigma}^{(2)} / \Gamma_{D_{03}}^{(0)}} \sqrt{\Gamma_{\pi\pi\sigma\pi\pi}^{(0)} / \lambda}}{M_{\pi\pi}^2 - m_\pi^2 + \im \mathcal{J}_{\mu_1\mu_2}(\hat{q})},$$

$$M_{\mu_1\mu_2}^{(D_{12})} = \frac{1}{\sqrt{2}} \left( \frac{m_{D_{12}} \Gamma_{D_{12}\pi\pi}^{(1)} / \Gamma_{D_{12}}^{(1)}}{M_{\pi\pi}^2 - m_{D_{12}}^2 + \im \Gamma_{D_{12}}^{(1)}} \times \mathcal{J}_{\mu_1\mu_2}(\hat{k}_1, \hat{\lambda}_1) + \mathcal{J}_{\mu_1\mu_2}(\hat{k}_2, \hat{\lambda}_2) \right).$$
The amplitude $\mathcal{M}_{\mu_{f},\mu_{i}}^{(D_{12})}$ for the above process (b) is symmetrized over two identical pions [24].

When taking into account only the dominating, i.e. the lowest, partial waves in vertices (indicated in superscripts of $\Gamma$'s in Eqs. (2)–(4)), the spin-angular terms $\mathcal{J}_{\mu_{f},\mu_{i}}^{(D_{12})}$ and $\mathcal{J}_{\mu_{f},\mu_{i}}^{(D_{12})}$ can be calculated by using the standard technique for the angular momenta coupling. Thus, the total angular momentum $J$ should be decomposed as $J = J_{1} + L$, i.e. $3 = 1 + 2$ for the process (a) and $\{3 = 2 + 1, 2 = 1 + 1\}$ for the process (b). The factor $\mathcal{J}_{\mu_{f},\mu_{i}}^{(D_{10}, \rho)}$ comes from the vertex $np \to D_{03}$ and, with the initial momentum $p$ directed along $z$ axis, gives just a constant $C_{\mu_{i}}$.

With the amplitudes defined in Eqs. (1)–(4), the differential cross sections as functions of the invariant masses squared $M_{\pi}^{2}$ and $M_{\pi}^{2}$ are given by

$$\frac{d\sigma}{d(M^{2}_{\pi})} = \frac{\rho^{(\pi\pi)}}{(4\pi)^{2}pE} \int d\Omega_{q}d\Omega_{k} \frac{1}{3} \sum_{\mu_{f},\mu_{i}} |\mathcal{M}_{\mu_{f},\mu_{i}}^{2}|^{2}, \quad (5)$$

$$\frac{d\sigma}{d(M^{2}_{\pi\pi})} = \frac{\rho^{(d\pi)}}{(4\pi)^{2}pE} \int d\Omega_{k}d\Omega_{l} \frac{1}{3} \sum_{\mu_{f},\mu_{i}} |\mathcal{M}_{\mu_{f},\mu_{i}}^{2}|^{2}, \quad (6)$$

where $\rho^{(\pi\pi)} = qk/2EM_{\pi\pi}$ and $\rho^{(d\pi)} = k_{l}l_{1}/2EM_{\pi\pi}$ are the Lorentz-invariant phase-space factors. The sum should be taken over all possible projections $\mu_{i}$ and $\mu_{f}$ of the total spin $S = 1$ in initial and final states, since the production of the dibaryon resonance with quantum numbers $I(J^{P}) = 0(3^{+})$ can occur in the $np$ triplet state only.

The energy dependence for the partial width of the resonance $\bar{R}$ with the invariant mass $M$ decaying into particles 1 and 2 with invariant masses $M_{1}$ and $M_{2}$ and the relative orbital angular momentum $l$ has been parameterized as

$$\Gamma^{(l)}_{R12}(q) = \Gamma^{(l)}_{R12} \left( \frac{q}{q^{*}} \right)^{2l+1} \left( \frac{(q^{*})^{2} + \varkappa^{2}}{q^{2} + \varkappa^{2}} \right)^{l+1}, \quad (7)$$

where $q = \sqrt{[(M^{2}_{1} - M_{1}^{2} - M_{2}^{2} - 4M_{1}^{2}M_{2}^{2})/2M]^{1/2} / 2M}$ is the modulus of the relative momentum between particles 1 and 2, and an asterisk denotes the values in the resonance point. Such a parametrization provides a correct near-threshold behaviour of the partial widths, however preventing an unphysical rise of the widths at higher energies (see [23] for a similar parametrization in case $l = 1$). Thus, with an appropriate value of the parameter $\varkappa$, the centre of the Breit–Wigner distribution can be properly reproduced. For the partial widths introduced in Eqs. (3)–(4), this is achieved with $\varkappa = 0.1–0.2$ GeV/c, while for the partial width $\Gamma^{(2)}_{D03 np}$ entering Eq. (2) one should use the larger value $\varkappa = 0.35$ GeV/c.

The masses and total widths of the dibaryon resonances $D_{03}$ and $D_{12}$ have been fixed in our calculations as [20]

$$m_{D_{03}} = 2370 \text{ MeV}, \quad \Gamma_{D_{03}} = 70 \text{ MeV},$$

$$m_{D_{12}} = 2150 \text{ MeV}, \quad \Gamma_{D_{12}} = 110 \text{ MeV}.$$
FIG. 2: (Color online) Differential cross sections as functions of the invariant masses squared (a) $M_{\pi\pi}^2$ and (b) $M_{d\pi}^2$ in the reaction $pn \rightarrow d + \pi^0\pi^0$ at the energy $\sqrt{s} = 2.38$ GeV. The contribution of the $\sigma$-production mechanism (see Fig. 1a) is shown by dashed lines while the contribution of the mechanism going through the intermediate dibaryon $D_{12}$ (see Fig. 1b) is shown by dash-dotted lines. The solid lines correspond to the summed cross sections. Shaded areas show the pure phase-space distributions. The experimental data (full circles) are taken from Ref. [7].

FIG. 3: (Color online) Angular distributions for the deuteron (a) and the pion (b) in the overall c.m.s. at the energy $\sqrt{s} = 2.38$ GeV. The meaning of curves is the same as in Fig. 2. The experimental data (full circles) are taken from Ref. [7].

The mass and width of the $\sigma$ meson extracted from the fit to the ABC peak are

$$m_\sigma \simeq 300 \text{ MeV}, \quad \Gamma_\sigma \simeq 100 \text{ MeV}.$$ 

These values are notably less than those for the free $\sigma$ mass and width, found by extrapolation from the dispersion relations for the $\pi\pi$ scattering amplitude to the $\sigma$ complex pole [27],

$$m_\sigma^{(0)} = 441^{+16}_{-16} \text{ MeV}, \quad \Gamma_\sigma^{(0)} = 544^{+18}_{-25} \text{ MeV}.$$ 

While the latter values are within the range for the $f_0(500)$ or $\sigma$ pole positions currently quoted in PDG tables [22]:

$$m_\sigma = 400-550 \text{ MeV}, \quad \Gamma_\sigma = 400-700 \text{ MeV},$$

the values found here are essentially out of this range. To resolve this discrepancy, one should bear in mind that the above range of pole positions for the $\sigma$ meson was fixed by including only those analyses consistent with the low-energy $\pi\pi$ scattering data as well as the advanced dispersion analyses such as performed in [27]. On the other hand, numerous theoretical investigations (see, e.g., [28, 29]) show that the mass and width of the $\sigma$ meson produced in hot and/or dense nuclear matter may be significantly shifted downwards due to the partial chiral symmetry restoration (CSR) effect. Besides that, it was demonstrated [30] that the partial CSR takes place also in strongly excited states of isolated hadrons (baryons and mesons) at the excitation energies $E^* \gtrsim 500$ MeV. In particular, the appearance of approximately degenerate parity doublets in the spectra of highly excited baryons may be considered as a direct manifestation of partial
CSR. In fact, the rise of baryon density or nuclear matter temperature as well as a high hadron excitation energy leads to an increase of quark kinetic energy, which results in the suppression of the chiral condensate in QCD vacuum. This, in turn, means the reduction of the $\sigma$-meson mass and the width for the $\sigma \to \pi\pi$ decay. So, the $\sigma$ meson, being a broad resonance in free space, may become a sharp resonance in dense or excited hadronic media.

We emphasize that within the dibaryon model [14, 15], the best description of the $NN$-scattering phase shifts and the properties of the lightest nuclei has been achieved with a rather low mass of the $\sigma$ meson, $m_\sigma \simeq 350$ MeV, whereas in the conventional meson-exchange $NN$-force models the $\sigma$ mass is taken to be 500–600 MeV. Since in the dibaryon model the initial $6q$ bag (with the quark configuration $|s^4p^2[42]|$) is a dense object ($r_{6q} \simeq 0.5$–0.6 fm) and is also the 2$\hbar\omega$-excited hadronic state, the renormalisation of the $\sigma$ mass in the field of the bag might be related to the partial CSR [14]. The situation is quite similar for the $D_{03}$ resonance, which also represents dense quark matter (the density of a 6q system with a radius $r \simeq 0.8$ fm corresponds to about six-fold normal nuclear density) and has an additional excitation energy of 500 MeV above the deuteron pole. Thus, the $\sigma$ meson produced from the $D_{03}$ decay should have the lower mass and width than those for the free $\sigma$ meson. As the $\sigma$ width found here is still quite large, the $\sigma$ meson is likely to decay before it escapes the field of the multi-quark bag and acquires its free-space parameters. This implies that when measuring the $\pi\pi$ invariant mass distribution, one should observe just the renormalised $\sigma$ meson with the reduced mass and width. So, one can suggest that the low values for the $\sigma$-meson parameters found here indicate a partial CSR in the excited dibaryon state. This conclusion is in agreement with the results of numerous theoretical studies concerning the CSR in hadronic and nuclear media [28–30]. Further experimental and theoretical efforts are called for to check the fundamental CSR effects in hadronic systems.

To summarize, we have proposed a new nonconventional model for the basic double-pionic fusion reaction $pn \to d + (\pi\pi)_0$ in the ABC region ($T_p = 1.0$–1.4 GeV). The model takes into account the $D_{03}$-dibaryon production and its decay into the final deuteron and two pions by two alternative ways: (i) through an emission of the $\sigma$ meson and (ii) through a generation of the intermediate isovector dibaryon resonance $D_{12}$. So, the suggested mechanisms for the $D_{03}$ decay have a remarkable resemblance with two analogous modes of the Roper resonance $N^*(1440)$ decay. A reasonable agreement with the data of the recent exclusive experiments done by the WASA-at-COSY Collaboration [2], without an assumption of the unnaturally soft form factor in the vertex $D_{03} \to \Delta\Delta$, is obtained.

Within the model proposed, the ABC effect is considered as a result of the $\sigma$-meson emission, whose mass and width, due to the partial restoration of chiral symmetry, are reduced in the field of the multi-quark bag as compared to their free-space values. In this way, the observed enhancement in the low-$M_{\pi\pi}$ spectrum, similarly to the instant photograph, shows just the renormalised $\sigma$ meson in the field of the bag. Hence, by extracting the $\sigma$ mass and width from the experimentally measured ABC peak, one is able to judge the degree of chiral symmetry restoration in excited and/or dense hadronic systems. With this interpretation, it is easily understood why the low-$M_{\pi\pi}$ enhancement is not seen in the reaction $pn \to pp + \pi^+\pi^-\pi^0$ [31]: although the $D_{03}$ resonance is produced there as well, but the $\sigma$ meson is not. So, we partially rehabilitate the initial interpretation of the ABC effect suggested by Abashian, Booth and Crowe [1], even though the $\sigma$-meson generation in our model is not related to the $\pi\pi$ final-state interaction. Thus, on the basis of the model proposed, one can treat ABC-type experiments as a direct observation of the $\sigma$-meson production in $NN$, $Nd$, etc., collisions.

The authors are grateful to Prof. H. Clement, Drs. M. Bashkanov and T. Skorodko from Physical Institute of Tuebingen University for fruitful discussions on the WASA-at-COSY experimental results. One of the authors (V.I.K.) also thanks Prof. A. Faessler for the hospitality at Tuebingen University where this work was begun. The work was done under partial financial support from RFBR grants Nos. 10-02-00096 and 12-02-00908.

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The quark-meson component gives a small contribution (ca. 2–3%) to the total deuteron wavefunction normalisation, so it should be visible only when probing the deuteron structure with high-momentum probes \[14\].

In case of emission of two neutral pions the $D_{12}$ denotes the isovector dibaryon with the isospin projection $I_3 = 0$ (the $np$ resonance).

The $D_{03}$ mass and width are taken from Ref. \[7\], and the parameters chosen for the $D_{12}$ are close to those found in Ref. \[20\].

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