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

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

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I. INTRODUCTION

The intensive interest in ϕ-meson production in different elementary reactions is mainly related to the investigation of the Okubo-Zweig-Iizuka (OZI) rule violation [1] that is thought to originate from the strangeness degrees of freedom in the nucleon and nucleon resonances. Based on the OZI rule, the ratio of ϕ- to ω-meson production under similar kinematic conditions is expected to be $R_{\mathrm{OZI}} \approx \tan^2 \Delta\theta_V \approx 4.2 \times 10^{-3}$ [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 Low Energy Antiproton Ring (LEAR) 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 π-nucleon σ term [5] and the lepton deep-inelastic scattering data [6]. This picture has also been applied to the ϕ-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 Apparatus for Studies of Nucleon and Kaon Ejectiles (ANKE) at COSY [9,10], and they obtained $\sigma(pp \to pp\phi)/\sigma(pp \to pp\omega) = (3.3 \pm 0.6) \times 10^{-2} \approx 8 \times R_{\mathrm{OZI}}$ [9] and $\sigma(pn \to d\phi)/\sigma(pn \to d\omega) = (4.0 \pm 1.9) \times 10^{-2} \approx 9 \times R_{\mathrm{OZI}}$ [10]. Several theoretical articles [11–16] 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 violation at the $\phi\rho\pi$ vertex is dominant, while the nucleonic current contribution had effect on the angular distribution because of 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 that would decay into the ϕN channel, and also the existing data were not enough to extract the parameters relevant to the resonances. However, that article as well as other ones [13,14] on the $pn \to d\phi$ reaction did not give simultaneous good predictions to the total cross section and angular distribution measured recently by the COSY-ANKE Collaboration [10]. In Ref. [15], it is found that the contributions from sub-ϕN-threshold $N^*(1535)$ resonance were dominant to the near-threshold ϕ production in proton-proton and $\pi^- p$ collisions, and all the experimental data could be nicely reproduced by the model.

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

Our article is organized as follows. In Sec. II, we present the formalism and ingredients of our computation. The numerical results and discussion are given in Sec. III.

II. FORMALISM AND INGREDIENTS

The Feynman diagrams for the $pn \to d\phi$ reaction are depicted in Fig. 1, both projectile and target excitations are included. We use the commonly used interaction Lagrangians for πNN, ηNN, and ρNN couplings:

$$\mathcal{L}_{\pi NN} = -ig_{\pi NN}\bar{N}\gamma_5\vec{\tau}\cdot\vec{\pi}N, \tag{1}$$

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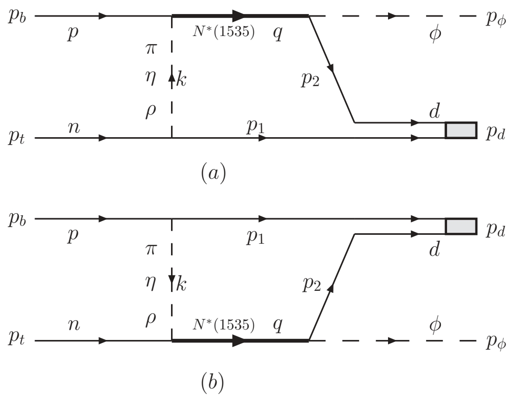

FIG. 1. Feynman diagrams for $pn \to d\phi$: (a) projectile excitation and (b) target excitation.

$$\mathcal{L}_{\eta NN} = -i g_{\eta NN} \bar{N} \gamma_5 \eta N, \tag{2}$$

$$\mathcal{L}_{\rho NN} = -g_{\rho NN} \bar{N} \left(\gamma_\mu + \frac{\kappa}{2m_N} \sigma_{\mu\nu} \partial^\nu \right) \vec{\tau} \cdot \vec{\rho}^\mu N. \tag{3}$$

At each vertex a relevant off-shell form factor is used. In our computation, we take the same form factors as those used in the well-known Bonn potential model [17],

$$F_M^{NN}(k_M^2) = \left(\frac{\Lambda_M^2 - m_M^2}{\Lambda_M^2 - k_M^2} \right)^n, \tag{4}$$

with $n = 1$ for π and η mesons and $n = 2$ for ρ mesons. k_M, m_M, and Λ_M are the four-momentum, mass, and cutoff parameters for the exchanged meson (M), respectively. The coupling constants and the cutoff parameters are taken as $g_{\pi NN}^2/4\pi = 14.4$, $g_{\eta NN}^2/4\pi = 0.4$, $g_{\rho NN}^2/4\pi = 0.9$, $\Lambda_\pi = \Lambda_\eta = 1.3$ GeV, $\Lambda_\rho = 1.6$ GeV, and $\kappa = 6.1$ [15,17–19].

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

$$\mathcal{L}_{\pi NN^*} = i g_{N^*N\pi} \bar{N} \vec{\tau} \cdot \vec{\pi} N^* + \text{h.c.}, \tag{5}$$

$$\mathcal{L}_{\eta NN^*} = i g_{N^*N\eta} \bar{N} \eta N^* + \text{h.c.}, \tag{6}$$

$$\mathcal{L}_{\rho NN^*} = i g_{N^*N\rho} \bar{N} \gamma_5 \left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2} \right) \vec{\tau} \cdot \vec{\rho}^\mu N^* + \text{h.c.}, \tag{7}$$

$$\mathcal{L}_{\phi NN^*} = i g_{N^*N\phi} \bar{N} \gamma_5 \left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2} \right) \phi^\mu N^* + \text{h.c.}. \tag{8}$$

Here N and N^* are the spin wave functions for the nucleon and $N^*(1535)$ resonance, respectively, and ρ^μ and ϕ^μ are the ρ- and ϕ-meson fields, respectively. For the $N^*(1535)$-N-meson vertexes, monopole form factors are used,

$$F_M^{N^*N}(k_M^2) = \frac{\Lambda_M^{*2} - m_M^2}{\Lambda_M^{*2} - k_M^2}, \tag{9}$$

with $\Lambda_\pi^* = \Lambda_\eta^* = \Lambda_\rho^* = 1.3$ 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 $pp \to pp\phi$ and $\pi^- p \to n\phi$ as described in Ref. [15]. For the sake of the 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 $N^*(1535)$ resonance, $A_{1/2}^{I=1} = (0.068 \pm 0.020)\,\text{GeV}^{-1}$, by the relation $A_{1/2}^{I=1} \propto g_{N^*N\rho} g_{\rho\gamma}$. 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 $N^*(1535)$, $A_{1/2}^{I=0} = (0.022 \pm 0.020)\,\text{GeV}^{-1}$ deduced from its branching ratios to γp and γn given by Particle Data Group (PDG) [21], by using the relation $A_{1/2}^{I=0} \propto g_{N^*N\omega} g_{\omega\gamma} + g_{N^*N\phi} g_{\phi\gamma} \approx (g_{N^*N\omega} + \sqrt{2} g_{N^*N\phi}) g_{\rho\gamma}/3$ and taking into account the uncertainty of $g_{N^*N\omega}$.

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	0.033
$N\eta$	0.45–0.60	0.53	0.28
$N\rho \to N\pi\pi$	0.02 ± 0.01	0.02	0.10
$N\phi$	–	–	0.13

For the neutron-proton-deuteron vertex, we take the effective interaction as [22,23]

$$i S_F^c(p_1)\left(-i \Gamma_\mu \varepsilon_d^\mu\right) i S_F(p_2) = \frac{(2\pi)^4}{\sqrt{2}} \delta\left(\frac{p_d \cdot q_r}{m_d} \right) u(p_1, s_1) \phi_s(Q_R) u(p_2, s_2), \tag{10}$$

with $i S_F(p)$ 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 ε_d^μ is the polarization vector of the deuteron. We neglect the D-wave part of the deuteron wave function because it gives only a minor contribution [14], and the S-wave deuteron wave function $\phi_S(Q_R)$ can be parametrized as the Reid soft core wave function [24]. We also calculate the results with parametrized Hulthén wave function [24], which has a distinctive difference from the Reid soft core wave function only below $r = 1$ fm. It reduces the cross section by about 20% 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 because the Reid soft core wave function is a more realistic description of the 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 π^0 exchange and projectile excitation diagram as an example,

$$\begin{aligned}\mathcal{M}_{pn \to d\phi}^{\pi^0, a} = {} & g_{\phi NN^*} g_{\pi NN^*} g_{\pi NN} \int d^4 q_r \frac{1}{\sqrt{2}} \delta\left(\frac{p_d \cdot q_r}{m_d} \right) \phi_s(Q_R) \\ & \times F_\pi^{NN}(k_\pi) F_\pi^{N^*N}(k_\pi) F_{N^*}(q) \\ & \times \bar{u}(p_2, s_2) \gamma_5 \left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2} \right)\end{aligned}$$

$$\times \varepsilon^{\mu *}(p_\phi, s_\phi) G_{N^*}(q) u(p_b, s_b) \times G_\pi(k_\pi) u(p_t, s_t) \gamma_5 \bar{u}(p_1, s_1), \quad (11)$$

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

$$F_{N^*}(q^2) = \frac{\Lambda^4}{\Lambda^4 + \left(q^2 - M^2_{N^*(1535)}\right)^2}, \quad (12)$$

with $\Lambda = 2.0$ GeV. $G_M(k_M)$ and $G_{N^*(1535)}(q)$ are the propagators of the $N^*(1535)$ resonance and exchanged meson, respectively, which can be written as [25]

$$G_{\pi/\eta}(k_{\pi/\eta}) = \frac{i}{k^2_{\pi/\eta} - m^2_{\pi/\eta}}, \quad (13)$$

$$G^{\mu\nu}_\rho(k_\rho) = -i \frac{g^{\mu\nu} - k^\mu_\rho k^\nu_\rho / k^2_\rho}{k^2_\rho - m^2_\rho}, \quad (14)$$

$$G_{N^*(1535)}(q) = \frac{i(\not{q} + M_{N^*(1535)})}{q^2 - M^2_{N^*(1535)} + i M_{N^*(1535)} \Gamma_{N^*(1535)}(q^2)}. \quad (15)$$

Here $\Gamma_{N^*}(q^2)$ is the energy-dependent total width of the $N^*(1535)$ resonance. According to PDG [21], the dominant decay channels for the $N^*(1535)$ resonance are πN and ηN, so we take

$$\Gamma_{N^*}(q^2) = \Gamma_{N^* \to N\pi} \frac{\rho_{\pi N}(q^2)}{\rho_{\pi N}\left(M^2_{N^*}\right)} + \Gamma_{N^* \to N\eta} \frac{\rho_{\eta N}(q^2)}{\rho_{\eta N}\left(M^2_{N^*}\right)}, \quad (16)$$

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

$$\rho_{\pi(\eta)N}(q^2) = \frac{2 p^{cm}_{\pi(\eta)N}(q^2)}{\sqrt{q^2}} = \frac{\sqrt{(q^2 - (m_N + m_{\pi(\eta)})^2)(q^2 - (m_N - m_{\pi(\eta)})^2)}}{q^2}. \quad (17)$$

It is too computer-time-consuming to directly compute Eq. (11), and we make the same approximation as Ref. [23] 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 because the deuteron wave function $\phi_s(Q_R)$ decreases rapidly with increasing Q_R. By evaluating these spinors at the point $q_r = 0$, from Eq. (11), we can straightforwardly get the simple factorized result

$$\mathcal{M}^{\pi^0,a}_{pn\to d\phi} = \mathcal{M}^{\pi^0,a}_{pn\to pn\phi} \times F_\pi(p_b, p_\phi), \quad (18)$$

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

$$\mathcal{M}^{\pi^0,a}_{pn\to pn\phi} = g_{\phi NN^*} g_{\pi NN^*} g_{\pi NN} \bar{u}(p_2, s_2) \times \gamma_5 \left(\gamma_\mu - \frac{q_\mu \not{q}}{q^2}\right) \varepsilon^{\mu *}(p_\phi, s_\phi)(\not{q} + M_{N^*(1535)}) \times u(p_b, s_b) \times u(p_t, s_t) \gamma_5 \bar{u}(p_1, s_1), \quad (19)$$

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

$$F_\pi(p_b, p_\phi) = \int d^4 q_r \frac{1}{\sqrt{2}} \delta\left(\frac{p_d \cdot q_r}{m_d}\right) \phi_s(Q_R) \times \frac{F^{NN}_\pi(k_\pi) F^{N^*N}_\pi(k_\pi) F_{N^*}(q) G_\pi(k_\pi)}{q^2 - M^2_{N^*(1535)} + i M_{N^*(1535)} \Gamma_{N^*(1535)}(q^2)}. \quad (20)$$

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 a 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

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

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

III. NUMERICAL RESULTS AND DISCUSSION

Figure 2 shows the π-meson exchange contribution to the cross section and ϕ-meson polar angular distribution in excess energy 50 MeV. 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 confidently use the approximation in the following calculations.

With the formalism and ingredients given above, the total cross section versus excess energy ε 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 curves correspond to contribution from π-, ρ-, η-meson exchange and their simple incoherent sum, respectively. In the calculation [15] of the $pp \to pp\phi$ reaction, the contribution from the π-meson exchange is larger than that from the ρ-meson exchange by a factor of two. Contrarily, in Fig. 3, we can see that the ρ-meson exchange is larger than the π-meson exchange by a factor two in the $pn \to d\phi$ 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 ρ-meson exchange diagram about a factor of four larger than that to the π-meson exchange compared with results without including any pn final state interaction (FSI). In the calculation [15] of the $pp \to pp\phi$ reaction, a simple global Jost factor is used for the pp FSI as in many other previous calculations and gives an equal enhancement factor to all meson exchanges. As pointed out in Ref. [22], this kind of treatment of FSI seems too simple. For the $pp \to pp\eta$ reaction, the use of the Paris wave function for the NN FSI results in an enhancement factor about a factor of 1.75 larger for the ρ-meson exchange than for the π-meson exchange. In our present calculation of the $pn \to d\phi$ reaction with pn as a bound state, the enhancement factor is then

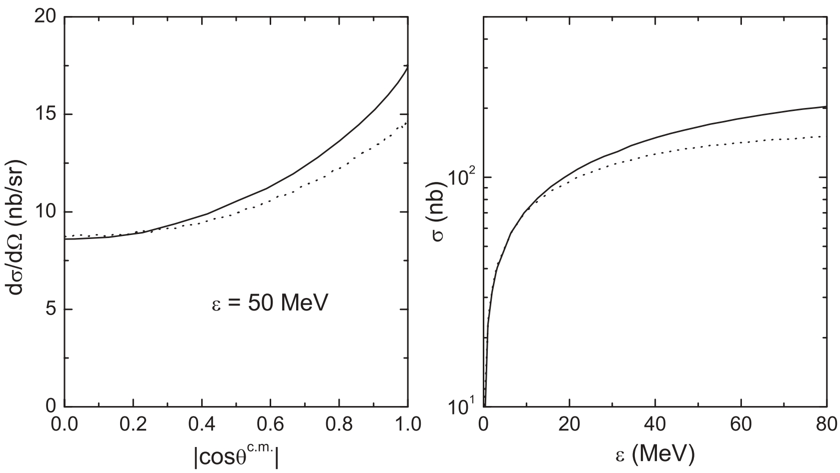

FIG. 2. π-meson exchange contribution to the cross section (right) and ϕ-meson polar angular distribution in excess energy 50 MeV (left). Solid lines represent the full calculation of Eq. (11), and dotted lines are the results of the calculation with approximation of Eqs. (18) and (19).

understandably larger for ρ-meson exchange than for π-meson exchange. The contribution from η-meson exchange is about three orders of magnitude smaller than that from ρ-meson exchange. This relative magnitude is smaller compared to the case of the $pp \to pp\phi$ reaction. The relative suppression of η-meson exchange is due to its isoscalar property while the isovector mesons play a more important role in the pn interaction because of the 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 ϕ-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 $pn \to d\phi$ follow the behavior of the corresponding distributions in the $pp \to pp\phi$ 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 at higher energies to verify these structures.

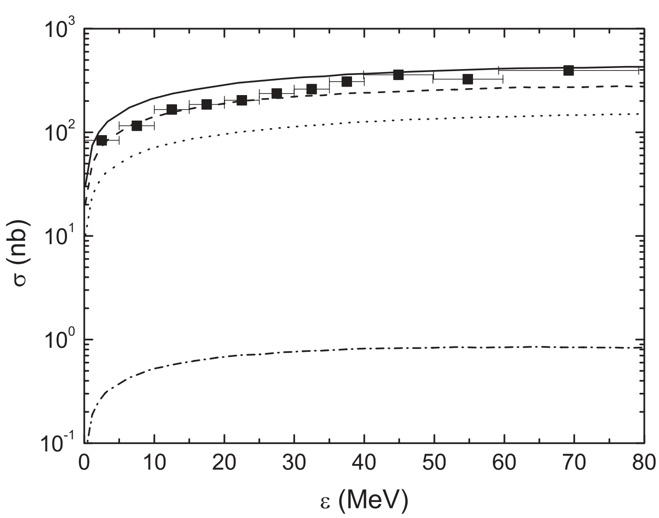

FIG. 3. Total cross section for $pn \to d\phi$. The dotted, dashed, dash-dotted, and solid curves correspond to contribution from π-, ρ-, η-meson exchange and their simple sum, respectively. The data are from Ref. [10].

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 currents 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 ϕ-meson production. Four parameter sets extracted from the analysis of $pp \to pp\phi/\omega$ were used to study the $pn \to d\phi$ reaction, but none of them

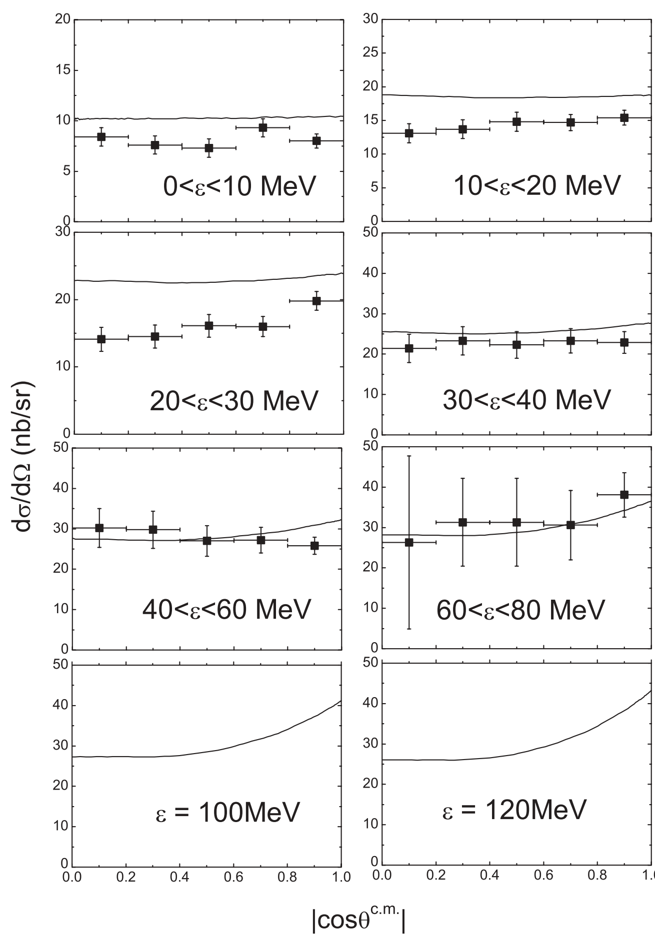

FIG. 4. ϕ-meson polar angular distributions in the overall c.m. system. The data are from Ref. [10].

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. 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 $pn \to d\phi$ reaction by only including mesonic and nucleonic currents. Kaptari and Kämpfer [13] used a modified model including the bremsstrahlung and conversion diagrams, corresponding to the nucleonic and mesonic currents, respectively, and found that 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 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 Figs. 3 and 4 as well as Ref. [15], if the $N^*(1535)$ resonance is dominant in the ϕ production in nucleon-nucleon collisions, a consistent description of $pp \to pp\phi$ and $pn \to d\phi$ reactions can be acquired. Certainly, it must be admitted that it cannot definitely exclude the contribution from the mesonic and nucleonic current because the 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 in deciding the portion of these contributions because the bending behavior is more prominent for the excess energy above 100 MeV.

According to above analysis, it is safe to conclude that the contribution from the $N^*(1535)$ resonance plays an important role in the ϕ-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 ϕ-meson production in pN collisions, and this may indicate a large $s\bar{s}$ component in the quark wave function of the $N^*(1535)$ 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 ϕ-meson production in the $\bar{p}p$ annihilations, the strange hadron loops, such as $K\bar{K}$, $K^*\bar{K}$, and $\Lambda\bar{\Lambda}$ loops, are found to play an important role [27]. It would be interesting to investigate the contribution through $N^*(1535)$ and $\bar{N}^*(1535)$ excitations. For the $\pi N \to \phi N$ reaction, although the total cross sections can be reproduced by the t-channel ρ-meson 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 ρ-meson exchange and the $g_{NN\phi}$ couplings and can be reduced by orders of magnitude within uncertainties of these ingredients. Alternative mechanisms [15,29] with large $N^*(1535)$ contributions can reproduce data perfectly. For the $\gamma p \to \phi p$ reaction, a much larger OZI rule violation for ϕ-meson production was suggested [30–32] with no indications for s-channel resonances above threshold [32]. The t-channel diffractive Pomeron exchange with photon transition to ϕ has been found to play a 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}He. A two-step model [35] underpredicted the total cross section by at least a factor of four, and the reaction dynamics involving the $N^*(1535)$ resonance may be necessary to resolve the ϕ production mechanism in this reaction.

In summary, we have phenomenologically investigated the role of the $N^*(1535)$ resonance in the $pn \to d\phi$ 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 inclusion 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 ϕ mesons maybe a very important origin of the OZI rule violation in the ϕ-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. C **58**, 175 (1993); Z. Weidenauer *et al.*, *ibid.* **59**, 387 (1993); V. G. Ableev *et al.*, Phys. Lett. **B334**, 237 (1994); C. Amsler *et al.*, *ibid.* **B346**, 363 (1995); V. G. Ableev *et al.*, Nucl. Phys. **A585**, 577 (1995); **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, *ibid.* **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. Meisser, Eur. Phys. J. A **27**, 263 (2006); A. Sibirtsev and W. Cassing, *ibid.* **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, *ibid.* **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. **B337**, 245 (1994); K. Tsushima, A. Sibirtsev, and A. W. Thomas, *ibid.* **B390**, 29 (1997); K. Tsushima, A. Sibirtsev, A. W. Thomas, and G. Q. Li, Phys. Rev. C **59**, 369 (1999); **61**, 029903(E) (2000).
[19] A. Sibirtsev and W. Cassing, arXiv:nucl-th/9802019; A. Sibirtsev, K. Tsushima, W. Cassing, and A. W. Thomas, Nucl. Phys. **A646**, 427 (1999).
[20] Ju-Jun Xie, Colin Wilkin, and Bing-Song Zou, Phys. Rev. C **77**, 058202 (2008).
[21] C. Amsler *et al.*, Phys. Lett. **B667**, 1 (2008).
[22] G. Fäldt and C. Wilkin, Phys. Scr. **64**, 427 (2001); Nucl. Phys. **A604**, 441 (1996).
[23] I. Bar-Nir, T. Risser, and M. D. Shuster, Nucl. Phys. **B87**, 109 (1975).
[24] P. Bosted and J. M. Laget, Nucl. Phys. **A296**, 413 (1978).
[25] W. H. Liang, P. N. Shen, J. X. Wang, and B. S. Zou, J. Phys. G **28**, 333 (2002).
[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. A **347**, 281 (1994); D. Buzatu and F. Lev, Phys. Lett. **B329**, 143 (1994); V. Mull, K. Holinde, and J. Speth, *ibid.* **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, *ibid.* **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, and 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).