Evidence of $N^*(1535)$ resonance contribution in the $pn \rightarrow d\phi$ reaction

Xu Cao$^{1,4,6}$, Ju-Jun Xie$^{2,4}$, Bing-Song Zou$^{3-6}$, and Hu-Shan Xu$^{1,4,5}$

1 Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou 730000, China
2 Department of Physics, Zhengzhou University, Zhengzhou Henan 450052, China
3 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China
4 Theoretical Physics Center for Sciences Facilities, Chinese Academy of Sciences, Beijing 100049, China
5 Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Collisions, Lanzhou 730000, China
6 Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

The $N^*(1535)$ resonance contributions to the $pn \rightarrow d\phi$ reaction are evaluated in an effective Lagrangian model. The $\pi-$, $\eta-$, and $\rho-$meson exchange are considered. It is shown that the contributions from $\pi-$ and $\rho-$meson exchange are dominant, while the contribution from $\eta-$meson exchange is negligibly small. Our theoretical results reproduce the experimental data of both total cross section and angular distribution well. This is another evidence that the $N^*(1535)$ resonance has large $s\bar{s}$ component leading to a large coupling to $N\phi$, which may be the real origin of the OZI rule violation in the $\pi N$ and $pN$ reactions.

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I. INTRODUCTION

The intensive interest in $\phi$-meson production in different elementary reactions is mainly related to the investigation of the Okubo-Zweig-Iizuka (OZI) rule violation [1] which is thought to originate from the strangeness degrees of freedom in the nucleon and nucleon resonances. Based on the OZI rule, the ratio of $\phi$- to $\omega$-meson production under similar kinematic conditions are expected to be $R_{\text{OZI}} \approx \tan^2 \Delta \theta_V \approx 4.2 \times 10^{-3}$ [2], with the small deviation $\Delta \theta_V = 3.7^\circ$ from ideal mixing of octet and singlet isoscalar vector mesons at the quark level. A significantly apparent OZI rule violation, however, was reported in $p\bar{p}$ annihilation at the LEAR facility at CERN [3]. Some authors attributed the origin of the OZI rule violation to the shake-out and rearrangement of the intrinsic $s\bar{s}$ content in the quark wave function of the nucleon [4], which was indicated by the analysis of the $\pi$-nucleon $\sigma$-term [5] and the lepton deep-inelastic scattering data [6]. This picture has also been applied to the $\phi$-meson electro- and photoproduction off the proton [7], and may give a natural explanation to the empiric evidence of a positive strangeness magnetic moment of the proton [8].

Recently, OZI rule violation was found in the $pN$ collisions at the ANKE facility at COSY [9, 10], and they obtained $\sigma(pp \to pp\phi)/\sigma(pp \to pp\omega) = (3.3 \pm 0.6) \times 10^{-2} \approx 8 \times R_{\text{OZI}}$ [9], and $\sigma(pn \to d\phi)/\sigma(pn \to d\omega) = (4.0 \pm 1.9) \times 10^{-2} \approx 9 \times R_{\text{OZI}}$ [10]. Several theoretical articles [11, 12, 13, 14, 15, 16] were published trying to advance our understanding on this problem. Using a relativistic meson exchange model, Nakayama et al. [12] concluded that the mesonic current involving the OZI rule violating $\phi\rho\pi$ vertex is dominant, while the nucleonic current contribution had effect on the angular distribution due to its destructive interference with the mesonic current. They did not consider the possible role of the nucleon resonances, because there were no experimentally observed baryonic resonances which would decay into the $\phi N$ channel, and also the existing data were not enough to extract the parameters relevant to the resonances. However, the paper as well as other ones [13, 14] on the $pn \to d\phi$ reaction did not give a simultaneous good predictions to the total cross section and angular distribution measured recently by COSY-ANKE Collaboration [10]. In Ref. [15], it is found that the contributions from sub-$\phi N$-threshold $N^*(1535)$ resonance were dominant to the near-threshold $\phi$ production in proton-proton and $\pi^- p$ collisions, and all the experimental data could be nicely reproduced by the model.

In this paper, we extend the model [15] to study the $pn \to d\phi$ reaction without introducing
any further model parameters. We assume the reaction is predominantly proceeded through the excitation and decay of the sub-$\phi N$-threshold $N^*(1535)$ resonance with the final nucleons merging to form the deuteron. We calculate the total and differential cross sections of $pn \rightarrow d\phi$ reaction in the frame of an effective Lagrangian approach with the same value of parameters as we have well used in Ref. [15].

Our paper is organized as follows. In Sect. III we present the formalism and ingredients in our computation. The numerical results and discussion are given in Sect. [III]

II. FORMALISM AND INGREDIENTS

The Feynman diagrams for the $pn \rightarrow d\phi$ reaction are depicted in Fig. 1, both projectile and target excitation are included. We use the commonly used interaction Lagrangians for $\pi NN$, $\eta NN$ and $\rho NN$ couplings,

$$\mathcal{L}_{\pi NN} = -ig_{\pi NN}\bar{N}\gamma_5\vec{\tau} \cdot \vec{\pi} N,$$

$$\mathcal{L}_{\eta NN} = -ig_{\eta NN}\bar{N}\gamma_5\eta N,$$

$$\mathcal{L}_{\rho NN} = -g_{\rho NN}\bar{N}(\gamma_\mu + \frac{\kappa}{2m_N}\sigma_{\mu\nu}\partial^\nu)\vec{\tau} \cdot \vec{\rho}^\mu N.$$
At each vertex a relevant off-shell form factor is used. In our computation, we take the same form factors as that used in the well-known Bonn potential model [17],

\[ F_{MN}^{NN}(k_M^2) = \left( \frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - k_M^2} \right)^n, \]

(4)

with \( n = 1 \) for \( \pi \) and \( \eta \)-meson, and \( n = 2 \) for \( \rho \)-meson. \( k_M, m_M \) and \( \Lambda_M \) are the 4-momentum, mass and cut-off parameters for the exchanged-meson \( (M) \), respectively. The coupling constants and the cutoff parameters are taken as [15, 17, 18, 19]:

\[ g_{\pi NN}^2 / 4\pi = 14.4, \]

\[ g_{\eta NN}^2 / 4\pi = 0.4, \]

\[ g_{\rho NN}^2 / 4\pi = 0.9, \]

\[ \Lambda_\pi = \Lambda_\eta = 1.3 \text{ GeV}, \]

\[ \Lambda_\rho = 1.6 \text{ GeV}, \]

and \( \kappa = 6.1 \).

The effective Lagrangian for \( N^*(1535)N\pi \), \( N^*(1535)N\eta \), \( N^*(1535)N\rho \) and \( N^*(1535)N\phi \) couplings are [15],

\[ \mathcal{L}_{\pi NN^*} = ig_{N^*NN\pi} \bar{N} \vec{\tau} \cdot \vec{\pi} N^* + h.c., \]

(5)

\[ \mathcal{L}_{\eta NN^*} = ig_{N^*NN\eta} \bar{N} \eta N^* + h.c., \]

(6)

\[ \mathcal{L}_{\rho NN^*} = ig_{N^*NN\rho} \bar{N} \gamma_5 (\gamma_\mu - \frac{q_\mu q}{q^2}) \vec{\rho} \cdot \vec{\tau} N^* + h.c., \]

(7)

\[ \mathcal{L}_{\phi NN^*} = ig_{N^*NN\phi} \bar{N} \gamma_5 (\gamma_\mu - \frac{q_\mu q}{q^2}) \phi N^* + h.c.. \]

(8)

Here \( N \) and \( N^* \) are the spin wave functions for the nucleon and \( N^*(1535) \) resonance; \( \rho^\mu \) and \( \phi^\mu \) are the \( \rho \)- and \( \phi \)-meson field, respectively. For the \( N^*(1535) \)-Meson vertexes, monopole form factors are used,

\[ F_{MN}^{NN}(k_M^2) = \left( \frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - k_M^2} \right)^n, \]

(9)

with \( \Lambda_\pi^* = \Lambda_\eta^* = \Lambda_\rho^* = 1.3 \text{ GeV}. \)

The \( N^*(1535)N\pi \), \( N^*(1535)N\eta \) and \( N^*(1535)N\rho \) coupling constants are determined from the experimentally observed partial decay widths of the \( N^*(1535) \) resonance, and the coupling strength of \( N^*(1535)N\phi \) is extracted from the data of \( pp \rightarrow pp\phi \) and \( \pi^- p \rightarrow n\phi \) as described in Ref. [15]. For the sake of completeness of this section, we list the values of these parameters in Table I. For the \( N^*(1535)N\rho \) coupling, it is shown in Ref. [20] that the value is consistent with the one estimated from the isovector radiative decay amplitude of the \( N^*(1535) \), \( A_{1/2}^{I=1} = (0.068 \pm 0.020) \text{ GeV}^{-1} \), by the relation \( A_{1/2}^{I=1} \propto g_{N^*NN\rho} g_{\rho\gamma} \).

For the \( N^*(1535)N\phi \) coupling, if the same effective Lagrangian approach [20] with vector-meson-dominance is used, it can be verified that the large value \( g_{\phi NN^*}^2 / 4\pi = 0.13 \) is still compatible with the constraint from the small isoscalar radiative decay amplitude of
TABLE I: Relevant $N^*(1535)$ parameters.

| Decay channel | Branching ratio | Adopted branching ratio $g^2/4\pi$ |
|---------------|-----------------|-----------------------------------|
| $N\pi$        | 0.35 – 0.55     | 0.45                              |
| $N\eta$       | 0.45 – 0.60     | 0.53                              |
| $N\rho \rightarrow N\pi\pi$ | 0.02 ± 0.01 | 0.02                              |
| $N\phi$       | —               | —                                 |

$N^*(1535)$, $A_{1/2}^I=0 = (0.022 \pm 0.020)$ GeV\(^{-1}\) deduced from PDG [25], by using the relation $A_{1/2}^I \propto g_{N^*N\omega}g_{\omega\gamma} + g_{N^*N\phi}g_{\phi\gamma} \approx (g_{N^*N\omega} + \sqrt{2}g_{N^*N\phi})g_{\rho\gamma}/3$ and taking into account the uncertainty of $g_{N^*N\omega}$.

For the neutron-proton-deuteron vertex, we take the effective interaction as [21, 22],

$$iS_F(p_1)(-i\Gamma_\mu\varepsilon_\mu_d)iS_F(p_2) = \frac{(2\pi)^4}{\sqrt{2}}\delta\left(\frac{p_d \cdot q_r}{m_d}\right)u(p_1, s_1)\phi_s(Q_R)u(p_2, s_2),$$

with $iS_F(p)$ being the nucleon propagator and $q_r = (p_1 - p_2)/2$ the neutron-proton relative four momentum. $Q_R = \sqrt{-q_r^2}$ is the deuteron internal momentum and $\varepsilon_\mu_d$ is the polarization vector of the deuteron. We neglect the D-wave part of the deuteron wave function since it gives only a minor contribution [14], and the S-wave deuteron wave function $\phi_S(Q_R)$ can be parameterized as the Reid soft core wave function [23]. We also calculate the results with parameterized Hulthén wave function [23], which has distinctive difference from Reid soft core wave function only below $r = 1$ fm. It gives about 20% smaller cross section without changing the shape of the angular distribution much and is still compatible with available experimental data. So the different choice of the deuteron wave function does not affect our final conclusions. But since Reid soft core wave function is a more realistic description of deuteron, hereafter our calculations are all based on the Reid soft core.

Then the invariant amplitude can be obtained straightforwardly by applying the Feynman rules to Fig. 1. Here we take explicitly the $\pi^0$ exchange and projectile excitation diagram as an example,

$$\mathcal{M}^{\pi^0,\alpha}_{pm \rightarrow d\phi} = g_{\phi NN^*}g_{\pi NN^*}g_{\pi NN} \int d^4q_s \frac{1}{\sqrt{2}}\delta\left(\frac{p_d \cdot q_r}{m_d}\right)\phi_s(Q_R)F^{NN}(k_\pi)F^{NN^*N}(k_\pi)F^{N^*N}(q_\pi) \times$$

$$\bar{u}(p_2, s_2)\gamma_5 \left(\gamma_\mu - \frac{q_\mu q_s}{q_2^2}\right)\varepsilon^{\mu\alpha}(p_\phi, s_\phi)G_{N^*}(q)u(p_0, s_0) \times$$

$$G_\pi(k_{\pi})u(p_t, s_t)\gamma_5 \bar{u}(p_1, s_1),$$

(11)
where the form factor for $N^*(1535)$ resonance, $F_{N^*}(q^2)$, is taken as,

$$F_{N^*}(q^2) = \frac{\Lambda^4}{\Lambda^4 + (q^2 - M_{N^*}^2)^2},$$

with $\Lambda = 2.0$ GeV. $G_M(k_M)$ and $G_{N^*}(q^2)$ are the propagators of the $N^*(1535)$ resonance and exchanged meson respectively, which can be written as $[24]$,

$$G_{\pi/\eta}(k_{\pi/\eta}) = \frac{i}{k_{\pi/\eta}^2 - m_{\pi/\eta}^2},$$

$$G_{\rho}(k_\rho) = -i \frac{g_{\rho\mu\nu} - k_\rho^\mu k_\rho^\nu/k_\rho^2}{k_\rho^2 - m_\rho^2},$$

$$G_{N^*}(q^2) = \frac{i(q + M_{N^*})}{q^2 - M_{N^*}^2} + iM_{N^*} \Gamma_{N^*}(q^2).$$

Here $\Gamma_{N^*}(q^2)$ is the energy dependent total width of the $N^*(1535)$ resonance. According to PDG $[25]$, the dominant decay channels for the $N^*(1535)$ resonance are $\pi N$ and $\eta N$, so we take,

$$\Gamma_{N^*}(q^2) = \Gamma_{N^* \to \pi N} \frac{\rho_{\pi N}(q^2)}{\rho_{\pi N}(M_{N^*}^2)} + \Gamma_{N^* \to \eta N} \frac{\rho_{\eta N}(q^2)}{\rho_{\eta N}(M_{N^*}^2)},$$

where $\rho_{\pi N}(q^2)$ is the following two-body phase space factor,

$$\rho_{\pi N}(q^2) = \frac{2p_{cm}^{cm}(q^2)}{\sqrt{q^2}} = \sqrt{(q^2 - (m_N + m_{\pi N})^2)(q^2 - (m_N - m_{\pi N})^2)}.$$

It is too computer-time-consuming to directly compute Eq. (11), and we make the same approximation as Ref. $[22]$ by ignoring the weak dependence of the dirac spinors $\bar{u}(p_1, s_1)$ and $\bar{u}(p_2, s_2)$ to the relative momentum $q_r$ since the deuteron wave function $\phi_s(Q_R)$ decreases rapidly with increasing $Q_R$. Evaluating these spinors at the point $q_r = 0$, from Eq. (11) we can straightforwardly get the simple factorized result,

$$\mathcal{M}_{pn \to p\phi}^{\pi^0, a_{pn \to p\phi}} = \mathcal{M}_{pn \to p\phi}^{\pi^0, a} \times F_\pi(p_b, p_\phi),$$

where $\mathcal{M}_{pn \to p\phi}^{\pi^0, a}$ is the invariant amplitude of process $pn \to pn\phi$ with vanishing $q_r$,

$$\mathcal{M}_{pn \to p\phi}^{\pi^0, a} = g_{\phi NN^*} g_{\pi NN^*} g_{\pi NN} \overline{u}(p_2, s_2) \gamma_5 \left( \gamma_\mu - \frac{q_\mu}{q^2} \right) \varepsilon^{\mu \nu \pi \phi}(p_\phi, s_\phi)(q + M_{N^*}(1535))u(p_b, s_b) \times u(p_1, s_1) \gamma_5 \overline{u}(p_1, s_1),$$

with $p_1 = p_2 = p_d/2$. On the other hand, all the four momenta in $F_\pi(p_b, p_\phi)$ are dependent on the $q_r$ and should be integrated out,

$$F_\pi(p_b, p_\phi) = \int d^4 q_r \frac{1}{\sqrt{2}} \frac{F_{\pi NN}^{NN}(k_\pi) F_{\pi N^* N}(k_\pi) F_{N^*}(q) G_{\pi}(k_\pi)}{q^2 - M_{N^*}^2(q^2)}.$$


This prescription could largely reduce the laborious computation, and a comparison of the full calculation Eq. (11) and the approximation Eq. (19) will be given later. Diagrams for the target excitation and other exchanged mesons are in the similar fashion. Isospin factors should be considered to take into account the contribution of charged mesons. Then the differential and total cross sections are calculated by,

$$\frac{d\sigma}{d\Omega} = \frac{m_p m_d m_n}{8\pi^2 s} \frac{|\vec{p}_\phi|}{|\vec{p}_t|} \sum_s |M_{pn\rightarrow d\phi}|^2. \quad (21)$$

with $M_{pn\rightarrow d\phi} = \sum_{i=\pi,\eta,\rho} (M_{i,a}^{pn\rightarrow d\phi} + M_{i,b}^{pn\rightarrow d\phi})$. The interference terms are ignored in our concrete calculations because the relative phases among different meson exchanges are unknown.

### III. NUMERICAL RESULTS AND DISCUSSION

Fig. 2 shows the $\pi$-meson exchange contribution to the cross section and $\phi$-meson polar angular distribution in excess energy 50MeV. The difference of the full calculation Eq. (11) and the approximation Eq. (19) is tolerable, and the former gives a slightly deeper rise in the angular distribution. Obviously this will not affect our final conclusions, so we will confidently use the approximation in our following calculations.

With the formalism and ingredients given above, the total cross section versus excess energy $\varepsilon$ is calculated by the parameters fixed in the previous study [15]. Our numerical results are depicted in Fig. 3 together with the experimental data. The dotted, dashed, dash-dotted and solid curve correspond to contribution from $\pi-$, $\rho-$, $\eta-$meson exchange and their simple incoherent sum, respectively. In the calculation [15] of $pp \rightarrow pp\phi$ reaction, contribution from the $\pi$-meson exchange is larger than that from the $\rho$-meson exchange by a factor of 2. Contrarily, in Fig. 3 we can see that $\rho$-meson exchange is larger than $\pi$-meson exchange by a factor 2 in $pn \rightarrow d\phi$ reaction in the present calculation. The main reason is that the use of deuteron wave function for the $pn$ final state interaction gives an enhancement factor to the $\rho$ exchange diagram about a factor of 4 larger than to the $\pi$ exchange compared with results without including any $pn$ FSI. In the calculation [15] of $pp \rightarrow pp\phi$ reaction, a simple global Jost factor is used for the $pp$ FSI as many other previous calculations, and gives an equal enhancement factor to all meson exchanges. As pointed out by Ref. [21], this kind of treatment of FSI seems too simple. For the $pp \rightarrow pp\eta$, the use of Paris wave function for the NN FSI results in enhancement factor about a factor of 1.75 larger for the
\( \rho \) exchange than for the \( \pi \) exchange. In our present calculation of \( pn \rightarrow d\phi \) reaction with \( pn \) as a bound state, the enhancement factor is then understandably more larger for \( \rho \) exchange than for the \( \pi \) exchange. The contribution from \( \eta \)-meson exchange is about three orders of magnitude smaller than that of \( \rho \)-meson exchange. This relative magnitude is smaller compared to the case of \( pp \rightarrow pp\phi \) reaction. The relative suppression of \( \eta \)-meson exchange is due to its iso-scalar property while the iso-vector mesons play more important role in the \( pn \) interaction due to participation of their charged members. The simple incoherent sum of these contributions can give a nice description of the experimental data.

As shown in Fig. 4, our calculated \( \phi \)-meson polar angular distributions are compatible with the experimental data and show some structure in high excess energy. It is seen that our angular distributions of \( pn \rightarrow d\phi \) follow the behaviour of the corresponding distributions in \( pp \rightarrow pp\phi \) reaction, modified slightly by the neutron-proton-deuteron vertex. The upward bending at forward and backward angles becomes more pronounced with the increasing excess energy, and it would be possible for the experiment performed in higher energies to verify these structures.

There are some interesting findings if we compare our results with those of others. In the model of Nakayama et al. [12], only mesonic and nucleonic current were considered, and they claimed that it was necessary to introduce an OZI rule violation at the \( \phi \rho \pi \) vertex in the mesonic current, which provided the enhancement of the \( \phi \)-meson production. Four parameter sets extracted from the analysis of \( pp \rightarrow pp\phi/\omega \) were used to study the \( pn \rightarrow d\phi \) reaction, but none of them could give a simultaneous explanation to the experimental data. The model parameter sets 1 and 2 underestimated the total cross section slightly though they can give a fairly flat angular distributions up to excess energy 100 MeV. The sets 3 and 4 reproduced much better the total cross section but the predicted angular distributions showed obvious downward bending at forward and backward angles, which was somewhat inconsistent with the experimental data. Those characteristics might mean that it could not reasonably account for the reaction dynamics of the \( pn \rightarrow d\phi \) reaction by only including mesonic and nucleonic currents. Kaptari et al. [13] used a modified model including the bremsstrahlung and conversion diagrams, corresponding to the nucleonic and mesonic currents respectively, and found conversion diagrams were predominant without introducing obvious OZI violation in \( \phi \rho \pi \) vertex. They predicted a rather small total cross section though their angular distribution results in the near-threshold region seemed to be

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consistent with the experimental data. Another theoretical work was finished by Grishina et al. [14], and their two-step model slightly underestimated the total cross section, though this might be attributed to the adopted large normalization factor arising from the initial state interaction. This normalization factor seemed to be somewhat arbitrary and it was a pity that they did not give their angular distributions. As clearly illustrated in Fig. 3 and Fig. 4 as well as Ref. [15], if the $N^*(1535)$ resonance is dominant in the $\phi$ production in nucleon-nucleon collisions, a consistent description of $pp \rightarrow pp\phi$ and $pn \rightarrow d\phi$ reactions can be acquired. Certainly, it has to be admitted that it cannot definitely exclude the contribution from the mesonic and nucleonic current because alternative combination of those currents and $N^*(1535)$ resonance would yield a good fit to the present data. Especially, it is noted that $N^*(1535)$ resonance gives upward bending but those currents give downward bending at forward and backward angles, and their merging is expected to give much flatter angular distributions as present data have shown. The higher energy data should be helpful to decide the portion of these contributions since the bending behavior is more prominent for

FIG. 2: $\pi$-meson exchange contribution to the cross section (Right) and $\phi$-meson polar angular distribution in excess energy 50MeV (Left). Solid lines represent the full calculation of Eq. (11), and dotted lines are the results of the calculation with approximation of Eqs. (18) (19).
FIG. 3: Total cross section for $pn \rightarrow d\phi$. The dotted, dashed, dash-dotted and solid curve correspond to contribution from $\pi^-, \rho^-, \eta$–meson exchange and their simple sum, respectively. The data are from Ref. [10].

the excess energy above 100MeV.

According to above analysis, it is safe to conclude that the contribution from $N^*(1535)$ resonance plays important role for the $\phi$-meson production in $pN$ collisions and may be the real origin of the large OZI rule violation. The significant $N^*(1535)N\phi$ coupling alone would be enough to explain the enhancement in the $\phi$-meson production in $pN$ collisions, and this may indicate large $s\bar{s}$ component in quark wave function of $N^*(1535)$ resonance and hence the large coupling of $N^*(1535)$ to strangeness decay channels [15, 26].

The large $N^*(1535)N\phi$ coupling should also play important role in other relevant processes. In the study of the $\phi$-meson production in the $\bar{p}p$ annihilations, the strange hadron loops, such as $K\bar{K}$, $K^*\bar{K}$, $\Lambda\bar{\Lambda}$ loops, are found to play important role [27]. It would be interesting to investigate the contribution through $N^*(1535)$ and $\bar{N}^*(1535)$ excitations. For the $\pi N \rightarrow \phi N$ reaction, although the total cross sections can be reproduced by the t-channel $\rho$ exchange and/or subthreshold nucleon pole contributions [11, 28], these contributions are very sensitive to the choice of off-shell form factors for the t-channel $\rho$ exchange and the $g_{NN\phi}$ couplings and can be reduced by orders of magnitude within uncertainties of these in-
FIG. 4: Angular distributions of $\phi$ meson polar angular in the overall c.m. system. The data are from Ref. [10].

Alternative mechanisms [15, 29] with large $N^*(1535)$ contribution can reproduce data perfectly. For the $\gamma p \rightarrow \phi p$ reaction, a much larger OZI rule violation for $\phi$-meson production was suggested [30, 31, 32] with no indications for s-channel resonances above threshold [32]. The t-channel diffractive Pomeron exchange with photon transition to $\phi$ is found to play dominant role [28, 33], but further mechanisms are needed to account for the bump structure in the forward angle differential cross section at low energy region [31]. It
would be interesting to check the role of $N^*(1535)$ and/or other s-channel $N^*$ through polarization observables. The role of $N^*(1535)$ can also be further explored in the $pd \to ^3\text{He}\phi$ reaction [34], though this channel is convoluted with the large momentum transfer between the deuteron and $^3\text{He}$. A two-step model [35] underpredicted the total cross section by at least a factor of four, and the reaction dynamics involving $N^*(1535)$ resonance may be necessary to resolve the $\phi$ production mechanism in this reaction.

In summary, we have phenomenologically investigated the role of the $N^*(1535)$ resonance in $pn \to d\phi$ reaction near threshold, and all model parameters are taken from a previous study of the $pp \to pp\phi$ reaction [15]. We have shown that the including of the dominant $N^*(1535)$ resonance contribution is necessary to reproduce the recently measured total and differential cross sections, though mesonic and nucleonic currents might also have some minor contributions. We argue that the large coupling of the intermediate $N^*(1535)$ resonance to $\phi$-meson maybe an very important origin of the OZI rule violation in the $\phi$-meson production. This can be further investigated in various other relevant reactions.

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[1] V. P. Nomokonov and M. G. Sapozhnikov, Phys. Part. Nucl. 34, 94 (2003).
[2] S. Okubo, Phys. Lett. 5, 165 (1963); G. Zweig, CERN Report No.8419/TH412 (1964); J. Iizuka, Prog. Theor. Phys. Suppl. 38, 21, (1966); H. J. Lipkin, Phys. Lett. B60, 371 (1976).
[3] J. Reifenröther et al., Phys. Lett. B267, 299 (1991); C. Amsler et al., Z. Phys. C58, 175 (1993); Z. Weidenauer et al., Z. Phys. C59, 387 (1993); V. G. Ableev et al., Phys. Lett. B334, 237 (1994); C. Amsler et al., Phys. Lett. B346, 363 (1995); V. G. Ableev et al., Nucl. Phys. A585, 577 (1995); V. G. Ableev et al., Nucl. Phys. A594, 375 (1995); A. Bertin et al., Phys. Lett. B388, 450 (1996).
[4] J. Ellis, M. Karliner, D. E. Kharzeev, and M. G. Sapozhnikov, Phys. Lett. B353, 319 (1995).
[5] J. F. Donoghue and C. R. Nappi, Phys. Lett. B168, 105 (1986); J. Gasser, H. Leutwyler, and M. E. Sainio, Phys. Lett. B253, 252 (1991).

[6] J. Ashman et al., Phys. Lett. B206, 364 (1988).

[7] A. I. Titov, Y. Oh, and S. N. Yang, Phys. Rev. Lett. 79, 1634 (1997); A. I. Titov, S. N. Yang, and Y. Oh, Nucl. Phys. A618, 259 (1997).

[8] B. S. Zou and D. O. Riska, Phys. Rev. Lett. 95, 072001 (2005).

[9] M. Hartmann et al., Phys. Rev. Lett. 96, 242301 (2006).

[10] Y. Maeda et al., Phys. Rev. Lett. 97, 142301 (2006).

[11] A. Sibirtsev, J. Haidenbauer, and U.-G. Meissner, Eur. Phys. J. A 27, 263 (2006); A. Sibirtsev and W. Cassing, Euro. Phys. J. A 7, 407 (2000).

[12] K. Nakayama, J. W. Durso, J. Haidenbauer, C. Hanhart, and J. Speth, Phys. Rev. C 60, 055209 (1999); K. Nakayama, J. Haidenbauer, and J. Speth, Phys. Rev. C 63, 015201 (2000); K. Nakayama, J. Haidenbauer, and J. Speth, Nucl. phys. A689, 402 (2001); K. Tsushima and K. Nakayama, Phys. Rev. C 68, 034612 (2003).

[13] L. P. Kaptari and B. Kämpfer, Eur. Phys. J. A 14, 211 (2002); 23, 291 (2005).

[14] V. Yu. Grishina, L. A. Kondratyuk, and M. Büscher, Phys. At. Nucl. 63, 1824 (2000).

[15] Ju-Jun Xie, Bing-Song Zou, and Huan-Ching Chiang, Phys. Rev. C 77, 015206 (2008).

[16] A. I. Titov, B. Kämpfer, and B. L. Reznik, Eur. Phys. J. A 7, 543 (2000).

[17] R. Machleidt, K. Holinde and C. Elster, Phys. Rep. 149, 1 (1987);
R. Machleidt, Adv. Nucl. Phys. 19, 189 (1989);
R. Brockmann and R. Machleidt, Phys. Rev. C 42, 1965 (1990).

[18] K. Tsushima, S. W. Huang and A. Faessler, Phys. Lett. B 337, 245 (1994);
K. Tsushima, A. Sibirtsev and A. W. Thomas, Phys. Lett. B 39, 29 (1997);
K. Tsushima, A. Sibirtsev, A. W. Thomas and G. Q. Li, Phys. Rev. C 59, 369 (1999), Erratum-ibid. C 61, 029903 (2000).

[19] A. Sibirtsev and W. Cassing, nucl-th/9802019
A. Sibirtsev, K. Tsushima, W. Cassing and A. W. Thomas, Nucl. Phys. A 646, 427 (1999).

[20] Ju-Jun Xie, Colin Wilkin, and Bing-Song Zou, Phys. Rev. C 77, 058202 (2008).

[21] G. Fäldt and C. Wilkin, Phys. Scr. 64, 427 (2001); Nucl. Phys. A604, 441 (1996).

[22] I. Bar-Nir, T. Risser, and M. D. Shuster, Nucl. Phys. B87, 109 (1975).

[23] P. Bosted and J. M. Laget, Nucl. Phys. A296, 413 (1978).
[24] W. H. Liang, P. N. Shen, J. X. Wang and B. S. Zou, J. Phys. G 28, 333 (2002).
[25] The Review of Particle Physics, C. Amsler et al., Phys. Lett. B 667, 1 (2008).
[26] Xu Cao and Xi-Guo Lee, Phys. Rev. C 78, 035207 (2008).
[27] M. P. Locher, Y. Lu, and B. S. Zou, Z. Phys. A347, 281 (1994); D. Buzatu and F. Lev, Phys. Lett. B329, 143 (1994); V. Mull, K. Holinde, and J. Speth, Phys. Lett. B334, 295 (1994).
[28] A. I. Titov, B. Kämpfer, and B. L. Reznik, Phys. Rev. C 65, 065202 (2002); A. I. Titov and T.-S. H. Lee, Phys. Rev. C 67, 065205 (2003).
[29] M. Döring, E. Oset, and B. S. Zou, Phys. Rev. C 78, 025207 (2008).
[30] A. Sibirtsev, Ulf-G. Meissner, and A. W. Thomas, Phys. Rev. D 71, 094011 (2005).
[31] T. Mibe et al, Phys. Rev. Lett. 95, 182001 (2005).
[32] J. Barth et al, Eur. Phys. J. A 17, 269 (2003).
[33] Q. Zhao, J.-P. Didelez, M. Guidal, B. Saghai, Nucl.Phys. A660, 323 (1999).
[34] F. Bellemann et al., Phys. Rev. C 75, 015204 (2007); R. Wurzinger et al., Phys. Lett. B374, 283 (1996).
[35] G. Fäldt and C. Wilkin, Phys. Lett. B354, 20 (1995).