Near threshold $\eta$ production in the $pp$ collisions

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We study the near threshold $\eta$ meson production in the $pp$ collisions within an effective Lagrangian approach and the isobar model by allowing for the various intermediate nucleon resonances due to the $\pi$, $\eta$, and $\rho$-meson exchanges. It is shown that the $\rho$-meson exchange is the dominant excitation mechanism of these resonances, and the contribution from the $N^*(1720)$ is dominant. The total cross section data can be reasonably reproduced, and the anisotropic angular distributions of the emitted $\eta$ meson are consistent with experimental measurements. Besides, the invariant mass spectra of $pp$ and $p\eta$ explain well the data at excess energy of 15 MeV, and are basically consistent with the data at excess energy of 40 MeV. However, our model calculations can not reasonably account for the two-peak structure in the $p\eta$ distribution at excess energy of 72 MeV, which suggests more complicated mechanism is needed at this energy region.

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I. INTRODUCTION

The meson production reaction in nucleon-nucleon collisions near threshold has the potential to gain new information on hadron properties and has been extensively studied in the context of understanding of the strong interaction in the non-perturbative energy domain in recent years [1]. On the production of the $\eta$ meson, the experimental database in proton-proton scattering near threshold has been expanded significantly. In addition to measurements of the $pp \rightarrow pp\eta$ total cross sections and angular distributions [2–8], there are analyzing powers [9] and full Dalitz plots [10]. Total cross sections are also available for the $pn \rightarrow d\eta$ and $pn \rightarrow pn\eta$ reactions [11–14]. In response to this wealth of data there have been a large number of theoretical investigations of the $\eta$ production in both proton-proton and proton-neutron reactions.
Since the $\eta$ meson couples strongly to the $N^*(1535)$ resonance, the production of the $\eta$ meson in the $NN$ collisions is thought to occur predominantly through the excitation of one of the nucleons to the $N^*(1535)$ resonance. Many theoretical efforts have been done within the framework of meson-exchange models, where the $N^*(1535)$ resonance is excited through the exchange of a single meson, with the $\eta$-meson being formed through the $N^*(1535)$ resonance decay. Contrary to the $N^*(1535)$ dominant interpretation, Peña et al. found the nucleonic currents are important [21]. The possibility of that the $N^*(1520)$ resonance is dominant via the $\rho$ and $\omega$ exchanges while the $N^*(1535)$ contribution is small due to the strong destructive interference among the exchange mesons is also studied [33]. In Ref. [34], the author considered only the final-state-interaction (FSI) enhancement factor and found the measured $pp$ and $\eta p$ effective mass spectra can be well reproduced by allowing for a linear energy dependence in the leading $^3P_0 \to ^1S_0$, s partial wave amplitude.

The large ratio of the production of the $\eta$ in proton-neutron compared to proton-proton collisions suggests that isovector exchange plays the major role [9]. Some authors [15, 22, 27, 32] suggested that pseudoscalar ($\pi$ and $\eta$) exchanges are dominant and there are no significant contribution from the $\rho$. In contrast, others [16, 19, 24, 25, 27] claimed that $\rho$-meson exchange plays an important and possibly dominant role. In Ref. [35], within an effective Lagrangian approach, the author investigated the $N^*(1535)N\rho$ coupling, and found that the value of the coupling constant is strong, which maybe indicate that the $\rho$ meson exchange is important in this reaction.

In Ref. [8], it is suggested that the higher partial waves may be important even at 15.5 MeV. Besides the $N^*(1535)$, the $\rho$ meson may also couple strongly to other higher resonances. The large branching ratio and the small phase space for the $N^*(1720) \to N\rho$ also suggests the $N^*(1720)N\rho$ coupling is strong.

With the inspire of these factors mentioned above, we shall restudy the $pp \to pp\eta$ reaction in an effective Lagrangian approach and the isobar model. The combination of the effective Lagrangian approach and the isobar model turns out to be a good method to study the hadron resonances production in the $\pi N$, $NN$, and $KN$ scattering [22, 32, 33, 35, 40]. In the present work, we assume that the near threshold $\eta$ meson production in proton-proton collisions is through the intermediate $N^*(1535)$, $N^*(1650)$, $N^*(1710)$, $N^*(1720)$, and nucleon pole due to the $\pi$, $\eta$, and $\rho$-meson exchanges. The proton-proton FSI and proton-$\eta$ FSI are also considered.
In the next section, we will present the formalism and ingredients necessary for our estimations, then numerical results and discussions are given in Sect. III. A short summary is given in the last section.

II. FORMALISM AND INGREDIENTS

The basic tree level Feynman diagrams for the $pp \rightarrow pp\eta$ reaction are depicted in Fig. 1.

We use the commonly used interaction Lagrangians for the $\pi NN$, $\eta NN$ and $\rho NN$ couplings,

$$L_{\pi NN} = -ig_{\pi NN}\bar{\psi}_N\gamma_5 \vec{\tau} \cdot \vec{\pi} \psi_N,$$

$$L_{\eta NN} = -ig_{\eta NN}\bar{\psi}_N\gamma_5 \eta \psi_N,$$

$$L_{\rho NN} = -g_{\rho NN}\bar{\psi}_N(\gamma_\mu + \frac{\kappa}{2m_N}\sigma_{\mu\nu}\partial^\nu)\vec{\tau} \cdot \vec{\rho} \psi_N.$$

At each vertex a relevant off-shell form factor is used. In our calculation, we take the same form factors as that used in the well-known Bonn potential model [41–43]:

$$F^{NN}_M (k_M^2) = \left(\frac{\Lambda^2_M - m^2_M}{\Lambda^2_M - k^2_M}\right)^n,$$

with $n=1$ for the $\pi^0$ and $\eta$-meson; $n=2$ for the $\rho^0$-meson. $k_M$, $m_M$, and $\Lambda_M$ are the 4-momentum, mass, and cut-off parameter for the exchanged-meson ($M$), respectively. The coupling constants are taken as [36, 37, 41–48]: $g_{\pi NN}^2/4\pi = 14.4$, $g_{\eta NN}^2/4\pi = 0.4$, $g_{\rho NN}^2/4\pi = 0.9$, and $\kappa = 6.1$.

We use the cutoff parameters $\Lambda_\pi = \Lambda_\eta = 0.8$ GeV, and $\Lambda_\rho = 1.85$ GeV [36, 37].
To calculate the invariant amplitudes of the diagrams in the Fig. we also need the interaction Lagrangians involving the nucleon resonances. In Ref. [49], a Lorentz covariant orbital-spin (L-S) scheme for the $N^*NM$ couplings has been illustrated in detail. With this scheme, we can easily write the effective $N^*N\pi$, $N^*N\eta$, and $N^*N\rho$ couplings,

$$\mathcal{L}_{\pi N N^*}(1535) = ig_{\pi N N^*}(1535) \overline{\psi}_N \gamma^5 \vec{p} \psi_{N^*}(1535) + h.c.,$$ (5)

$$\mathcal{L}_{\eta N N^*}(1535) = ig_{\eta N N^*}(1535) \overline{\psi}_N \eta \psi_{N^*}(1535) + h.c.,$$ (6)

$$\mathcal{L}_{\rho N N^*}(1535) = ig_{\rho N N^*}(1535) \overline{\psi}_N \gamma^5 (\gamma_\mu - \frac{q_\mu}{q^2}) \vec{p} \cdot \vec{\rho}(p_\rho) \psi_{N^*}(1535) + h.c.,$$ (7)

$$\mathcal{L}_{\pi N N^*}(1650) = ig_{\pi N N^*}(1650) \overline{\psi}_N \vec{p} \cdot \vec{\pi} \psi_{N^*}(1650) + h.c.,$$ (8)

$$\mathcal{L}_{\eta N N^*}(1650) = ig_{\eta N N^*}(1650) \overline{\psi}_N \eta \psi_{N^*}(1650) + h.c.,$$ (9)

$$\mathcal{L}_{\rho N N^*}(1650) = ig_{\rho N N^*}(1650) \overline{\psi}_N \gamma^5 (\gamma_\mu - \frac{q_\mu}{q^2}) \vec{p} \cdot \vec{\rho}(p_\rho) \psi_{N^*}(1650) + h.c.,$$ (10)

$$\mathcal{L}_{\pi N N^*}(1710) = -ig_{\pi N N^*}(1710) \overline{\psi}_N \gamma^5 \vec{p} \cdot \vec{\pi} \psi_{N^*}(1710) + h.c.,$$ (11)

$$\mathcal{L}_{\eta N N^*}(1710) = -ig_{\eta N N^*}(1710) \overline{\psi}_N \gamma^5 \eta \psi_{N^*}(1710) + h.c.,$$ (12)

$$\mathcal{L}_{\rho N N^*}(1710) = -g_{\rho N N^*}(1710) \overline{\psi}_N \gamma^5 (\gamma_\mu + \frac{k_\mu}{2m_N}) \sigma_{\mu\nu} \vec{\rho} \cdot \vec{\pi} \psi_{N^*}(1710) + h.c.,$$ (13)

$$\mathcal{L}_{\pi N N^*}(1720) = g_{\pi N N^*}(1720) \overline{\psi}_N \gamma^5 \vec{p} \cdot \vec{\rho}(p_\rho) \psi_{N^*}(1720) + h.c.,$$ (14)

$$\mathcal{L}_{\eta N N^*}(1720) = g_{\eta N N^*}(1720) \overline{\psi}_N \gamma^5 \eta \psi_{N^*}(1720) + h.c.,$$ (15)

$$\mathcal{L}_{\rho N N^*}(1720) = g_{\rho N N^*}(1720) \overline{\psi}_N \gamma^5 \vec{p} \cdot \vec{\rho}(p_\rho) \psi_{N^*}(1720) + h.c.,$$ (16)

The monopole form factors for the $N^*-N$-Meson vertexes are used,

$$F_{M}(N^* N) = \frac{\Lambda^2 - m^2}{\Lambda^2 - k_M^2}.$$ (17)

The $N^*NM$ coupling constants can be determined from the experimentally observed partial decay widths of nucleon resonances. With the effective Lagrangians described above, the coupling constants of the $N^*N\pi$ and $N^*N\eta$ can be calculated straightforwardly. For the $N^*N\rho$ coupling constants, we get them from the partial decay widths $\Gamma_{N^*\rightarrow N\rho\rightarrow N\pi}$ if the $N^*$ resonance is below the threshold (More details can be found in Ref. [36, 37]). All the coupling constants and cut-off parameters are listed in Table II.

The form factors for the nucleon pole and $N^*$ resonances, $F_N(q^2)$ and $F_{N^*}(q^2)$, similar as in Refs. [52, 53], are introduced to describe the off-shell properties of the amplitudes,

$$F_N(q^2) = \frac{A^2_N}{\Lambda^2_N + (q^2 - m^2_N)^2},$$ (18)
TABLE I: Relevant parameters of the resonances used in our calculation. The widths and branching ratios are taken from the PDG [50].

| Resonance Width(GeV) | Decay channel | Branching ratios | $g^2/4\pi$ | Cut-off(GeV) |
|----------------------|---------------|------------------|-------------|--------------|
| $N^*(1535)$ 0.15     | $N\pi$        | 0.45             | 0.037       | 0.8          |
|                     | $N\eta$       | 0.42             | 0.28        | 0.8          |
|                     | $N\rho$       | 0.02             | 5.55        | 0.8          |
| $N^*(1650)$ 0.15     | $N\pi$        | 0.70             | 0.052       | 1.5          |
|                     | $N\eta$       | 0.10             | 0.036       | 1.5          |
|                     | $N\rho$       | 0.01             | 0.0064      | 1.5          |
| $N^*(1710)$ 0.1      | $N\pi$        | 0.125            | 0.072       | 1.5          |
|                     | $N\eta$       | 0.20             | 0.97        | 1.5          |
|                     | $N\rho$       | 0.15             | 0.019       | 1.5          |
| $N^*(1720)$ 0.25     | $N\pi$        | 0.11             | 0.11        | 1.5          |
|                     | $N\eta$       | 0.04             | 0.35        | 1.5          |
|                     | $N\rho$       | 0.775            | 635.11      | 1.5          |

\[
F_{N^*}(q^2) = \frac{\Lambda_{N^*}^4}{\Lambda_{N^*}^4 + (q^2 - M_{N^*}^2)^2}, \tag{19}
\]

with $\Lambda_N = 1.0\ GeV$ and $\Lambda_{N^*} = 2.0\ GeV$.

The meson propagators used in our calculation are:

\[
G_{\pi/\eta}(k_{\pi/\eta}) = \frac{i}{k_{\pi/\eta}^2 - m_{\pi/\eta}^2}, \tag{20}
\]

\[
G_{\rho}^{\mu\nu}(k_{\rho}) = -i\left(\frac{g^{\mu\nu} - k_{\mu}k_{\rho}/k_{\rho}^2}{k_{\rho}^2 - m_{\rho}^2}\right). \tag{21}
\]

The propagators of the $N^*$ resonances can be written as

\[
G_{N^*}(q) = \frac{q + M_{N^*}}{q^2 - M_{N^*}^2 + iM_{N^*}\Gamma_{N^*}}, \tag{22}
\]

for spin-$\frac{1}{2}$ resonances, and

\[
G_{N^*}^{\mu\nu}(q) = \frac{-P_{\mu\nu}(q)}{q^2 - M_{N^*}^2 + iM_{N^*}\Gamma_{N^*}}, \tag{23}
\]

with

\[
P_{\mu\nu}(q) = -(q + M_{N^*}) \left[ g_{\mu\nu} - \frac{1}{3}\gamma_{\mu}\gamma_{\nu} - \frac{1}{3M_{N^*}}(\gamma_{\mu}q_{\nu} - \gamma_{\nu}q_{\mu}) - \frac{2}{3M_{N^*}^2}q_{\mu}q_{\nu} \right], \tag{24}
\]
for spin-$\frac{3}{2}$ resonances.

As usual, for the $N^∗(1535)$ resonance, the energy-dependent total width $\Gamma_{N^∗(1535)}(s)$ is employed in Eq. (22) [54]. According to the PDG [50], the dominant decay channels for the $N^∗(1535)$ resonance are $\pi N$ and $\eta N$, so we take

$$\Gamma_{N^∗(1535)}(s) = \Gamma_{N^∗(1535)→\pi N} + \Gamma_{N^∗(1535)→\eta N},$$

(25)

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

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

(26)

For the $pp→pp\eta$ reaction, the full invariant amplitude for the nucleon pole or $N^*$ resonances in our calculation is

$$\mathcal{M}^{N/N^*} = \sum_{i=\pi, \eta, \rho} \mathcal{M}_i^{N/N^*},$$

(27)

$$\mathcal{M}_i^{N/N^*} = \sum_{j=a, b, c, d} \eta_j \mathcal{M}_{i,j}^{N/N^*},$$

(28)

where $\eta_a = \eta_d = 1$ and $\eta_b = \eta_c = -1$. The interference terms between different resonances are ignored.

Each amplitude can be obtained straightforwardly with the effective couplings and following the Feynman rules. Here we give explicitly the amplitude $\mathcal{M}_i^{N^∗(1535)}$, as an example,

$$\mathcal{M}_i^{N^∗(1535)} = g_{\pi NN}g_{\pi N^∗(1535)}g_{\eta NN^∗(1535)}F_{\pi}^N(k_\pi^2)F_{\pi}^{N^∗(1535)N}(k_\pi^2)F_{N^∗(1535)}(q^2) \times G_{\pi}(k_\pi)\bar{u}(p_3, s_3)\gamma_5u(p_2, s_2)\bar{u}(p_4, s_4)G_{N^∗(1535)}(q)u(p_1, s_1),$$

(29)

where $s_i$ ($i = 1, 2, 3, 4$) and $p_i$ ($i = 1, 2, 3, 4$) represent the spin projection and 4-momenta of the two initial and two final protons, respectively.

The FSI enhancement factor in the di-proton state is taken into account by means of the general framework based on the Jost function formalism with

$$F_{pp}(k) = |J(k)|^{-1} = \frac{k + i\beta}{k - i\alpha},$$

(30)

where $k$ is the internal momentum of $pp$ subsystem, and the parameters $\alpha = 0.1$ fm$^{-1}$ and $\beta = 0.5$ fm$^{-1}$ are used as [53]. For the $p\eta$ FSI, we use the formalism in the scattering length approximation,

$$F_{pp}(k_{pp}) = \frac{1}{1 - ik_{pp}\alpha},$$

(31)
where the parameter $a$ is an effective scattering length. It is taken as $a = (0.487 + i 0.171)\text{fm}$ in the present calculation.

The overall final state interaction is therefore the product of these enhancements:

$$ F_{FSI} = F_{pp}(k) \times F_{np}(k_{np1}) \times F_{np}(k_{np2}), $$

(32)

Then the calculations of the differential and total cross sections are straightforward,

$$ d\sigma(pp \rightarrow pp\eta) = \frac{1}{4} \frac{m_{p}^{2}}{F} \sum_{s_i} \sum_{s_f} |M|^{2} \frac{m_{p}d^{3}p_{3}m_{p}d^{3}p_{4}d^{3}p_{5}}{E_{3}E_{4}2E_{5}2} \delta^{4}(p_{1} + p_{2} - p_{3} - p_{4} - p_{5}), $$

(33)

with the flux factor

$$ F = (2\pi)^{5} \sqrt{(p_{1} \cdot p_{2})^{2} - m_{p}^{4}}. $$

(34)

The factor $\frac{1}{2}$ before the $\delta$ function in Eq. (33) comes from the two identical protons in the final states.

III. NUMERICAL RESULTS AND DISCUSSIONS

With the formalism and ingredients given above, for the $pp \rightarrow pp\eta$ reaction, the total cross section versus excess energy $\varepsilon$ up to 80 MeV, the invariant mass spectra, angular distributions, and Dalitz Plot at excess energy $\varepsilon = 15, 40, \text{and } 72 \text{ MeV}$ are calculated by using a Monte Carlo multi-particle phase space integration program.

The total cross section is shown in Fig. 2 together with the experimental data. Our results fairly agree with the experimental data. From Fig. 2, one can see that the contribution from the t-channel $\rho$ and $\pi$-meson exchanges are important and the $\rho$ exchange plays the dominant role, but the contribution from the $\eta$-meson exchange is negligible. Fig. 2 also shows that the contributions from the $N^*(1720)$ and $N^*(1535)$ are important and the $N^*(1720)$ plays the dominant role. The contribution of the $N^*(1535)$ is smaller than that of the $N^*(1720)$ due to the strong destructive interference among the exchange mesons, which is similar with the result of Ref. [33]. The contributions from the $N^*(1650)$ and $N^*(1710)$ can be negligible.

The invariant mass spectra, angular distributions, and Dalitz Plot at excess energy $\varepsilon = 15 \text{ MeV}$ are shown in Fig. 3 together with experimental data. The measured $pp$ and $p\eta$ invariant mass spectra and the angular distribution of $\eta$ can be well reproduced. From Fig. 3 (a) and (d), one can see that the $pp$ FSI plays an important role.
FIG. 2: Total cross sections vs excess energies $\varepsilon$ for the $pp \rightarrow ppm$ reaction from present calculation (solid curves) are compared with experimental data [2, 17, 56–59]. (a): The dashed, dotted, and dashed-dotted lines stand for contributions from the $\pi$, $\rho$, and $\eta$-meson exchanges, respectively. (b): The dashed, dotted, short-dotted, dashed-dotted, and dot-short-dashed lines stand for contributions from the $N$, $N^*(1535)$, $N^*(1650)$, $N^*(1710)$, and $N^*(1720)$, respectively.

The invariant mass spectra, angular distributions, and Dalitz Plot at excess energy $\varepsilon = 40$ MeV as well as the experimental data are shown in Fig. 4. For the invariant mass spectra of proton-proton and proton-$\eta$, the theoretical results are in agreement with the experimental data except for those near threshold of proton-proton (proton-$\eta$). This small discrepancy indicates the $pp$ FSI used in our calculation may be somewhat strong at this region.

For the angular distribution of the emitted $\eta$ meson in the overall c.m. frame, there are two groups of data which do not agree with each other [8, 57]. One is isotropic [57], while the other is anisotropic [8], as shown in Fig. 4 (c). Our result indicates that the angular distribution of the $\eta$ meson is anisotropic, consistent with the data from Ref. [8]. As pointed out by Ref. [8, 17, 58], the anisotropy is probably due to a mainly destructive interference between the dominant $\rho$ exchange and $\pi$ exchange. It is interesting to point out that the $N^*(1535)$ dominant interpretations [22, 28, 60] give almost isotropic angular distribution of the $\eta$ at this region except for that the Ref. [27] gives the anisotropic angular distribution of the $\eta$ by allowing for the contributions from baryonic and mesonic currents.

The invariant mass spectra, angular distributions, and Dalitz Plot at excess energy $\varepsilon = 72$ MeV as well as the experimental data are shown in Fig. 5. The experimental data shown in
FIG. 3: Differential cross sections (solid lines) and the Dalitz Plot for the $pp \rightarrow pp\eta$ reaction at the excess energy of $\varepsilon = 15$ MeV compared with the experimental data [56, 57] and phase space distribution (dashed lines). (a): Distribution of the square of the proton-proton invariant mass; (b): Distribution of the square of the proton-\eta invariant mass; (c): Angular distribution of the emitted \eta meson in the c.m frame of the total system; (d): Dalitz Plot.

Fig. 5 (a) indicate the $pp$ FSI should be rather weak, so the $pp$ FSI is ignored at this energy region. This rough procedure has been used in the double-pion production in nucleon-nucleon collisions and the results turn out to be considerably improved [61]. Our $pp$ invariant mass spectrum can reasonably account for the data.

The two-peak structure in the proton-$\eta$ distribution can not be reproduced in our calculation which is similar with the result from Ref. [33]. This suggests that the structure in the $p\eta$ distribution can not be simply interpreted by the $N^*(1535)$, $N^*(1650)$, $N^*(1710)$, and $N^*(1720)$
resonances, and more complicated mechanism is strongly called for.

Our angular distribution of the $\eta$ at $\varepsilon = 72$ MeV again indicates that the $\eta$ distribution is anisotropic, consistent with the data from Ref. [8]. To our knowledge, there is as yet no theoretical paper for addressing the angular distribution of $\eta$ at this region. It is noted that a preliminary experimental results about the behavior of the $\eta$ meson angular distribution at excess energy 57 MeV [62] are consistent with that of Ref. [8] at excess energy 72 MeV.
FIG. 5: The notations are same as that used in Fig. 3 but at the excess energy of $\varepsilon = 72$ MeV, and the $pp$ FSI is ignored. Experimental data are taken from Ref. [8].

IV. SUMMARY AND CONCLUSION

In this paper we have calculated the $pp \rightarrow pp\eta$ reaction within an effective Lagrangian approach and the isobar model. Our model calculations can reasonably reproduce the total cross sections up to excess energy 80 MeV.

It is shown that for the $pp \rightarrow pp\eta$ reaction, the contribution of the $\rho$-meson exchange is larger than that of the the $\pi$ exchange, and the contribution of the $N^*(1720)$ is larger than that of the $N^*(1535)$.

Also, the same cut off parameters for the $N^*(1650)$, $N^*(1710)$, and $N^*(1720)$ resonances are used, which is suitable to investigate the relative contributions of the $N^*(1650)$, $N^*(1710)$, and
$N^*(1720)$ resonances. Our results show that the contributions from the $N^*(1650)$ and $N^*(1710)$ are negligible.

Our calculations can reasonably explain the measured $pp$ and $p\eta$ invariant mass spectra at excess energy 15 and 40 MeV, but fail to explain the two-peak structure in the proton-$\eta$ distribution at excess energy 72 MeV, which suggests at this energy region, more complicated mechanism is needed.

We give the anisotropic angular distribution of the $\eta$ at $\varepsilon = 40$ and 72 MeV, consistent with the data from Ref. [8]. This favors the interpretation that the interference between the $\rho$ exchange and $\pi$ exchange is mainly destructive.

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[1] C. Hanhart, Phys. Rept. **397**, 155 (2004).
[2] A. M. Bergdolt *et al.*, Phys. Rev. D **48**, R2969 (1993).
[3] E. Chiavassa *et al.*, Phys. Lett. B **322**, 270 (1994).
[4] H. Calén *et al.*, Phys. Lett. B **366**, 39 (1996).
[5] F. Hibou *et al.*, Phys. Lett. B **438**, 41 (1998).
[6] J. Smyrski *et al.*, Phys. Lett. B **474**, 182 (2000).
[7] G. Agakishiev *et al.*, Eur. Phys. J. A **48**, 74 (2012).
[8] H. Petrén *et al.*, Phys. Rev. C **82**, 055206 (2010).
[9] R. Czyżykiewicz *et al.*, Phys. Rev. Lett. **98**, 122003 (2007).
[10] C. Pauly, Ph. D. thesis, University of Hamburg (2006).
[11] H. Calén *et al.*, Phys. Rev. Lett. **79**, 2642 (1997).
[12] H. Calén *et al.*, Phys. Rev. C **58**, 2667 (1998).
[13] H. Calén *et al.*, Phys. Rev. Lett. **80**, 2069 (1998).
[14] P. Moskal *et al.*, Phys. Rev. C **79**, 015208 (2009).
[15] M. Batinić, A. Svare, and T.-S. H. Lee, Physica Scripta, **56**, 321 (1997).
[16] A. Moalem, E. Gedalin, L. Razdolskaya, and Z. Shorer, Nucl. Phys. A **600**, 445 (1996).
[17] J. F. Germond and C. Wilkin, Nucl. Phys. A 518, 308 (1990).
[18] J. M. Laget, F. Wellers, and J. F. Lecolley, Phys. Lett. B 257, 254 (1991).
[19] T. Vetter, A. Engel, T. Biró, and U. Mosel, Phys. Lett. B 263, 153 (1991).
[20] B. L. Alvaredo and E. Oset, Phys. Lett. B 324, 125 (1994).
[21] M. T. Pena, H. Garcilazo, and D. O. Riska, Nucl. Phys. A 683, 322 (2001).
[22] R. Shyam, Phys. Rev. C 75, 055201 (2007).
[23] E. Gedalin, A. Moalem, and L. Razdolskaya, Nucl. Phys. A 634, 368 (1998).
[24] A. B. Santra and B. K. Jain, Nucl. Phys. A 634, 309 (1998).
[25] G. Fäldt and C. Wilkin, Physica Scripta, 64, 427 (2001).
[26] V. Varu et al., Phys. Rev. C 67, 024002 (2003).
[27] K. Nakayama, J. Speth, and T.-S. H. Lee, Phys. Rev. C 65, 045210 (2002).
[28] K. Nakayama, J. Haidenbauer, C. Hanhart, and J. Speth, Phys. Rev. C 68, 045201 (2003).
[29] V. Bernard, N. Kaiser, and Ulf-G. Meissner, Eur. Phys. J. A 4, 259 (1999).
[30] P. Moskal, M. Wolke, A. Khoukaz, and W. Oelert, Prog. Part. Nucl. Phys. 49, 1 (2002).
[31] D. O. Riska and G. Brown, Nucl. Phys. A 679, 577 (2001).
[32] X. Cao and X. G. Lee, Phys. Rev. C 78, 035207 (2008).
[33] K. Nakayama, Y. Oh, and H. Haberzettl, J. Korean Phys. Soc. 59, 224 (2011).
[34] A. Deloff, Phys. Rev. C 69, 035206 (2004).
[35] J. J. Xie, C. Wilkin, and B. S. Zou, Phys. Rev. C 77, 058202 (2008).
[36] J. J. Xie and B. S. Zou, Phys. Lett. B 649, 405 (2007).
[37] J. J. Xie, B. S. Zou, and H. Q. Chaing, Phys. Rev. C 77, 015206 (2008).
[38] Q. F. Lü, X. H. Liu, J. J. Xie, and D. M. Li, Mod. Phys. Lett. A 29, 1450012 (2014).
[39] Q. F. Lü, J. J. Xie, and D. M. Li, Phys. Rev. C 90, 034002 (2014).
[40] Q. F. Lü, R. Wang, J. J. Xie, X. R. Chen, and D. M. Li, [arXiv:1412.6272]
[41] R. Machleidt, K. Holinde, and C. Elster, Phys. Rep. 149, 1 (1987).
[42] R. Machleidt, Adv. Nucl. Phys. 19, 189 (1989).
[43] R. Brockmann and R. Machleidt, Phys. Rev. C 42, 1965 (1990).
[44] K. Tsushima, S. W. Huang, and A. Faessler, Phys. Lett. B 337, 245 (1994).
[45] K. Tsushima, A. Sibirtsev, and A. W. Thomas, Phys. Lett. B 39, 29 (1997).
[46] K. Tsushima, A. Sibirtsev, A. W. Thomas, and G. Q. Li, Phys. Rev. C 59, 369 (1999), Erratum-ibid. C 61, 029903 (2000).
[47] A. Sibirtsev and W. Cassing, nucl-th/9802019.
[48] A. Sibirtsev, K. Tsushima, W. Cassing, and A. W. Thomas, Nucl. Phys. A 646, 427 (1999).
[49] B. S. Zou and F. Hussain, Phys. Rev. C 67, 015204 (2003).
[50] K. A. Olive et al. (Particle Data Group), Chin. Phys. C 38, 090001 (2014).
[51] G. Penner and U. Mosel, Phys. Rev. C 66, 055211 (2002); ibid. C 66, 055212 (2002);
    V. Shklyar, H. Lenske and U. Mosel, Phys. Rev. C 72, 015210 (2005).
[52] T. Feuster and U. Mosel, Phys. Rev. C 58, 457 (1998).
[53] T. Feuster and U. Mosel, Phys. Rev. C 59, 460 (1999).
[54] W. H. Liang, P. N. Shen, J. X. Wang, and B. S. Zou, J. Phys. G 28, 333 (2002).
[55] Y. Maeda et al., Phys. Rev. C 77, 015204 (2008).
[56] P. Moskal et al., Phys. Rev. C 69, 025203 (2004).
[57] M. Abdel-Bary et al., Eur. Phys. J. A 16, 127 (2003).
[58] H. Calen et al., Phys. Lett. B 458, 190 (1999).
[59] F. Balestra et al., Phys. Rev. C 69, 064003 (2004).
[60] A. Fix and H. Arenhoevel, Phys. Rev. C 69, 014001 (2004).
[61] X. Cao, B. S. Zou, and H. S. Xu, Phys. Rev. C 81, 065201 (2010).
[62] N. Shah [WASA-at-COSY Collaboration], AIP Conf. Proc. 1374, 402 (2011).