Pion-assisted $N\Delta$ and $\Delta\Delta$ dibaryons, and beyond

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Abstract Experimental evidence for $I^P(3^+) = 0(3^+)$ nonstrange dibaryon $D_{03}(2370)$ has been presented recently by the WASA-at-COSY Collaboration. Here I review new hadronic-basis Faddeev calculations of $L = 0$ nonstrange pion-assisted $N\Delta$ and $\Delta\Delta$ dibaryon candidates. These calculations are so far the only ones to reproduce the relatively small $D_{03}(2370)$ width of 70–80 MeV. Predictions are also given for the location and width of $D_{30}$, the $I^P(3^+) = 3(0^+)$ exotic partner of $D_{03}(2370)$. Extensions to strangeness $S=−1$ dibaryons are briefly discussed.

Keywords Faddeev equations · nucleon-nucleon interactions · pion-baryon interactions · dibaryons

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1 Introduction

The WASA-at-COSY Collaboration has presented recently striking evidence for a $I^P = 0(3^+)$ nonstrange dibaryon resonance some 80–90 MeV below $2M_\Delta \approx 2.46$ GeV, with a relatively small width of $\Gamma \approx 70–80$ MeV, by observing a distinct resonance in $pn \to d\pi\pi$ reactions as shown in Fig. 1. Isospin $I = 0$ is uniquely fixed in this particular $\pi^0\pi^0$ production reaction and the spin-parity $3^+$ assignment follows from the measured deuteron and pions angular distributions, assuming $s$-wave $\Delta\Delta$ decaying pair. The shape of the $M^2_{d\pi}$ distribution on the right panel supports $\Delta\Delta$ assignment and its peak at $\sqrt{s} \approx 2.13$ GeV, almost at the $D_{12}(2150) N\Delta$ dibaryon location (see below), might suggest a possible role for $D_{12}$ in forming the $\Delta\Delta$ dibaryon $D_{03}$. 

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Further evidence supporting the $D_{03}(2370)$ dibaryon assignment comes from very recent measurements of $pn$ elastic scattering as a function of energy, taking sufficiently small steps around $\sqrt{s} = 2370$ MeV \[^{3}\]. This is shown in Fig. 2 left for the Argand diagram of the $^3D_3$ partial wave, and in the right panel for the speed plot of the $^3D_3$ partial wave, within a new SAID partial wave analysis incorporating these measurements.

$N\Delta$ and $\Delta\Delta$ s-wave dibaryon resonances $D_{IS}$ with isospin $I$ and spin $S$ were proposed by Dyson and Xuong \[^{4}\] as early as 1964, when quarks were still perceived as merely mathematical entities. They focused on the lowest-dimension SU(6) multiplet in the $56 \times 56$ product that contains the SU(3) $10$ and $27$ multiplets in which the deuteron $D_{01}$ and $NN$ virtual state $D_{10}$ are classified. This yields two dibaryon candidates, $D_{12} (N\Delta)$ and $D_{03} (\Delta\Delta)$ as listed in Table \[^{1}\]. Identifying the constant $A$ in the resulting mass formula...
M = A + B[I(I + 1) + S(S + 1) - 2] with the NN threshold mass 1878 MeV, a value \( B \approx 47 \) MeV was reached by assigning \( D_{12} \) to the \( pp \leftrightarrow \pi^+ d \) resonance at \( \sqrt{s} = 2160 \) MeV (near the \( N\Delta \) threshold) which was observed already during the 1950’s. This led to the prediction \( M(D_{03}) = 2350 \) MeV. The \( D_{03} \) dibaryon has been the subject of several quark-based model calculations since 1980, see Ref. [5] for a representative although perhaps somewhat incomplete listing.

Table 1  Nonstrange s-wave dibaryon SU(6) predictions [4].

| dibaryon | I  | S  | SU(3) legend | mass   |
|----------|----|----|--------------|--------|
| \( D_{01} \) | 0 | 1 | 10           | deuteron | \( A \) |
| \( D_{10} \) | 1 | 0 | 27           | \( nn \)  | \( A \) |
| \( D_{12} \) | 1 | 2 | 27           | \( N\Delta \) | \( A + 6B \) |
| \( D_{21} \) | 2 | 1 | 35           | \( N\Delta \) | \( A + 6B \) |
| \( D_{03} \) | 0 | 3 | 28           | \( \Delta\Delta \) | \( A + 10B \) |
| \( D_{30} \) | 3 | 0 | 28           | \( \Delta\Delta \) | \( A + 10B \) |

It is shown below that the pion-assisted methodology applied recently by Gal and Garcilazo [6,7] couples \( D_{12} \) and \( D_{03} \) dynamically in a perfectly natural way, the analogue of which has not emerged in quark-based models. These hadronic-based calculations emphasize the long-range physics aspects of nonstrange dibaryons. Extensions to strangeness \( S = -1 \) pion-assisted dibaryons are also briefly discussed.

2 Pion-assisted nonstrange dibaryons

2.1 \( N\Delta \) dibaryons

The \( D_{1S} \) dibaryon candidates from Table 1 have been calculated recently in Ref. [7] by solving Faddeev equations with relativistic kinematics for the \( \pi NN \) three-body system, where the \( \pi N \) subsystem is dominated by the \( P_{33} \Delta(1232) \) resonance channel and the \( NN \) subsystem is dominated by the \( ^3S_1 \) and \(^1S_0 \) channels. The coupled Faddeev equations give rise then to an effective \( N\Delta \) Lippmann-Schwinger (LS) equation for the three-body \( S \)-matrix pole, with energy-dependent kernels that incorporate spectator-hadron propagators, as shown diagrammatically in Fig. 3 where circles denote the \( N\Delta T \) matrix.

Fig. 3  \( N\Delta \) dibaryon’s Lippmann-Schwinger equation [7].
Fig. 4 Coupled-channel fits (solid) to the SAID (dashed) $NN^1D_2$ phase shift $\delta$ (left panel) and inelasticity $\eta$ (right panel) as obtained in Ref. [6], see text.

Of the $L=0$ $N\Delta$ dibaryon candidates $D_{1S}$ with $IS=12,21,11,22$, the latter two do not provide resonant solutions. For $D_{12}$, only $^3S_1$ contributes out of the two $NN$ interactions, while for $D_{21}$ only $^1S_0$ contributes. Since the $^3S_1$ interaction is the more attractive one, $D_{12}$ lies below $D_{21}$ as borne out by the calculated masses listed in Table 2 for two choices of the $P_{33}$ interaction form factor corresponding to spatial sizes of 1.35 fm and 0.9 fm of the $\Delta$ isobar. The two dibaryons are found to be degenerate to within less than 20 MeV, close to the $N\Delta$ threshold at $\approx 2.17$ GeV with a width similar to that of the $\Delta$ baryon. In particular, the mass values calculated for $D_{12}$ are reasonably close to the values $W = 2148 - i63$ MeV [8] and $W = 2144 - i55$ MeV [9] derived in $pp(^1D_2)\leftrightarrow \pi d(^3P_2)$ coupled-channel phenomenological analyses.

| $W^{>}(D_{12})$ | $W^{>}(D_{21})$ | $W^{<}(D_{12})$ | $W^{<}(D_{21})$ |
|-----------------|-----------------|-----------------|-----------------|
| 2147−160        | 2165−164        | 2159−170        | 2169−169        |

2.2 $\Delta\Delta$ dibaryons

Generally, four-body $\pi\pi NN$ configurations appear in $\Delta\Delta$ dibaryons. Nevertheless, attempting to capture its most relevant degrees of freedom, the $D_{03}$ dibaryon was studied in Ref. [6] by solving a $\pi N \Delta'$ three-body model, where $\Delta'$
is a stable $\Delta(1232)$ and the $N\Delta'$ interaction is dominated by the $D_{12}$ dibaryon. The $I(J^P) = 1(2^+)$ $N\Delta'$ interaction was not assumed to resonate but, rather, it was fitted within a $NN-\pi NN-N\Delta'$ coupled-channel caricature model to the $NN^1D_2 T$-matrix, requiring that the resulting $N\Delta'$ separable-interaction form factor is representative of long-range physics, with momentum-space soft cutoff $\Lambda \leq 3$ fm$^{-1}$. A fit of this kind is shown in Fig. 4.

The Faddeev equations of the $\pi N \Delta'$ three-body model give rise, as before, to an effective LS equation for the $\Delta\Delta'$ $S$-matrix pole corresponding to $D_{03}$. This LS equation is shown diagrammatically in Fig. 5 where $D$ stands for the $D_{12}$ dibaryon. The $\pi N$ interaction was assumed again to be dominated by the $P_{33}$ $\Delta$ resonance, using two different parametrizations of its form factor that span a reasonable range of the $\Delta$ hadronic size. The calculation of $D_{03}$ was extended in Ref. [7] to other $D_{1S}$ $\Delta\Delta$ dibaryon candidates, with $D$ now standing for both $N\Delta$ dibaryons $D_{12}$ and $D_{21}$. Since $D_{21}$ is almost degenerate with $D_{12}$, and with no $NN$ observables to constrain the input $(I, S)=(2, 1)$ $N\Delta'$ interaction, the latter was taken the same as for $(I, S)=(1, 2)$. The lowest and also narrowest $\Delta\Delta$ dibaryons found are $D_{03}$ and $D_{30}$.

Representative results for $D_{03}$ and $D_{30}$ are assembled in Table 3, where the calculated mass and width values listed in each row correspond to the specific spectator-$\Delta'$ complex mass $W(\Delta')=1211-1i49.5$ MeV value used in the propagator of the LS equation shown in Fig. 5. The value $x=1$ in the first row corresponds to the free-space $\Delta(1232)$ $S$-matrix pole. It is implicitly assumed thereby that the decay $\Delta' \rightarrow N\pi$ proceeds independently of the $\Delta \rightarrow N\pi$ isobar decay. However, as pointed out in Ref. [6], care must be exercised to ensure that the decay nucleons and pions satisfy Fermi-Dirac and Bose-Einstein statistics requirements, respectively. Assuming $L = 0$ for the decay-nucleon pair, this leads to the suppression factor $x=2/3$ depicted in the second row. It is seen that the widths obtained upon applying this width-suppression are only moderately smaller, by less than 15 MeV, than those calculated disregarding this quantum-statistics correlation.

The mass and width values calculated for $D_{03}$ [6] agree very well with those determined by the WASA-at-COSY Collaboration [1, 2, 3], reproducing in particular the reported width value $\Gamma(D_{03}) \approx 70$ MeV which is considerably below the phase-space estimate $\Gamma_\Delta \leq \Gamma(D_{03}) \leq 2\Gamma_\Delta$, with $\Gamma_\Delta \approx 118$ MeV. No other calculation so far has succeeded to do that. Similarly small widths
Table 3 \( \Delta\Delta \) dibaryon \( S \)-matrix poles (in MeV) obtained in Refs. [6,7] by using in the propagator of the LS equation depicted in Fig. 5 a spectator-\( \Delta' \) complex mass \( W(\Delta') = 1211 - i\times 9.3 \text{ MeV} \), where \( x \) is a width-suppression factor (see text). The last two columns give mass and width values averaged over those from the > and < columns, with > and < defined in Table 2 caption. Other \( \Delta\Delta \) dibaryon candidates are discussed in Ref. [7].

| \( x \) | \( W^>(\Delta_03) \) | \( W^>(\Delta_{30}) \) | \( W^<(\Delta_03) \) | \( W^<(\Delta_{30}) \) | \( W_{av}(\Delta_03) \) | \( W_{av}(\Delta_{30}) \) |
|---|---|---|---|---|---|---|
| 1 | 2383−i47 | 2412−i49 | 2342−i31 | 2370−i30 | 2363−i39 | 2391−i39 |
| 2/3 | 2383−i41 | 2411−i41 | 2343−i24 | 2370−i22 | 2363−i33 | 2390−i32 |

hold for \( \Delta_{30} \) which is located according to Table 3 about 30 MeV above \( \Delta_{03} \). Adding \( \approx 20 \text{ MeV} \) for the \( \Delta_{30} \) input mass excess relative to \( \Delta_{12} \), the resulting \( \Delta_{30} \) to \( \Delta_{03} \) mass excess of roughly 50 MeV agrees with that found recently by H. Huang et al. [5] in a quark-based calculation. A more complete discussion of these and of other \( \Delta_1S \) \( \Delta\Delta \) dibaryon candidates is found in Ref. [7].

Bashkanov, Brodsky and Clement [10] have emphasized recently the dominant role that six-quark hidden-color configurations might play in binding \( \Delta_{03} \) and the exotic \( I = 3/2 \) \( \Delta_30 \). The recent calculations by H. Huang et al. [5], however, find that these configurations play a marginal role, enhancing dibaryon binding by merely 15±5 MeV and reducing the dibaryon width from 175 to 150 MeV for \( \Delta_{03} \), still twice as big as the reported width, and from 216 to 200 MeV for \( \Delta_{30} \). These minor contributions of six-quark hidden-color configurations are in line with the secondary role found for them in studies of the \( NN \) interaction in the context of the \( \Delta_01 \) and \( \Delta_{10} \) \( NN \) ‘dibaryons’ [11].

3 Extension to strangeness \( S = -1 \)

Recent searches of a \( \Lambda(1405)N \) dibaryon have been reported from experiments at Frascati [12], SPring-8 [13], GSI [14] and J-PARC [15,16,17]. A missing-mass spectrum measured in the \( d(\pi^+, K^+) \) reaction at 1.69 GeV/c in J-PARC is shown in Fig. 6, indicating \( \approx 22 \text{ MeV} \) attractive shift of the unresolved \( Y^*(1385+1405) \) quasi-free peak complex. This is consistent with the attraction expected in the \( I = 1/2 \), \( J^P = 0^− \) \( \Lambda(1405)N \) s-wave channel shown in Ref. [18] to overlap substantially with a \( KNN \) quasibound state known also as ‘\( K^- pp \)’ which is being searched for in these experiments. The lower-energy components of this \( KNN \) dibaryon–\( \pi \Lambda N \) and \( \pi \Sigma N \)–do not support any strongly attractive meson-baryon s-wave interaction.

The \( \pi \Lambda N–\pi \Sigma N \) system, however, can benefit from strong meson-baryon \( p \)-wave interactions fitted to the \( \Delta(1232) \rightarrow \pi N \) and \( \Sigma(1385) \rightarrow \pi A–\pi \Sigma \) form factors by fully aligning isospin and angular momentum: \( I = 3/2 \), \( J^P = 2^+ \). Such \( S = -1 \) pion-assisted dibaryon was introduced in Ref. [19], predicting a dibaryon resonance about 10–20 MeV below the \( \pi \Sigma N \) threshold obtained by solving \( \pi YN \) coupled-channel Faddeev equations [20]. This prediction, however, is sensitive to the \( p \)-wave form factors assumed. Adding a \( KNN \) channel hardly matters, since its leading \( ^3S_1 \) \( NN \) configuration is Pauli forbidden.
This $S = -1$ pion-assisted dibaryon, denoted $Y^*$, overlaps with $s$-wave $^5S_2$, $I = 3/2 \Sigma(1385)N$ and $\Delta(1232)Y^*$ dibaryon configurations, the lower of which is $\Sigma(1385)N$. These quantum numbers differ from $\ ^1S_0, I = 1/2$ for $\Lambda(1405)N$ which is being searched upon. A recent search for the $I = 3/2 \ Y^*$ dibaryon in

\[ p + p \rightarrow Y^{++} + K^0 \]

\[ \leftrightarrow \Sigma^+ + p \] (1)

by the HADES Collaboration at GSI [21] found no $Y^*$ dibaryon signal. Other possible search reactions are

\[ \pi^+ + d \rightarrow Y^{++/-} + K^{0/+} \]

\[ \leftrightarrow \Sigma^{\pm} + p(n) , \] (2)

again offering distinct $I = 3/2$ decay channels. Other decay channels such as

\[ \pi^+ + d \rightarrow Y^+ + K^+ \]

\[ \leftrightarrow \Sigma^0 + p \] (3)

allow for both $I = 1/2, 3/2$. E27 has just reported [17] a dibaryon signal near the $\pi\Sigma N$ threshold in reaction (3). This requires further experimental study.

4 Conclusion

It was shown how the 1964 Dyson-Xuong SU(6)-based classification and predictions of nonstrange dibaryons [4] are confirmed in the hadronic model of $N\Delta$ and $\Delta\Delta$ pion-assisted dibaryons [6,7]. The input for dibaryon calculations in
this model consists of nucleons, pions and $\Delta$'s, interacting via long-range pairwise interactions. These calculations reproduce the two nonstrange dibaryons established experimentally and phenomenologically so far, the $N\Delta$ dibaryon $D_{12}^{\pm}[8,9]$ and the $\Delta\Delta$ dibaryon $D_{03}^{++}[1,2,3]$, and predict several exotic $N\Delta$ and $\Delta\Delta$ dibaryons. We note that, within the $\pi N\Delta$ three-body model of $D_{03}^{++}$, $D_{12}^{\pm}$ provides a two-body decay channel $\pi D_{12}^{\pm}$ with threshold lower than $\Delta\Delta$ which proves instrumental in obtaining a relatively small width for $D_{03}^{++}[7]$.

Finally, a straightforward extension of nonstrange pion-assisted dibaryon phenomenology to strangeness $S=-1$ was briefly discussed in connection to recent searches of kaonic nuclear clusters, see Ref. [22] for a recent review.

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