Possible molecular states from $N\Delta$ interaction

Zhi-Tao Lu, Han-Yu Jiang, Jun He∗
Department of Physics and Institute of Theoretical Physics,
Nanjing Normal University, Nanjing 210097, People’s Republic of China
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Recently, a hint for dibaryon $N\Delta(D_{21})$ was observed at WASA-AT-COSY with a mass about $30 \pm 10$ MeV below the $N\Delta$ threshold. It has a relatively small binding energy compared with the $d^*(2380)$ and a width close to the width of the $\Delta$ baryon, which suggests that it may be a dibaryon in a molecular state picture. In this work, we study the possible S-wave molecular states from the $N\Delta$ interaction within the quasipotential Bethe-Salpeter equation approach. The interaction is described by exchanging $\pi$, $p$, and $\omega$ mesons. With reasonable parameter, a $D_{21}$ bound state can be produced from the interaction. Another two bound states, $D_{12}$ and $D_{22}$, can also be produced with smaller binding energy with the same parameter. The $\pi$ exchange is found to play a most important role to bind two baryons to form the molecular states. Experimental search for the $N\Delta(D_{12})$ and $N\Delta(D_{22})$ states will be helpful to understanding the hint of the dibaryon $N\Delta(D_{21})$.

I. INTRODUCTION

In the past two decades, the study of exotic hadrons becomes one of the most important topics in the community of hadron physics. The core issue of the hadron physics is to understand how quarks combine into a hadron. In the conventional quark model, a hadron is composed of $q\bar{q}$ as a meson or $qqq$ as a baryon. It is natural to expect the existence of hadrons composed of more quarks, which are called exotic states. The deuteron can be also seen as a hadron, which is a quark system with six quarks, though we called it a nucleus. The existence of the nucleus and the hypernucleus inspires us to search for molecular states as loosely bound states of hadrons. Such a picture has been widely applied to interpret the experimentally observed XYZ particles and the hidden-charm pentaquarks $P_c$. More and more structures observed near thresholds of two hadrons give people more confidence about the existence of molecular states. If we turn back to the deuteron, which is a molecular state, it is interesting to study possible molecular states composed of two nucleons and/or its resonances, such as systems $N\Delta$ and $\Delta\Delta$.

The hadron carrying baryon number $B = 2$ is called dibaryon. The history of the study of dibaryons is even much longer than that of the XYZ particles. Dyson and Xueong first predicted dibaryon states in 1964 based on the SU(6) symmetry [15] almost at the same time of the proposal of the quark model. With a simple mass formula, the mass of deuteron was obtained at 1876 MeV, and the masses of dibaryon $\Delta\Delta(D_{03,30})$ and of dibaryon $N\Delta(D_{12,21})$ were predicted as 2376 and 2176 MeV, respectively. After observing an experimental hint in 1977 [16], Kamae and Fujita made a calculation in the one-boson-exchange model at hadronic level to reproduce an anomaly at 2380 MeV in the process $\gamma d \rightarrow pn$ [17]. The existence of the $\Delta\Delta(D_{03})$ was supported by many theoretical calculations especially the constituent quark model [18–21]. The $N\Delta(D_{12})$ was also predicted in the literature [22–24]. The existence of $N\Delta(D_{12})$ state was favored by some early analyses of experimental data, such as partial-wave analysis of the reaction $\pi^+d \rightarrow pp$ [25], an analyses of $pp$ and $np$ scatterings by the SAID group [26], and a study of the phase shifts for the $N\Delta$ scattering with a nearby S-matrix pole based on the data of process $pp \rightarrow npn^*$ [27]. However, the $N\Delta(D_{21})$ was not supported by the early calculation in the constituent quark model [24, 28, 29].

After the efforts of more than half a century in both theoretical and experimental sides[16–34], a candidate of dibaryon with $I(J^P) = 0(3^+)$ carrying a mass of about 2370 MeV and a width of about 70 MeV was observed in the process $pp \rightarrow d\pi^0\pi^0$ at WASA-at-COSY [35], denoted as $d^*(2380)$. Later, a series of measurements confirmed the existence of this state [36–38]. Such state was also confirmed by a recent measurement within the Crystal Ball at MAMI, where the photoproduction process was performed [39]. The observation of the $d^*(2380)$ attracts much attention of theorists, and a large amount of interpretations were proposed to understand its properties and internal structure [40–52].

Because the $\Delta$ signal can be found in the final states of its decay, one may guess that it is a $\Delta\Delta$ bound state. However, such assumption leads to a binding energy about 80 MeV considering the mass of $\Delta$ baryon is about 1232 MeV. Such large binding energy prefers a compact hexaquark instead of a bound state of two $\Delta$ baryons. The conclusion is further supported by the relatively smaller width of 70 MeV of the $d^*(2380)$, which is even smaller than the width of one $\Delta$ baryon, about 120 MeV. Gal and Garciat, proposed that the $d^*(2380)$ is from a three-body $NN\pi$ system with a Faddeev equation calculation [40, 41]. In their study, the $N\Delta(D_{12,21})$ was also studied in the three-body $NN\pi$ interaction and found slightly below the $N\Delta$ threshold. Recently, an isotensor dibaryon $N\Delta$ with quantum numbers $I^P = 1^+(D_{21})$ with a mass of 2140(10) MeV and a width of 110(10) MeV was reported at WASA-at-COSY [53]. Its mass is about $30 \pm 10$ MeV below the $N\Delta$ threshold. Considering that the width of nucleon is zero (for proton) or very small (for neutron) and the $\Delta$ baryon has a width of about 120 MeV, the width of this $N\Delta(D_{21})$ state is almost the sum that of nucleon and $\Delta$ baryon. Hence, compared with the $d^*(2380)$, such state is obviously consistent with the molecular state picture. In Ref. [54], the author studied the $N\Delta$ states in the constituent quark model, and found that it is less likely for

*Electronic address: Corresponding author: junhe@njnu.edu.cn
in the quasipotential Bethe-Salpeter equation (qBSE) to find S-wave bound states from the $N\Delta$ interaction.

The paper is organized as follows. After the introduction, we present the effective Lagrangians and relevant coupling constants to describe the $N\Delta$ interaction, with which we deduce the potential. And the qBSE is also briefly introduced. In Sec. III, we will present the numerical results, and the contributions from different exchanges and diagrams are also discussed. Finally, the article ends with a summary in Sec. IV.

II. THEORETICAL FRAMEWORK

In the current work, we will describe the $N\Delta$ interaction in the one-boson-exchange model, in which the interaction is usually mediated by the exchange of the light mesons including pseudoscalar mesons ($\pi$ and $\eta$), vector mesons ($\rho$, $\omega$, and $\phi$) and scalar meson $\sigma$. The coupling of $\eta$ meson and nucleon is small [55–62], and the coupling of the $\phi$ meson and nucleon is suppressed according to the OZI rule. Besides, we do not consider the scalar meson exchange as done in Refs. [63, 64]. Hence, we only consider the exchanges of $\pi$, $\rho$, and $\omega$ mesons in the calculation. There are two diagrams for the $N\Delta$ interaction as shown in Fig. 1. In the cross diagram, the $\omega$ exchange is forbidden due to the conservation of the isospin.

![Fig. 1: The diagrams for the direct (left) and cross (right) potentials. The thin (brown) and thick (blue) lines are for $N$ and $\Delta$ mesons, respectively. The $I^{i(0)}_\pi$ is the flavor factor for direct or cross diagram with $i$ exchange, which is explained in text.](image)

We need the Lagrangians for the vertices of nucleon, $\Delta$ baryon, and pseudoscalar meson $\pi$, which is written as [63, 64]

\[
\mathcal{L}_{NN\pi} = -\frac{g_{NN\pi}}{m_\pi} N \gamma^\mu \gamma^5 \tau \cdot \partial_\mu \pi N, \\
\mathcal{L}_{N\Delta\pi} = \frac{g_{N\Delta\pi}}{m_\pi} \bar{\Delta}_\tau \gamma^\mu \gamma^5 \gamma^\nu \tau \cdot \partial_\nu \Delta \mu', \\
\mathcal{L}_{N\pi\pi} = \frac{g_{N\pi\pi}}{m_\pi} \bar{\Delta} \gamma^\nu \gamma^5 \gamma^\mu \partial_\nu \pi N + \text{H.c.},
\]

where the $N$, $\Delta$, and $\pi$ are nucleon, $\Delta$ baryon, and pion meson fields. The coupling constants $g_{NN\pi}^2/4\pi = 0.08$, $g_{N\Delta\pi} = 1.78$, and $g_{N\pi\pi} = -2.049$, which were obtained from fitting the experimental data in Refs. [63–65].

The Lagrangians for the vertices of nucleon, $\Delta$ baryon, and vector meson $\rho/\omega$ are written as [63, 64],

\[
\mathcal{L}_{NN\rho} = -g_{NN\rho} \bar{N} [\gamma^\mu - \frac{g_\rho}{2m_N} \sigma^{\mu\nu} \partial_\nu] \rho_\mu N, \\
\mathcal{L}_{NN\omega} = -g_{NN\omega} \bar{N} [\gamma^\mu - \frac{g_\omega}{2m_N} \sigma^{\mu\nu} \partial_\nu] \omega_\mu N, \\
\mathcal{L}_{N\Delta\rho} = -g_{N\Delta\rho} \bar{\Delta} \gamma^\mu \frac{-2m_N g_{N\rho}}{m_\Delta} \rho_\mu \cdot T \Delta^\tau, \\
\mathcal{L}_{N\Delta\omega} = -g_{N\Delta\omega} \bar{\Delta} \gamma^\mu \frac{-2m_N g_{N\omega}}{m_\Delta} \omega_\mu \cdot T \Delta^\tau, \\
\mathcal{L}_{N\rho\rho} = -\frac{g_{\rho\rho}}{m_\rho} \bar{\Delta} \gamma^\nu \gamma^5 \gamma^\mu S^\dagger \cdot \rho_\mu N + \text{H.c.},
\]

where $\rho_\mu = \partial_\mu \rho - \frac{1}{2m_\rho} \Gamma_{\mu\nu\rho} \partial_\nu$, and $\rho$ and $\omega$ denotes the $\rho$ or $\omega$ meson field. The coupling constants $g_{NN\rho} = -3.1$, $g_{N\Delta\rho} = 4.3$, $g_{NN\omega} = -6.08$, $g_{N\Delta\omega} = 1.825$, $g_{N\rho} = 0$, $g_{N\Delta\rho} = 6.1$, cited from Refs. [63–65]. The coupling constants for $\omega$ meson can be related to these $\rho$ meson with SU(3) symmetry as $g_{NN\omega} = 3g_{NN\rho}$, $g_{N\Delta\omega} = 3/2g_{N\Delta\rho}$, and $g_{N\rho} = g_{N\Delta\rho}$. Besides, the $T$ and the $S$ matrices are provided as follows,

\[
T \cdot \varphi = \sqrt{\frac{4}{15}} \begin{pmatrix} \sqrt{\frac{3}{5}} \varphi^0 & \sqrt{\frac{3}{5}} \varphi^+ & 0 \\ \sqrt{\frac{3}{5}} \varphi^- & \sqrt{\frac{1}{5}} \varphi^0 & \sqrt{2} \varphi^+ \\ 0 & \sqrt{\frac{1}{5}} \varphi^- & -\frac{\sqrt{2}}{5} \varphi^0 \end{pmatrix}, \tag{5}
\]

\[
S \cdot \varphi = \begin{pmatrix} -\varphi^- & \sqrt{\frac{3}{5}} \varphi^0 & \sqrt{\frac{3}{5}} \varphi^+ \\ \sqrt{\frac{3}{5}} \varphi^- & \sqrt{\frac{1}{5}} \varphi^0 & \sqrt{2} \varphi^+ \\ 0 & -\sqrt{\frac{1}{5}} \varphi^- & \frac{\sqrt{2}}{5} \varphi^0 \end{pmatrix}, \tag{6}
\]

where $\phi = \pi$ or $\rho$, and the +, −, and 0 denote the charges of the mesons.

Using the Lagrangians above, the potential of the $N\Delta$ interaction can be constructed as,

\[
\mathcal{V}_{\pi}^d = I_{\pi} \frac{g_{NN\pi} g_{N\Delta\pi}}{m_\pi^2} \bar{u}(k'_1) \gamma^\nu \gamma^5 (\gamma^\mu - \frac{g_\rho}{2m_N} \sigma^{\mu\nu} \partial_\nu) q_\mu u(k_1), \tag{7}
\]

\[
\mathcal{V}_{\rho}^d = -I_{\rho} \frac{g_{NN\rho} g_{N\Delta\rho}}{m_\rho^2} \bar{u}(k'_1) \left( \gamma_\mu - \frac{g_\rho}{2m_N} \sigma^{\mu\nu} \partial_\nu \right) q_\mu u(k_1), \tag{8}
\]

\[
\mathcal{V}_{\omega}^d = -I_{\omega} \frac{g_{NN\omega} g_{N\Delta\omega}}{m_\omega^2} \bar{u}(k'_1) \left( \gamma_\mu - \frac{g_\omega}{2m_N} \sigma^{\mu\nu} \partial_\nu \right) q_\mu u(k_1), \tag{9}
\]

\[
\mathcal{V}_{\pi}^c = I_{\pi} \frac{g_{NN\pi}^2}{m_\pi^2} \bar{u}(k'_1) \gamma^\nu (\gamma^\mu q_\mu - g^{\mu\nu} q_\mu) u(k_1), \tag{10}
\]

\[
\mathcal{V}_{\rho}^c = -I_{\rho} \frac{g_{NN\rho} g_{N\Delta\rho}}{m_\rho^2} \bar{u}(k'_1) \gamma^\nu (\gamma^\mu q_\mu - g^{\mu\nu} q_\mu) u(k_1), \tag{11}
\]

where the $\bar{\nu}$ and $u'^\dagger$ are the spinor for nucleon and the Rarita-Schwinger vector-spinor for $\Delta$ baryon, respectively. And $q$, $k_{1(2)}$, and $k'_{1(2)}$ are the momenta of the exchange meson, initial and final nucleons or $\Delta$ baryons. The flavor factors $I_{i(0)}^{d(0)}$ for certain meson exchange and total isospin are presented in Table I.
With the spectator approximation, the GP down in the center-of-mass frame with $\delta$ as suggested by the $\delta$ function in Eq. (17). The $p_\Lambda^{\alpha_0}$ for the lighter nucleon is then $W - E_\Lambda(p')$. Here and hereafter, a definition $p = |p|$ will be adopted.

The partial wave potential is defined with the potential of the interaction obtained in the above as

$$V_{\rho,1}(p',p) = 2\pi \int d\cos \theta \left[d^4s_{\rho,1}(0)\rho V_{\rho,1}(p',p) + \eta d^4s_{\rho,1}(0)\rho V_{\rho,2}(p',p)\right],$$

where $\eta = PP(1-P)$ with $P$ and $J$ being parity and spin for system, nucleon or baryon. The initial and final relative momenta are chosen as $p = (0,0,p)$ and $p' = (p'\sin \theta,0,p'\cos \theta)$. The $d^4s_{\delta,1}(\theta)$ is the Wigner d-matrix.

In our qBSE approach, the $\Delta$ baryon is set on-shell while the nucleon is still possible to be off-shell. Hence, we introduce a form factor into the propagator to reflect the off-shell effect as an exponential regularization, $G_0(p) = e^{-\frac{m_\rho^2}{m^2}},$ where the $k_1$ and $m_\rho$ are the momentum and the mass of the nucleon. With such regularization, the integral equation is convergent even if we do not consider the form factor into the propagator of the exchanged meson. The cutoff $\Lambda_\alpha$ is parameterized as in the $\Lambda_e$ case, that is, $\Lambda_e = m_e + \alpha_e 0.22 \text{ GeV}$ with $m_e$ being the mass of exchanged meson and $\alpha_e$ serving the same function as the parameter $\alpha_e$. The $\alpha_e$ and $\alpha_r$ play an analogous role in the calculation of the binding energy. Hence, we take these two parameter as a parameter $\alpha$ for simplification.

### III. NUMERICAL RESULTS

The scattering amplitudes of the $\Lambda\Delta$ interaction can be obtained by inserting the potential kernel in Eqs. (7-11) into the qBSE in Eq. (16). The bound state can be searched as the pole in real axis of the complex energy plane below the threshold. In the current work, we will consider four $S$-wave states from the $\Lambda\Delta$ interaction, $D_{11}, D_{12}, D_{21}$, and $D_{22}$, with spin isospin $I J = 11, 12, 21,$ and $22$, respectively. The results with the variation of the parameter $\alpha$ are presented in Fig. 2.

Among the four $S$-wave states considered, three bound states are produced from the $\Lambda\Delta$ interaction, that is, $D_{12}, D_{21}$, and $D_{22}$. The $D_{21}$ state, which hint was observed at WASA-at-COSY, appears at an $\alpha$ of about 2, and its binding energy increases with the increase of $\alpha$. The experimental value of the binding energy can be reached at $\alpha$ of about 3 to 3.5. In the figure, we present the experimental results of the mass and corresponding uncertainty as a horizontal line and a grey band in the middle panel for reference. The values of $\alpha$ can be determined by comparing the theoretical result and experiment. Here, we take the results with $f_2$ as an example, the determined value of $\alpha$ and its uncertainty are shown as a red vertical line and a cyan band. For $f_2$, two other bound states appears at larger $\alpha$, 2.5 and 2.8, for the $D_{12}$ and $D_{22}$ states, respectively. For $f_1$, values of $\alpha$ about 0.5 larger are needed to produce these two states. If we choose the value of $\alpha$ for $f_2$ as shown in figure as red line, the binding energies

| $I$ | $f_1^0$ | $f_2^0$ | $f_1^0$ | $f_2^0$ |
|----|--------|--------|--------|--------|
| 1  | $-\sqrt{15}/3$ | $-\sqrt{15}/3$ | 1       | $-1/3$ |
| 2  | $\sqrt{15}/5$   | $\sqrt{15}/5$   | 1       | 1       |

TABLE I: The flavor factors $f^{(c)}$ for certain meson exchange and total isospin.
of the $D_{12}$ and $D_{22}$ states are about 2 and 8 MeV, respectively. After considering the uncertainties, the binding energies of these two states are several and ten MeV, respectively. Hence, the $D_{12}$ and $D_{22}$ states are bound much more shallowly than the $D_{21}$ state. In the current work, we consider four types of the form factors as shown in the figure. As suggested by the results, the different choices of the form factor do not affect the conclusion obtained above with $f_2$.

In the above, we present the results for $N\Delta$ interaction. The $NN$ scattering has been studied explicitly in Refs. [67, 68] by Gross and his collaborators with the same spectator approximation adopted in the current work. Because there are some differences in the explicit treatment between the current work and Refs. [67, 68]. It is interesting to see if the deuteron can be reproduced with current Lagrangians and theoretical frames. The potential can be obtained easily by replacing $\Delta$ by $N$, and the $\sigma$ exchange is introduced by a Lagrangian $\mathcal{L}_{\sigma NN} = g_{\sigma NN} \bar{N}N\sigma$ with a coupling constant $g_{\sigma NN} \approx 5$ [74, 75]. In Fig. 3, we present the results for the $NN$ interaction with isospin $I = 0$ and spin $J = 1$ with $f_2(q^2)$. It is found that with an $\alpha$ about 2 the bound state was produced from the $NN$ interaction, which can be related to the deuteron. Considering the $NN$ and $N\Delta$ interaction are different, one can say the $\alpha$ about 3.2 adopted in the $N\Delta$ interaction is consistent with the $\alpha$ value to reproduce the deuteron, about 2.7. The result with full model is very close to that with $\pi$ exchange only. Without $\pi$ exchange, no bound state can be found. It suggest that the $\pi$ exchange is crucial to reproduce the deuteron. However, with $\rho$ or $\sigma$ exchange, bound state can also be produced from the $NN$ interaction. If we remove the $\rho$ or $\sigma$ exchange, the bound state is still remained. It suggest that the $\pi, \rho$, and $\sigma$ exchanges provide attractive force. The $\omega$ exchange can not provide a bound state. If we remove the contribution from $\omega$ exchange, a bound state will appear below $\alpha = 2$. It suggests that the $\omega$ provides repulsive force. Such results are consistent with usual conclusion of the OBE model of the nuclear force [75].

We would like to remind that the calculation here is very crude compared with the works by Gross et al. [67, 68] and we do not fit experimental data of $NN$ scattering. It is given only to show that our approach can give the basic results of nuclear force.

FIG. 2: The variation of the binding energy $E_B = M_\beta - W$ on parameter $\alpha$ with $M_\beta$ and $W$ being the $N\Delta$ threshold and position of bound states. The triangle (purple), square (red), circle (blue), and diamond (green) and the corresponding lines are for form factors of types in Eqs. (12-15). The horizontal line and the grey band in middle panel are for the experimental mass and its uncertainties observed at WASA-at-COSY [53]. The red line and cyan band are for the $\alpha$ determined by the experiment with form factor $f_2$.

FIG. 3: The variation of the binding energy $E_B$ for the $NN$ interaction with isospin $I = 0$ and spin $J = 1$ with $f_2(q^2)$ in Eq. (13). The horizontal line are for the experimental mass of deuteron.

In the current work, we consider three exchanges of the $\pi$, $\rho$, and $\omega$ mesons. In Fig. 4 we present the results with only one exchange to discuss the role played by each exchange. Here we only present the results for three states which are bound by the interaction. For the $D_{12}$ state, the bound state can not be produced only with the $\omega$ exchange. With the $\rho$ exchange, the bound state still exists but appears at larger $\alpha$ of about 3.0. It suggests that the attraction is very weak compared with the full model, and a larger value of $\alpha$ is needed to compensate it. For the results with only the $\pi$ exchange, one can find that the binding even becomes stronger than that with all three exchanges. Explicit analysis suggests that the $\omega$ exchange will weaken the attraction, which leads to the larger $\alpha$ needed in
the full model, which is also analogous to the deuteron case. Hence, for the $D_{12}$ state, the main attraction is from the $\pi$ exchange. The $\rho$ exchange provides marginal attraction while inclusion of the $\omega$ exchange weakens the attraction. For the $D_{21}$ and $D_{22}$ states, only with $\pi$ exchange, the bound states can be produced, but the $\alpha$ needed is smaller than for the full model. It suggests that the $\pi$ exchange plays the most important role in producing the bound states as for the $D_{12}$ state as in the deuteron case.

![FIG. 4: The binding energy $E_B$ with variation of the $\alpha$ with exchange of only one meson.](image)

In our model, two diagrams are considered for the interaction, that is, the direct and cross diagrams as shown in Fig. 1. Here, we present the results with only one diagram. For different states different diagrams are important in producing the bound states. The attraction from the direct diagram is enough to produce the $D_{12}$ state while no bound states can be produced with the direct diagram for the $D_{21}$ and $D_{22}$ states. These two states are mainly produced from the contributions from the cross diagram. Such result suggests that the cross diagram is important and can not be neglected in the calculation.

IV. SUMMARY AND DISCUSSION

Inspired by the experimental hint of the dibaryon $N\Delta(D_{21})$ at WASA-at-COSY, we study the possible molecular states from the $N\Delta$ interaction. Within the one-boson-exchange model, the interaction is constructed with the help of the effective Lagrangians, which coupling constants are determined by experiment and SU(3) symmetry. After inserting the potential to the qBSE, we search the bound states from the S-wave $N\Delta$ interaction.

Three of four states considered in the current work, $D_{12}$, $D_{21}$, and $D_{22}$, are bound by the interaction and molecular states can be produced with reasonable parameters. We also perform a crude calculation about the deuteron within the current theoretical frame for reference. The deuteron can be reproduced from the $NN$ interaction with a parameter a little smaller than the one for $D_{21}$ state. The results suggest that the $\pi$ exchange plays the most important role in producing these bound states. The $\rho$ exchange provides a marginal contribution to produce the $D_{12}$ state while the $\omega$ exchange will weaken the interaction. The binding of the $D_{21}$ state is deepest among the three states. With values of the parameter $\alpha$ for which the experimental value of the binding energy for $D_{21}$ state is obtained, the other two states are predicted with much small binding energy.

The $d^*(2380)$ is the second observed dibaryon besides the deuteron. However, it seems to be a compact hexaquark instead of a molecular state like the deuteron. It is interesting to find more dibaryons to understand the internal structure of the dibaryons. The masses of the dibaryon $N\Delta(D_{21})$ suggested by the WASA-at-COSY Collaboration is close the the $N\Delta$ threshold, and it has a width very close to the sum of widths of a nucleon and a $\Delta$ baryon, which supports it as a molecular state. However, the experimental hint of the state $N\Delta(D_{21})$ at WASA-at-COSY is very weak and not confirmed by other experiments. The existence of such state requires further theoretical and experimental studies. Based on our work, the existence of $N\Delta(D_{21})$ suggests the possible existence of other two $N\Delta$ molecular states $D_{21}$, and $D_{22}$. It is interesting to search for such states in the experiment.

Acknowledgments

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