ABC effect as a signal of chiral symmetry restoration in hadronic collisions

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A nonconventional mechanism for the basic 2π-fusion reaction $pn \to d + (\pi\pi)_0$ in the energy region $T_p =$ 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 an 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—$D_{03} \to d + \sigma \to d + (\pi\pi)_0$ and $D_{03} \to D_{12} + \pi \to d + (\pi\pi)_0$—is shown to give a strong near-threshold enhancement in the $\pi\pi$ invariant mass spectrum, which is well known as the Abashian-Booth-Crowe (ABC) effect. The σ-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 σ meson. So, this result might be considered as an indication of partial chiral symmetry restoration in dense and excited quark matter.

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The famous Abashian-Booth-Crowe (ABC) effect discovered more than 50 years ago [1] is observed in double-pionic fusion reactions [1–3] 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 σ meson. However, later on the interpretation was abandoned 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, another interpretation [4] for the ABC effect, based on generation of two Δ 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 a quantitative description of the data, it allowed reproduction of the differential cross section shapes found in 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 2π-fusion reaction $pn \to d + \pi^0\pi^0$ done by the CELSIUS/WASA [6] and then by the WASA-at-COSY [7] Collaborations. 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 behavior of the experimental energy and angular distributions, giving just a low background in the considered energy region ($T_p = 1.0$–1.4 GeV). At the same time, the most intriguing discovery from these exclusive experiments was the observation of a pronounced resonance structure in the total 2π-production cross section. This fact has been interpreted as generation of the dibaryon resonance D_{03} in the pn collision, with quantum numbers $I(J^P) = 0(3^+)$, mass $m_{D_{03}} \simeq 2.37$ GeV, and total width $\Gamma_{D_{03}} \simeq 70$ MeV [7]. Such a resonance state had 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.* [7] performed microscopic calculations based on the mechanism $pn \to D_{03} \to \Delta\Delta \to d + \pi^0\pi^0$. With such an "$s$-channel $\Delta\Delta$" model they succeeded in providing a very good description of the energy and angular distributions observed in the reaction $pn \to d + \pi^0\pi^0$. However, 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 [7] only when a very soft form factor $f_{\Delta\Delta}$ was used for the $D_{03} \to \Delta\Delta$ vertex with a cutoff parameter $\Lambda_{\Delta\Delta} = 0.15$ GeV$/c$. Such a low value of $\Lambda_{\Delta\Delta}$ means that the characteristic radius of the D_{03} state must be even larger than that of the deuteron. This is incompatible with the observed strong Δ-Δ 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., Refs. [10,11]), which all predict a radius for the $0(3^+)$ $\Delta\Delta$ bound state of $r(D_{03}) \simeq 0.7$–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 Δ's are almost fully overlapped with each other. Moreover, the large width of the free Δ isobar, $\Gamma_\Delta \simeq 120$ MeV, would not allow two Δ's to separate a 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 the concept of the bound state of two isolated quasifree Δ isobars, which therefore looks to be rather inconsistent. As will be shown below, a reasonable explanation of the ABC effect in the basic 2π-fusion reaction may be found within an alternative model, involving σ-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 the short-range nuclear force [14]. In this concept,

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the conventional t-channel σ-meson exchange between two isolated nucleons is replaced by the s-channel σ exchange with the σ field surrounding the whole $6q$ bag, which appears in the overlap region of two nucleons. An emission of a light scalar meson occurs within a virtual transition of the $6q$ 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 σ field to the multiquark 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 nuclei properties are at the same level of accuracy as those of other modern NN-force models, such as Bonn and Argonne, still keeping quite moderate values for short-range cutoff parameters ($\Lambda_{\pi NN}$, etc.), which are compatible with the QCD and quark model estimations (for details, see Refs. [14,15], and references therein to the earlier works).

According to the dibaryon model, the deuteron wave function, 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.[1] The second component of the deuteron has the structure $D_{01} \sim s^6 + \sigma \quad (l_\sigma = 0, 2)$ (a compact $6q$ bag dressed with a σ 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_{01} and classify them with respect to 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 $s^6 + \sigma \quad (l_\sigma = 2, 4)$.

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 mass $m_{D_{12}} \simeq 2.15$ GeV, as discovered in the analysis of pp scattering in the $^1D_2$ partial wave [16,17]. The production of the D_{12} resonance was later confirmed in π^+d elastic scattering [18,19] and particularly in the reaction $\pi^+d \to pp$ [20], where the total cross section at 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 [7]) and $D_{12} + \pi$ systems. It becomes a resonance also in the $d(D_{01}) + \sigma$ system, if the σ mass is less than 500 MeV. So, there are two basic possibilities for the decay of the D_{03} resonance into a deuteron (i.e., into its quark-meson component D_{01}) and two pions:

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

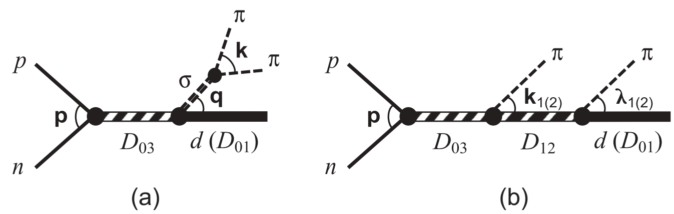

FIG. 1. The leading mechanisms for the reaction $pn \to d + (\pi\pi)_0$ in the ABC region. The three-momenta in the c.m. frame of two particles are indicated between the respective lines.

(ii) by 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 $D_{03} \to d + \pi\pi$ can be confronted with two quite similar mechanisms for the Roper resonance (excited nucleon) decay $N^*(1440) \to N + \pi\pi$ [21]: $N^*(1440) \to N + (\pi\pi)^{s\text{-wave}}_{I=0}(\sigma)$ and $N^*(1440) \to \Delta + \pi$. It should be stressed that the model [22] based on an excitation of the Roper resonance and its subsequent decay via these two channels was quite successfully applied to the reactions $NN \to d + \pi\pi$ and $NN \to NN + \pi\pi$ at 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 $pn \to d + (\pi\pi)_0$ in the ABC region ($T_p = 1.0$–1.4 GeV):

(i) $pn \to D_{03} \to d + \sigma,\ \sigma \to (\pi\pi)_0$;
(ii) $pn \to D_{03} \to D_{12} + \pi,\ D_{12} \to d + \pi$.

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

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

$$\mathcal{M}_{\mu_i\mu_f} = \mathcal{M}^{(D_{03})}_{\mu_i}\big(\mathcal{M}^{(\sigma)}_{\mu_i\mu_f} + \mathcal{M}^{(D_{12})}_{\mu_i\mu_f}\big), \tag{1}$$

where

$$\mathcal{M}^{(D_{03})}_{\mu_i} = \frac{m^2_{D_{03}}\sqrt{\Gamma^{(2)}_{D_{03}np}/p}}{E^2 - m^2_{D_{03}} + i m_{D_{03}}\Gamma_{D_{03}}}\mathcal{J}^{(D_{03})}_{\mu_i\mu_i}(\hat{p}), \tag{2}$$

$$\mathcal{M}^{(\sigma)}_{\mu_i\mu_f} = \frac{m_\sigma\sqrt{\Gamma^{(2)}_{D_{03}d\sigma}/q}\,\sqrt{\Gamma^{(0)}_{\sigma\pi^0\pi^0}/k}}{M^2_{\pi\pi} - m^2_\sigma + i m_\sigma\Gamma_\sigma}\mathcal{J}^{(\sigma)}_{\mu_i\mu_f}(\hat{q}), \tag{3}$$

$$\mathcal{M}^{(D_{12})}_{\mu_i\mu_f} = \frac{1}{\sqrt{2}}\left(\frac{m_{D_{12}}\sqrt{\Gamma^{(1)}_{D_{03}D_{12}\pi^0}/k_1}\,\sqrt{\Gamma^{(1)}_{D_{12}d\pi^0}/\lambda_1}}{M^2_{d\pi} - m^2_{D_{12}} + i m_{D_{12}}\Gamma_{D_{12}}}\times\mathcal{J}^{(D_{12})}_{\mu_i\mu_f}(\hat{k}_1,\hat{\lambda}_1) + [\vec{k}_1,\vec{\lambda}_1 \to \vec{k}_2,\vec{\lambda}_2]\right). \tag{4}$$

The amplitude $\mathcal{M}^{(D_{12})}_{\mu_i\mu_f}$ for the above process (b) is symmetrized over two identical pions.[2]

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

[2] 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).

When taking into account only the dominating, i.e., the lowest, partial waves in vertices [indicated by superscripts of Γ's in Eqs. (2)–(4)], the spin-angular terms $\mathcal{J}^{(\sigma)}_{\mu_i\mu_f}$ and $\mathcal{J}^{(D_{12})}_{\mu_i\mu_f}$ can be calculated by using the standard technique for angular momenta coupling. The total angular momentum J should be decomposed as $J = J_1 + L$, i.e., $3 = 1 + 2$ for process (a) and $\{3 = 2 + 1, 2 = 1 + 1\}$ for process (b). The factor $\mathcal{J}^{(D_{03})}_{\mu_i\mu_i}(\hat{p})$ comes from the vertex $np \to D_{03}$ and, with the initial momentum $\vec{p}$ directed along the z axis, gives just a constant C_{μ_i}.

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

$$\frac{d\sigma}{d(M^2_{\pi\pi})} = \frac{\rho^{(\pi\pi)}}{(4\pi)^5 pE} \int\!\!\int d\Omega_q d\Omega_k \frac{1}{3} \sum_{\mu_i,\mu_f} |\mathcal{M}_{\mu_i\mu_f}|^2, \qquad (5)$$

$$\frac{d\sigma}{d(M^2_{d\pi})} = \frac{\rho^{(d\pi)}}{(4\pi)^5 pE} \int\!\!\int d\Omega_{k_1} d\Omega_{\lambda_1} \frac{1}{3} \sum_{\mu_i,\mu_f} |\mathcal{M}_{\mu_i\mu_f}|^2, \qquad (6)$$

where $\rho^{(\pi\pi)} = qk/2EM_{\pi\pi}$ and $\rho^{(d\pi)} = k_1\lambda_1/2EM_{d\pi}$ are the Lorentz-invariant phase-space factors. The sum should be taken over all possible projections μ_i and μ_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 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 parametrized as

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

where $q = [(M^2 - M_1^2 - M_2^2)^2 - 4M_1^2M_2^2]^{1/2}/2M$ 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 behavior 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 center of the Breit-Wigner distribution can be properly reproduced. For the partial widths introduced in Eqs. (3) and (4), this is achieved with $\varkappa = 0.1$–0.2 GeV/c, while for the partial width $\Gamma^{(2)}_{D_{03}np}$ 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[3]

$$m_{D_{03}} = 2370 \text{ MeV}, \quad \Gamma_{D_{03}} = 70 \text{ MeV},$$
$$m_{D_{12}} = 2150 \text{ MeV}, \quad \Gamma_{D_{12}} = 110 \text{ MeV}.$$

The remaining model parameters, i.e., the mass and width of the σ meson and the relative weight of the amplitudes corresponding to processes (a) and (b), were derived from the fit to the experimental data [7] on the $M^2_{\pi\pi}$ spectrum, and then the $M^2_{d\pi}$ spectrum was calculated using the same parameter values.

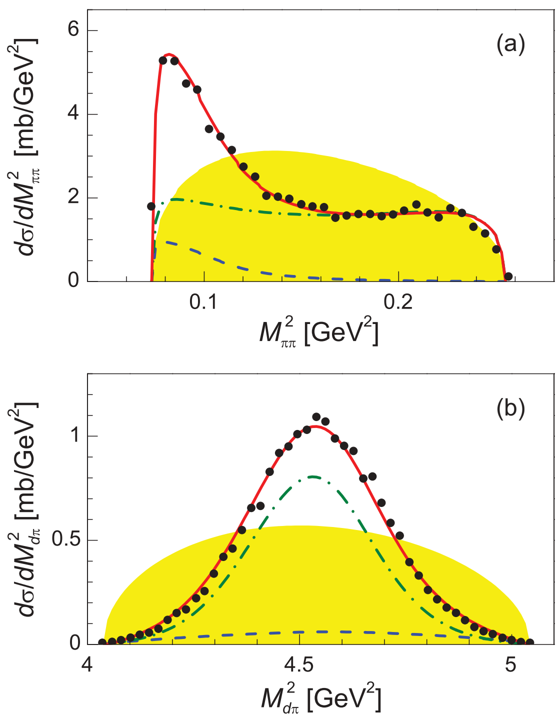

FIG. 2. (Color online) Differential cross sections as functions of the invariant masses squared (a) $M^2_{\pi\pi}$ and (b) $M^2_{d\pi}$ in the reaction $pn \to d + \pi^0\pi^0$ at energy $\sqrt{s} = 2.38$ GeV. The contribution of the σ-production mechanism [see Fig. 1(a)] is shown by dashed lines while the contribution of the mechanism going through the intermediate dibaryon D_{12} [see Fig. 1(b)] 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].

The results for the $M^2_{\pi\pi}$ and $M^2_{d\pi}$ distributions at the peak energy (where the total cross section has a maximum) $\sqrt{s} = 2.38$ GeV, or $T_p = 1.14$ GeV, are presented in Fig. 2. The results are normalized to the experimental value of the total cross section $(\sigma_T)_{\rm peak} \simeq 0.43$ mb [7]. It is evident that our simple model reproduces the shapes of these two distributions almost perfectly. We observe that, although the cross section for the σ-generation process (a) alone is rather moderate, its contribution is crucial to reproduce the shape of the $M^2_{\pi\pi}$ distribution. Thus, its constructive interference with the D_{12}-production mechanism (b) at low $M^2_{\pi\pi}$ leads just to the observed height of the ABC peak. On the other hand, when the $M^2_{d\pi}$ distribution is considered [see Fig. 2(b)], the σ-production mechanism plays the role of a smooth background, while process (b) alone almost gives the observed resonance enhancement.

The resonance peak in the $M^2_{d\pi}$ spectrum was associated previously with an excitation of the intermediate Δ isobar [7]. However, our results show that this peak may reflect just generation of the intermediate isovector dibaryon D_{12}, which then decays into the final deuteron and pion. In fact, the suggested mechanism of two-pion emission through the D_{12} excitation is quite similar to the s-channel ΔΔ model used

[3]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. [19].

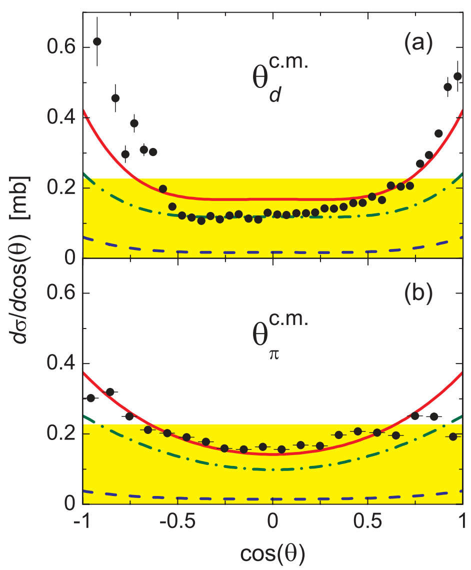

FIG. 3. (Color online) Angular distributions for the deuteron (a) and the pion (b) in the overall c.m. frame at energy $\sqrt{s} = 2.38$ GeV. The meaning of the curves is the same as in Fig. 2. The experimental data (full circles) are taken from Ref. [7].

in [7], however without a soft form factor $f_{\Delta\Delta}$. The point is that the D_{12} dibaryon is located near the $N\Delta$ threshold, so it has a large probability of being in the $N + \Delta$ ($^5S_2$) state. Therefore, one needs additional tests to distinguish between these two mechanisms.

We also calculated the angular distributions for the final deuteron and pion emissions in the overall c.m. frame and then compared our model predictions with the experimental data. Our results for the angular distributions are shown in Fig. 3. The agreement with the data is not as good as for the invariant mass distributions; however, it is still quite reasonable. Moreover, if we confront our model predictions with those found in [7] on the basis of the s-channel $\Delta\Delta$ model, the description of the above two angular distributions seems to be not worse than that reached in [7]. So, with only three basic parameters extracted from the experimental $M^2_{\pi\pi}$ spectrum, our simple model is able to reproduce four differential distributions measured in the $pn \to d + \pi^0\pi^0$ reaction.

Besides the two considered decay modes of the D_{03} resonance, one can also treat other channels for the decay $D_{03} \to d + \pi\pi$, i.e., via simultaneous emission of two uncorrelated pions without formation of the σ meson or sequential emission of two pions through other intermediate isovector dibaryons [16,17], such as the $1(3^-)$ state (corresponding to the $^3F_3$ NN partial wave). In these cases, the pions may be emitted in s and d waves relative to the $6q$ bag, thus forming the d-wave $\pi\pi$ pair. In fact, one can see from Fig. 3 that the deuteron and pion c.m. angular distributions show some additional d-wave admixture which is not fully taken into account by the present model. Including the corrections from the d-wave pion emission would not affect significantly the shape of the invariant mass spectra, but it may improve the description of the angular distributions at forward and backward directions. In a complete theoretical picture the conventional t-channel $\Delta\Delta$ mechanism should also be taken into account as the main background process to D_{03} production.

The mass and width of the σ 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 σ mass and width, found by extrapolation from the dispersion relations for the $\pi\pi$ scattering amplitude to the σ complex pole [24],

$$m_\sigma^{(0)} = 441^{+16}_{-8} \text{ MeV}, \quad \Gamma_\sigma^{(0)} = 544^{+18}_{-25} \text{ MeV}.$$

While the latter values are within the range for the $f_0(500)$ or σ pole positions currently quoted in Particle Data Group tables [21],

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

the values found here are essentially outside of this range. To resolve this discrepancy, one should bear in mind that the above range of pole positions for the σ 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 [24]. On the other hand, numerous theoretical investigations (see, e.g., Refs. [25,26]) show that the mass and width of the σ meson produced in hot and/or dense nuclear matter may be significantly shifted downward due to the partial chiral symmetry restoration (CSR) effect. Besides that, it was demonstrated [27] that the partial CSR takes place also in strongly excited states of *isolated hadrons* (baryons and mesons) at 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 σ-meson mass and width for the $\sigma \to \pi\pi$ decay. So, the σ 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 NN-scattering phase shifts and properties of the lightest nuclei has been achieved with a rather low mass of the σ meson, $m_\sigma \simeq 350$ MeV, whereas in the conventional meson-exchange NN-force models the σ mass is taken to be 500–600 MeV. Since in the dibaryon model the initial $6q$ bag (with the quark configuration $|s^4p^2[42]\rangle$) is a dense object ($r_{6q} \simeq 0.5$–0.6 fm) and is also the $2\hbar\omega$-excited hadronic state, the renormalization of the σ 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 radius $r \simeq 0.8$ fm corresponds to about a six-fold normal nuclear density) and has an additional excitation energy of 500 MeV above the deuteron pole. Thus, the σ meson produced from the D_{03} decay should have a lower mass and width than those for the free σ meson. As the σ width found here is still quite large, the σ meson is likely to decay *before* it escapes the field of the multiquark bag and acquires its free-space parameters. This implies that when measuring the $\pi\pi$ invariant mass distribution, one should observe just the renormalized σ meson with the reduced mass and width. So, one can suggest that the low values for the σ-meson parameters found here indicate a partial CSR in the excited dibaryon state. This conclusion is in an agreement with the results of numerous theoretical studies concerning the CSR in hadronic and nuclear media [25–27]. Further experimental and theoretical efforts are called for to check the fundamental CSR effects in hadronic systems.

To summarize, we have proposed a 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 D_{03}-dibaryon production and its decay into the final deuteron and two pions by two alternative ways: (i) through emission of a σ meson and (ii) through generation of the intermediate isovector dibaryon resonance D_{12}. So, the suggested mechanisms for the D_{03} decay are remarkably reminiscent of two analogous modes of the Roper resonance $N^*(1440)$ decay. Reasonable agreement with the data from the recent exclusive experiments done by the WASA-at-COSY Collaboration [7], *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 a result of emission of a σ meson, whose mass and width, due to the partial restoration of chiral symmetry, are reduced in the field of the multiquark 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 renormalized σ meson in the field of the bag. Hence, by extracting the σ 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 $pn \to pp + \pi^-\pi^0$ [28]: although the D_{03} resonance is produced there as well, the σ meson is not. So, we partially rehabilitate the initial interpretation of the ABC effect suggested by Abashian, Booth and Crowe [1], even though the σ-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 σ-meson production in NN, Nd, etc., collisions.

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