MESON ASSISTED DIBARYONS

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We discuss a new type of $L = 0$ positive-parity dibaryons, $\pi BB'$, where the dominant binding mechanism is provided by resonating p-wave pion–baryon interactions. Recent calculations of such pion assisted dibaryons are reviewed with special emphasis placed on the non-strange $I(J^P) = 1(2^+)$ $N\varDelta$ dibaryon $\mathcal{D}_{12}(2150)$ studied recently at JLab, and on the $0(3^+)$ $\varDelta\varDelta$ dibaryon $\mathcal{D}_{03}(2380)$ discovered recently by the WASA-at-COSY Collaboration. We discuss recent searches by the HADES Collaboration at GSI and by the E15 and E27 Experiments at J-PARC for a strangeness $\mathcal{S} = -1$ $I(J^P) = \frac{1}{2}(0^-)$ K^-pp dibaryon and perhaps also for a strange $I(J^P) = \frac{3}{2}(2^+)$ $N\varSigma(1385)$ pion assisted dibaryon $\mathcal{Y}_{\frac{3}{2}2}(2270)$. Charm $\mathcal{C} = +1$ dibaryons, predicted with the same $I(J^P)$ values, are also briefly reviewed.

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1. Introduction

The present overview is focused on the notion of pion assisted dibaryons, $\pi BB'$. The idea is to enhance the binding of $L = 0$ BB' configurations through the strong p-wave πB and $\pi B'$ attraction. In the $\mathcal{S} = 0$ non-strange sector, for the πNN system, we show how certain $N\varDelta$ near-threshold quasibound states emerge, and for the $\pi N\varDelta$ system we show how certain $\varDelta\varDelta$ quasibound states emerge, notably the $I(J^P) = 0(3^+)$ $\mathcal{D}_{03}(2380)$ dibaryon discovered recently by the WASA-at-COSY Collaboration [1–3].

In the strangeness $\mathcal{S} = -1$ sector, we focus attention to a $\pi\varLambda N$–$\pi\varSigma N$ dibaryon in a spin and isospin stretched configuration $I(J^P) = \frac{3}{2}(2^+)$ predicted near the $\pi\varSigma N$ threshold at $\sqrt{s} \approx 2270$ MeV [4][1]. This pion assisted dibaryon, resembling a two-body quasibound state of $N\varSigma(1385)$ and to a lesser extent $\varDelta(1232)Y$, with $Y \equiv \varLambda, \varSigma$, may be looked for in the same production reactions used to search for a K^-pp $I(J^P) = \frac{1}{2}(0^-)$ $\bar{K}$ assisted dibaryon (but with s-wave K^- meson) which may also be viewed as a $N\varLambda(1405)$ quasibound state [7]. For a recent overview of K^-pp and its implications to $\bar{K}$-nuclear phenomenology, see Ref. [8].

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[1] Earlier versions of this work are detailed in Refs. [5, 6].

In the charm $\mathcal{C} = +1$ sector, we briefly review two recently suggested charmed dibaryons, with $I(J^P) = \frac{1}{2}(0^-)$ and $\frac{3}{2}(2^+)$ configurations, in perfect analogy to the $\mathcal{S} = -1$ dibaryons discussed above.

The present overview updates a review of dibaryons published a few years ago [9] when the mere observation of just a peak in the $pn \to d\pi^0\pi^0$ reaction [1], see left panel of Fig. 1, was not generally accepted as evidence for the $I(J^P) = 0(3^+)$ $\mathcal{D}_{03}(2380)$ $\Delta\Delta$ dibaryon resonance. A corresponding peak was subsequently seen also in $pn \to d\pi^+\pi^-$ [2], with a cross section related to that of $pn \to d\pi^0\pi^0$ by assuming an underlying $\mathcal{D}_{03}(2380)$ dibaryon resonance. Recent measurements by WASA-at-COSY [3] of pn scattering and analyzing power, as shown by the pn ${}^3D_3$ partial wave Argand diagram in the right panel of Fig. 1, provide a 'smoking gun' for this dibaryon which is the *only* dibaryon established unambiguously so far. My own work with Garcilazo, interpreting $\mathcal{D}_{03}(2380)$ as a $\pi N\Delta$ pion assisted dibaryon, took a while to develop [10, 11]. Before getting to this main subject, we start in the next section with a brief overview of dibaryon expectations from quark models, then moving on to discuss meson assisted dibaryons in the non-strange, strange and charmed sectors mentioned above.

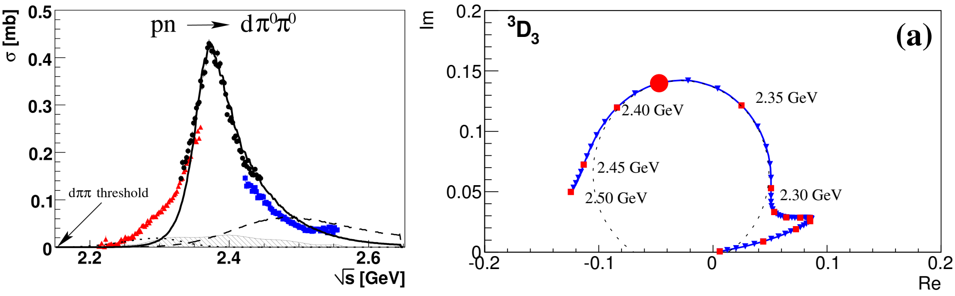

Fig. 1. $\mathcal{D}_{03}(2380)$ $\Delta\Delta$ dibaryon resonance signatures in recent experiments by the WASA-at-COSY Collaboration. Left: from observing a peak in the $pn \to d\pi^0\pi^0$ reaction [1]. Right: from the Argand diagram of the ${}^3D_3$ partial wave in pn scattering [3].

2. Quark models

Historically, discussions of six-quark ($6q$) dibaryons were based on symmetry considerations related to the color-magnetic (CM) gluon exchange interaction

$$V_{\rm CM} = \sum_{i<j} -(\lambda_i \cdot \lambda_j)(s_i \cdot s_j)v(r_{ij})\,, \tag{1}$$

where λ_i and s_i are the color and spin operators of the $i^{\rm th}$ quark and $v(r_{ij})$ is a flavor-conserving short-ranged interaction between quarks i, j.

For $L = 0$ spatially symmetric color-singlet n-quark cluster, the matrix element of $v(r_{ij})$ is independent of the particular i, j pair and is denoted $\mathcal{M}_0$, allowing for a closed form summation over i and j in Eq. (1) and resulting in

$$\langle V_{\rm CM}\rangle = \left[-\frac{n(10-n)}{4} + \Delta\mathcal{P}_{\rm f} + \frac{S(S+1)}{3}\right]\mathcal{M}_0\,, \qquad (2)$$

where $\mathcal{P}_{\rm f}$ sums over ±1 for any symmetric/antisymmetric flavor pair, $\Delta\mathcal{P}_{\rm f}$ means with respect to the SU(3)$_{\rm f}$ **1** antisymmetric representation of n quarks, $n = 3$ for baryons and $n = 6$ for dibaryons, S is the total Pauli spin, and where $\mathcal{M}_0 \sim 75$ MeV from the $\varDelta$–N mass difference. The leading strangeness $\mathcal{S} = 0, -1, -2, -3$ dibaryon candidates arising from these CM interaction considerations are listed in Table I following Ref. [12], where $\varDelta\langle V_{\rm CM}\rangle = \langle V_{\rm CM}\rangle_{6q} - \langle V_{\rm CM}\rangle_B - \langle V_{\rm CM}\rangle_{B'}$ stands for the CM gain in the $6q$ dibaryon configuration with respect to the sum of CM contributions from the separate B and B' $3q$ baryons that define the lowest BB' threshold.

TABLE I

Leading $6q$ $L = 0$ dibaryon candidates [12], their BB' structure and the CM interaction gain with respect to the lowest BB' threshold calculated by means of Eq. (2). Asterisks are used for the $\mathbf{10}_{\rm f}$ baryons $\varSigma^* \equiv \varSigma(1385)$ and $\varXi^* \equiv \varXi(1530)$. The symbol $[i, j, k]$ stands for the Young tablaux of the SU(3)$_{\rm f}$ representation, with i arrays in the first row, j arrays in the second row and k arrays in the third row, from which $\mathcal{P}_{\rm f}$ is evaluated. The $\overline{\mathbf{10}}$ SU(3)$_{\rm f}$ representation is denoted here $\mathbf{10}^*$.

$-\mathcal{S}$	SU(3)$_{\rm f}$	I	J^π	BB' structure	$\frac{\varDelta\langle V_{\rm CM}\rangle}{M_0}$
0	[3,3,0] $\mathbf{10}^*$	0	3^+	$\varDelta\varDelta$	0
1	[3,2,1] **8**	1/2	2^+	$\frac{1}{\sqrt5}(N\varSigma^* + 2\varDelta\varSigma)$	-1
2	[2,2,2] **1**	0	0^+	$\frac{1}{\sqrt8}(\varLambda\varLambda + 2N\varXi - \sqrt3\varSigma\varSigma)$	-2
3	[3,2,1] **8**	1/2	2^+	$\frac{1}{\sqrt5}(\sqrt2N\varOmega - \varLambda\varXi^* + \varSigma^*\varXi - \varSigma\varXi^*)$	-1

Except for $\mathcal{S} = -1$, the leading dibaryon candidates listed in Table I are the ones mostly dealt with in quark-model calculations. The table shows clearly the prominence of the $\mathcal{S} = -2$ H dibaryon that was first predicted by Jaffe [13] as a genuine bound state well below the $\varLambda\varLambda$ threshold. However, more realistic $6q$ quark cluster model calculations that *(i)* break SU(3)$_{\rm f}$, *(ii)* account for full quark antisymmetrization, and *(iii)* also make contact via resonating group methods (RGM) with related BB' coupled channels and thresholds, placed the H near the $\varXi N$ threshold at $E_{\varLambda\varLambda} \approx 26$ MeV [14]. Recent experimental searches for a weakly decaying $\varLambda\varLambda$ bound state by Belle [15] and ALICE [16] imply that Jaffe's H dibaryon is particle-unstable against strong decay. This is confirmed by recent lattice QCD (LQCD) simulations [17] and by chiral EFT arguments [18] suggesting that the H could appear at most as a resonance near the ΞN threshold at $E_{\Lambda\Lambda} \approx 26$ MeV, in agreement with the prediction of the 1983 first $6q$ RGM calculation [14]. For $\mathcal{S} = -3$, the 2^+ deeply bound ΩN dibaryon predicted in Ref. [19], together with a 1^+ companion, is more likely according to recent LQCD simulations [20] to be just weakly bound with respect to the Ω–N threshold, well above the lower $\mathcal{S} = -3$ thresholds Ξ–Λ and Ξ–Σ, again far from being particle-stable.

For $\mathcal{S} = 0$, although the recently established $\mathcal{D}_{03}(2380)$ [1] lies below the $\Delta\Delta$ threshold, it is far from being particle-stable and is considerably less bound than suggested *e.g.* in Ref. [21]. In fact, a recent study of non-strange $6q$ spatially symmetric $L = 0$ dibaryons [22], superseding $6q$ bag-model calculations [13, 23], finds such a $\Delta\Delta$ dibaryon at several hundreds of MeV above the Δ–Δ threshold, concluding that "the recently observed peak in the $I(J^P) = 0(3^+)$ channel should be a molecular configuration composed of two Δ baryons". Indeed, the hadronic-based calculations reviewed below emphasize the long-range physics aspects of non-strange dibaryons.

3. Non-strange dibaryons

$N\Delta$ and $\Delta\Delta$ s-wave dibaryon resonances $\mathcal{D}_{IS}$ with isospin I and spin S were proposed as early as 1964, when quarks were still perceived as merely mathematical entities, by Dyson and Xuong [24] who focused on the lowest-dimension SU(6) multiplet in the $\mathbf{56} \times \mathbf{56}$ product that contains the SU(3) $\overline{\mathbf{10}}$ and $\mathbf{27}$ multiplets in which the deuteron $\mathcal{D}_{01}$ and NN virtual state $\mathcal{D}_{10}$ are classified. This yields two dibaryon candidates, $\mathcal{D}_{12}$ ($N\Delta$) and $\mathcal{D}_{03}$ ($\Delta\Delta$) as listed in Table II. 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 determined by assigning $\mathcal{D}_{12}$ to the $pp \leftrightarrow \pi^+ d$

TABLE II

Non-strange s-wave dibaryon SU(6) predictions [24]. The $\overline{\mathbf{10}}$ SU(3)$_\mathrm{f}$ representation is denoted here $\mathbf{10}^*$.

Dibaryon	I	S	SU(3)	Legend	Mass
$\mathcal{D}_{01}$	0	1	$\mathbf{10}^*$	deuteron	A
$\mathcal{D}_{10}$	1	0	$\mathbf{27}$	nn	A
$\mathcal{D}_{12}$	1	2	$\mathbf{27}$	$N\Delta$	$A+6B$
$\mathcal{D}_{21}$	2	1	$\mathbf{35}$	$N\Delta$	$A+6B$
$\mathcal{D}_{03}$	0	3	$\mathbf{10}^*$	$\Delta\Delta$	$A+10B$
$\mathcal{D}_{30}$	3	0	$\mathbf{28}$	$\Delta\Delta$	$A+10B$

resonance at $\sqrt{s} = 2160$ MeV (near the $N\Delta$ threshold) which was observed already during the 1950s. This led to the prediction $M(\mathcal{D}_{03}) = 2350$ MeV. The $\mathcal{D}_{03}$ dibaryon was the subject of many quark-based model calculations since 1980, as reviewed elsewhere [25].

It is shown below that the pion-assisted methodology applied recently by Gal and Garcilazo [10, 11] couples $\mathcal{D}_{12}$ and $\mathcal{D}_{03}$ dynamically in a perfectly natural way, the analogue of which has not emerged in quark-based models. As stated earlier in this review, our hadronic-based calculations emphasize the long-range physics aspects of non-strange dibaryons.

3.1. NΔ dibaryons

The $\mathcal{D}_{12}$ dibaryon shows up experimentally as $NN(^1D_2) \leftrightarrow \pi d(^3P_2)$ coupled-channel resonance corresponding to a quasibound $N\Delta$ with mass $M \approx 2.15$ GeV, near the $N\Delta$ threshold, and width $\Gamma \approx 0.12$ GeV as derived from the Argand diagram of the $^1D_2$ partial wave in pp elastic scattering, using the SAID partial-wave analysis [26]. The contribution of $\mathcal{D}_{12}$ to the $pp \to d\pi^+$ cross section in a recent reaction model calculation [27] is shown by dashed lines in Fig. 2.

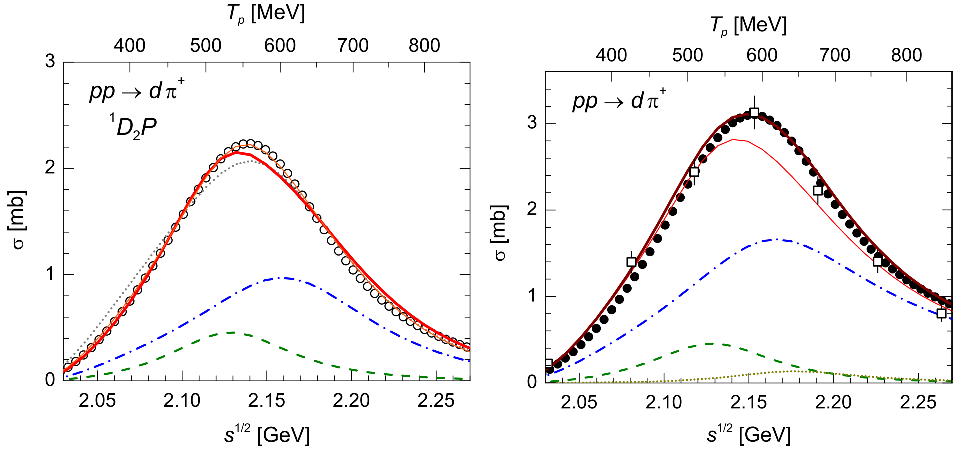

Fig. 2. $\mathcal{D}_{12}$ dibaryon s-channel (dashed) contributions to $pp \to d\pi^+$ $^1D_2{}^3P_2$ partial-wave (left panel) and total (right panel) cross sections from SAID [26], plus a small $^3F_3{}^3D_3$ dibaryon (dotted) contribution, in a model [27] that includes non-resonant t-channel exchange (dot-dashed) contributions with amplitudes interfering constructively with s-channel amplitudes. Model sensitivities are exhibited in thin lines.

In our recent work [11], we have calculated this dibaryon and other $N\Delta$ dibaryon candidates such as $\mathcal{D}_{21}$ (see Table II) by solving Faddeev equations with relativistic kinematics for the πNN three-body system, where the πN 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 [11].

Of the four $L = 0$, $IS = 12, 21, 11, 22$ $N\Delta$ dibaryon candidates $\mathcal{D}_{IS}$, the latter two do not provide resonant solutions. For $\mathcal{D}_{12}$ ($\mathcal{D}_{21}$), only $^3S_1$ ($^1S_0$) contributes out of the two NN interactions. Since the $^3S_1$ interaction is the more attractive one, $\mathcal{D}_{12}$ lies below $\mathcal{D}_{21}$ as borne out by the calculated masses listed in Table III for two choices of the P_{33} interaction form factor corresponding to Δ-isobar spatial sizes 1.35 and 0.9 fm. The two dibaryons are found to be degenerate to within less than 20 MeV. The mass values calculated for $\mathcal{D}_{12}$ are reasonably close to those from Refs. [28, 29].

TABLE III

$N\Delta$ dibaryon S-matrix poles (in MeV) for $\mathcal{D}_{12}$ and $\mathcal{D}_{21}$ obtained by solving the LS equation, Fig. 3, derived from πNN Faddeev equations [11] are listed for large ($>$) and small ($<$) sized πN P_{33} form factors and also cited from non-Faddeev determinations [28, 29].

$\mathcal{D}_{12}(>)$	$\mathcal{D}_{21}(>)$	$\mathcal{D}_{12}(<)$	$\mathcal{D}_{21}(<)$	$\mathcal{D}_{12}$ [28]	$\mathcal{D}_{12}$ [29]
$2147 - i60$	$2165 - i64$	$2159 - i70$	$2169 - i69$	$2148 - i63$	$2144 - i55$

3.2. ΔΔ dibaryons

The relevance of the $\mathcal{D}_{12}(2150)$ $N\Delta$ dibaryon to the physics of the $\mathcal{D}_{03}(2380)$ $\Delta\Delta$ dibaryon is demonstrated in Fig. 4 by showing, in the left panel, a $d\pi^{\pm}$ invariant-mass correlation near the $N\Delta$ threshold as deduced from preliminary CLAS data on the $\gamma d \to d\pi^+\pi^-$ reaction [30] and, in the right panel, a $d\pi$ invariant-mass distribution peaking near the $N\Delta$ threshold as deduced from the WASA-at-COSY $pn \to d\pi^0\pi^0$ reaction by which the

$\mathcal{D}_{03}(2380)$ dibaryon was discovered [1]. The $\gamma d \to d\pi^+\pi^-$ preliminary CLAS data suggest a subthreshold $\mathcal{D}_{12}(2150)$ dibaryon with mass 2115±10 MeV and width 125±25 MeV, consistently with past deductions. The peaking of the $d\pi$ invariant-mass distribution in the $pn \to d\pi^0\pi^0$ reaction essentially at this $\mathcal{D}_{12}(2150)$ mass value suggests that the two-body decay modes of $\mathcal{D}_{03}(2380)$ are almost saturated by the $\mathcal{D}_{12}(2150) + \pi$ decay mode, as reflected in the calculation [27] depicted in the right panel.

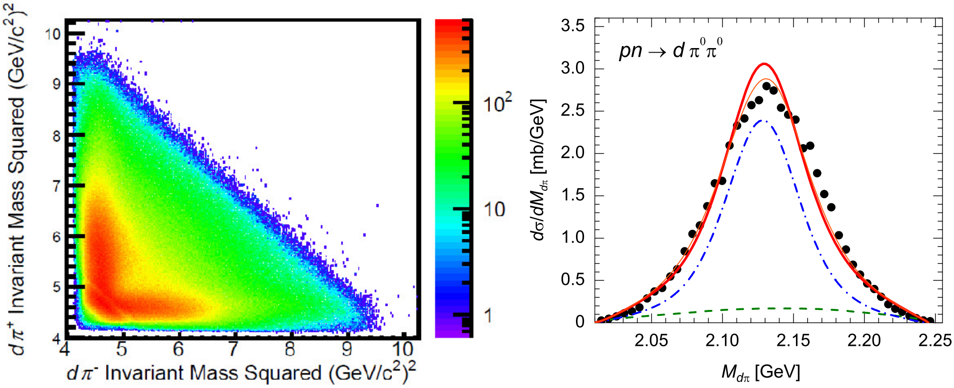

Fig. 4. Left: $\mathcal{D}_{12}(2150)$ $N\Delta$ dibaryon resonance signal in the Dalitz plot of $M^2_{d\pi^+}$ *vs.* $M^2_{d\pi^-}$ from preliminary $\gamma d \to d\pi^+\pi^-$ measurements by the CLAS g13 Collaboration at JLab [30]. Right: WASA-at-COSY $M_{d\pi}$ distribution [1] and as calculated for two (solid lines) input parametrizations of $\mathcal{D}_{12}(2150)$ [27]. The dot-dashed line gives the $\mathcal{D}_{12}(2150) + \pi$ contribution to the two-body decay of $\mathcal{D}_{03}(2380)$, and the dashed line gives a scalar–isoscalar emission contribution.

Four-body $\pi\pi NN$ calculations are required, strictly speaking, to discuss $\Delta\Delta$ dibaryons. In Ref. [10], we studied the $\mathcal{D}_{03}$ dibaryon by solving a $\pi N\Delta'$ three-body model, where Δ' is a stable $\Delta(1232)$ and the $N\Delta'$ interaction is dominated by the $\mathcal{D}_{12}$ dibaryon. The $I(J^P) = 1(2^+)$ $N\Delta'$ interaction was not assumed to resonate, but was fitted within a NN–πNN–$N\Delta'$ 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 Λ below 3.5 fm^{-1}.

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 $\mathcal{D}_{03}$. This LS equation is shown diagrammatically in Fig. 5, where D stands for the $\mathcal{D}_{12}$ dibaryon. The πN interaction was assumed again to be dominated by the P_{33} Δ resonance, using two different parametrizations of its form factor that span a reasonable range of the Δ hadronic size. In Ref. [11], we have extended the calculation of $\mathcal{D}_{03}$ to other $\mathcal{D}_{IS}$ $\Delta\Delta$ dibaryon candidates, with D now standing for both $N\Delta$ dibaryons $\mathcal{D}_{12}$ and $\mathcal{D}_{21}$. Since $\mathcal{D}_{21}$ is almost degenerate with $\mathcal{D}_{12}$, 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 model dependence of this assumption requires further study. $\mathcal{D}_{03}$ and $\mathcal{D}_{30}$ are the lowest and narrowest $\Delta\Delta$ dibaryons.

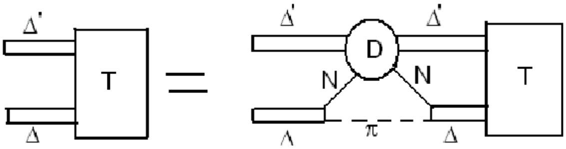

Fig. 5. S-matrix pole equation for $\mathcal{D}_{03}(2370)$ $\Delta\Delta$ dibaryon [10].

Representative results for $\mathcal{D}_{03}$ and $\mathcal{D}_{30}$ are assembled in Table IV, where the calculated mass and width values listed in each row correspond to the value listed there of the spectator-Δ' complex mass $W(\Delta')$ used in the propagator of the LS equation shown in Fig. 5. The value of $W(\Delta')$ in the first row is that of the $\Delta(1232)$ S-matrix pole. It is implicitly assumed thereby that the decay $\Delta' \to N\pi$ proceeds independently of the $\Delta \to N\pi$ isobar decay. However, as pointed out in Ref. [10], 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 $2/3$ depicted in the value of $W(\Delta')$ listed 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. A more complete discussion of these and other $\mathcal{D}_{IS}$ $\Delta\Delta$ dibaryon candidates is found in Ref. [11].

TABLE IV

$\Delta\Delta$ dibaryon S-matrix poles (in MeV) obtained in Refs. [10, 11] by using a spectator-Δ' complex mass $W(\Delta')$ (first column) in the propagator of the LS equation depicted in Fig. 5. The superscripts $>$ and $<$ stand for two choices of the πN P_{33} form factor, with spatial sizes of 1.35 fm ($>$) and 0.9 fm ($<$).

$W(\Delta')$	$W^{>}(\mathcal{D}_{03})$	$W^{>}(\mathcal{D}_{30})$	$W^{<}(\mathcal{D}_{03})$	$W^{<}(\mathcal{D}_{30})$
$1211-i49.5$	$2383-i47$	$2412-i49$	$2342-i31$	$2370-i30$
$1211-i(2/3)49.5$	$2383-i41$	$2411-i41$	$2343-i24$	$2370-i22$

The mass and width values $W^{>}(\mathcal{D}_{03})$ in Table IV agree very well with those determined by the WASA-at-COSY Collaboration [1–3], reproducing in particular the reported width $\Gamma(\mathcal{D}_{03}) \approx 80$ MeV which is considerably below the rough estimate $2\Gamma_{\Delta} \approx 200$ MeV for two free-space Δs, using the $\Delta(1232)$ pole position from SAID [26]. However, the reduced phase space for each $\Delta \to N\pi$ decay suppresses this estimate by a factor 0.555, which together with the suppression factor 2/3 from the previous paragraph yields the estimate $\Gamma(\Delta\Delta)_{03} \approx 73$ MeV, to which the partial decay widths to $NN\pi$ and NN need to be added. This results in a total width estimate of about 90 MeV, compared to 82 MeV from Table IV. A similar estimate can be obtained by considering $\mathcal{D}_{03}$ decay as occurring through its lower $\pi\mathcal{D}_{12}$ channel.

The $\mathcal{D}_{30}$ dibaryon in our calculations is located only ≈ 30 MeV above $\mathcal{D}_{03}$, and with a similar width. Allowing its $\mathcal{D}_{21}$ input parameters to depart from those found for $\mathcal{D}_{12}$ would increase the $\mathcal{D}_{30}$ mass by 20–30 MeV, in close agreement with the quark-based calculations of Ref. [31]. Note, however, that the widths calculated there are much larger than ours. The $I = 3$ exotic $\mathcal{D}_{30}$ dibaryon was discussed in Ref. [32], where the dominant role that six-quark hidden-color (HC) configurations might play in binding $\mathcal{D}_{03}$ and $\mathcal{D}_{30}$ was emphasized. However, recent explicit quark-based calculations [31] find HC configurations to play a marginal role, enhancing dibaryon binding by merely 15 ± 5 MeV and reducing the dibaryon width from 175 to 150 MeV for $\mathcal{D}_{03}$, still twice as big as the reported width, and from 216 to 200 MeV for $\mathcal{D}_{30}$. This is in line with the negligible role found long ago for HC configurations in the dibaryon calculation of Ref. [33]. In contrast, a very recent calculation [34] claims that $6q$ HC configurations reduce substantially the calculated width of $\mathcal{D}_{03}$ down to $\Gamma \approx 70$ MeV, the argument given being that HC components cannot decay to colorless hadrons. This argument overlooks the strong coupling between colorless and HC BB' components in any realistic $6q$ wavefunction, through which the HC components decay by using the colorless components for intermediate states.

4. Strange dibaryons

Recent searches for a $\bar{K}NN$ (known as K^-pp) $I(J^P) = \frac{1}{2}(0^-)$ dibaryon have been reported by experiments at Frascati [35], SPring-8 [36], GSI [37, 38] and J-PARC [39–41]. 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 ≈ 22 MeV attractive shift of the unresolved $Y^*(1385 + 1405)$ quasi-free peak complex. This is consistent with the attraction expected in the $I(J^P) = \frac{1}{2}(0^-)$ $\Lambda(1405)N$ s-wave channel shown in Ref. [7] to overlap substantially with K^-pp. Chirally motivated calculations of K^-pp find binding energies of few tens of MeV and larger widths, see the recent review [8]. Such relatively shallow K^-pp binding persists upon including the $\pi\Lambda N$ and $\pi\Sigma N$ lower-mass channels [42]. No bound-state signal has been found experimentally so far in this energy regime but several past experiments, notably the latest report from J-PARC's experiment E27 [41], claimed a bound state signal near the $\pi\Sigma N$ threshold, about 100 MeV below the K^-pp threshold. Such a deeply bound $I(J^P) = \frac{1}{2}(0^-)$ K^-pp state is unacceptable theoretically.

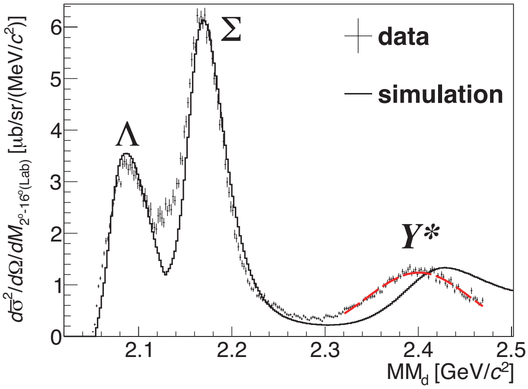

Fig. 6. J-PARC E27 missing-mass spectrum in $d(\pi^+, K^+)$ at 1.69 GeV/c [40].

The $\pi\Lambda N$–$\pi\Sigma N$ system, however, may benefit from strong meson–baryon p-wave interactions, fitted to the $\Delta(1232) \to \pi N$ and $\Sigma(1385) \to \pi\Lambda$–$\pi\Sigma$ form factors, by aligning isospin and angular momentum to $I(J^P) = \frac{3}{2}(2^+)$. Such a $\mathcal{S} = -1$ pion assisted dibaryon was studied in Ref. [4] by solving πYN coupled-channel Faddeev equations, thereby predicting a dibaryon resonance $\mathcal{Y}_{\frac{3}{2}2^+}$ slightly below the $\pi\Sigma N$ threshold ($\sqrt{s_{\text{th}}} \approx 2270$ MeV). Adding a $\bar{K}NN$ channel hardly matters, since its leading ${}^3S_1$ NN configuration is Pauli forbidden. Note that with isospin $I = \frac{3}{2}$, this dibaryon differs from the $I(J^P) = \frac{1}{2}(0^-)$ K^-pp and from the $I(J^P) = \frac{1}{2}(2^+)$ dibaryon listed in Table I which according to our calculations might lie almost 100 MeV above $\mathcal{Y}_{\frac{3}{2}2^+}(2270)$.

The $\mathcal{S} = -1$ $\mathcal{Y}_{\frac{3}{2}2^+}(2270)$ dibaryon is expected to have good overlap with ${}^5S_2$, $I = \frac{3}{2}$ $\Sigma(1385)N$ and $\Delta(1232)Y$ dibaryon configurations, the lower of which $\Sigma(1385)N$ lies about 50 MeV above the $\pi\Sigma N$ threshold. We emphasize that these quantum numbers differ from ${}^1S_0$, $I = \frac{1}{2}$ for $\Lambda(1405)N$ which is normally being searched upon. A recent search in

$$\begin{aligned} p + p \;&\to\; \mathcal{Y}^{++} + K^0 \\ &\quad\hookrightarrow\; \Sigma^+ + p \end{aligned} \tag{3}$$

by the HADES Collaboration at GSI [43] found no $\mathcal{Y}$ dibaryon signal. It is not clear whether the pp experiments were able to deal with as small cross sections as 0.1 μb or less that are likely to be needed in order to excite $\mathcal{Y}$ dibaryon candidates [38]. Other possible search reactions are

$$\begin{aligned} \pi^{\pm} + d \quad &\rightarrow \quad \mathcal{Y}^{++/-} + K^{0/+} \\ &\qquad \hookrightarrow \Sigma^{\pm} + p(n) \,, \end{aligned} \tag{4}$$

again offering distinct $I = \frac{3}{2}$ decay channels. Other decay channels such as

$$\begin{aligned} \pi^{+} + d \quad &\rightarrow \quad \mathcal{Y}^{+} + K^{+} \\ &\qquad \hookrightarrow \Sigma^{0} + p \end{aligned} \tag{5}$$

allow for both $I = \frac{1}{2}, \frac{3}{2}$. E27 has just reported [41] a dibaryon signal near the $\pi\Sigma N$ threshold in reaction (5). This requires further experimental study.

5. Charmed dibaryons

Pion assisted dibaryon candidates in the charm $\mathcal{C} = +1$ sector have been discussed recently in Ref. [44]. In this work, the same formalism applied earlier in the strangeness $\mathcal{S} = -1$ sector to the $\pi\Lambda N$ system [4] was applied to the charmed $\pi\Lambda_c N$ system, replacing the $\Lambda(1116)$ baryon by the $\Lambda_c(2286)$ charmed baryon and the $\Sigma(1385)$ resonance by the $\Sigma_c(2520)$ charmed resonance, but disregarding the coupling of $\pi\Lambda_c(2286)N$ to $\pi\Sigma(2455)N$. The $\Lambda_c(2286)N$ system was studied in a chiral constituent quark model [45] with a separable s-wave interaction. Separable p-wave interactions were used for the pion–baryon channels, dominated here by the $\Delta(1232)$ and $\Sigma_c(2520)$ resonances. Faddeev equations using relativistic kinematics were solved to look for bound states and resonances with quantum numbers $I(J^P) = \frac{3}{2}(2^+)$. Some of the tested models generated a very narrow bound-state or resonance below the $\Sigma_c(2455)N$ threshold, violating isospin in its strong decay to $\Lambda_c(2286)N$. Note that the $\Sigma_c(2455)N$ threshold lies ≈ 27 MeV above the $\pi\Lambda_c(2286)N$ threshold. The prediction of this charmed pion assisted dibaryon is robust since it depends little on the $\Lambda_c N$ spin-triplet s-wave interaction, even if the precise energy of the resonance is not pinned down between threshold at $\sqrt{s_{\rm th}} \approx 3363$ MeV and several tens of MeV above threshold. This resonance may be viewed as a $\Sigma_c(2520)N$ dibaryon bound state and is likely to be the *lowest lying* charmed dibaryon, considerably below the mass ≈ 3500 MeV predicted recently for a DNN bound state with quantum numbers $I(J^P) = \frac{1}{2}(0^-)$ that may be viewed also as a $\Lambda_c(2595)N$ dibaryon bound state [46]. The DNN bound state resembles in structure and quantum numbers the $K^- pp$ quasibound state that may also be viewed as a $\Lambda(1405)N$ dibaryon bound state.

Denoting the $I(J^P) = \frac{3}{2}(2^+)$ $\pi\Lambda_c N$ dibaryon by $\mathcal{C}$, this $\mathcal{C}_{\frac{3}{2}2^+}(3370)$ dibaryon candidate could be searched with proton and pion beams in the high-momentum hadron beam line extension approved at J-PARC by, *e.g.*

$$\begin{array}{rcl} p + p & \rightarrow & \mathcal{C}^{+++} + D^- \\ & & \hookrightarrow \Sigma_c^{++}(2455) + p \,, \end{array} \tag{6}$$

$$\begin{array}{rcl} \pi^+ + d & \rightarrow & \mathcal{C}^{+++} + D^- \\ & & \hookrightarrow \Sigma_c^{++}(2455) + p \,, \end{array} \tag{7}$$

$$\begin{array}{rcl} \pi^- + d & \rightarrow & \mathcal{C}^{+} + D^- \\ & & \hookrightarrow \Sigma_c^{+/0}(2455) + n/p \,. \end{array} \tag{8}$$

The $\mathcal{C}_{\frac{3}{2}2^+}(3370)$ dibaryon may be looked for both within inclusive missing-mass measurements that focus on the outgoing D^- charmed meson, and in exclusive invariant-mass measurements that focus on the decay $\Sigma_c(2455)N$ pair, provided that $\mathcal{C}$ is located above the $\Sigma_c(2455)N$ threshold.

6. Conclusion

It was shown how the 1964 Dyson–Xuong SU(6)-based classification and predictions of non-strange dibaryons [24] are confirmed in the hadronic model of $N\Delta$ and $\Delta\Delta$ pion-assisted dibaryons [10, 11]. The input for dibaryon calculations in this model consists of nucleons, pions and Δs, interacting via long-range pairwise interactions. These calculations reproduce the two nonstrange dibaryons established experimentally and phenomenologically so far, the $N\Delta$ dibaryon $\mathcal{D}_{12}$ [28, 29] and the $\Delta\Delta$ dibaryon $\mathcal{D}_{03}$ [1–3], and predict several exotic $N\Delta$ and $\Delta\Delta$ dibaryons. We note that, within the $\pi N\Delta$ three-body model of $\mathcal{D}_{03}$, $\mathcal{D}_{12}$ provides a two-body decay channel $\pi\mathcal{D}_{12}$ with threshold lower than $\Delta\Delta$ which proves instrumental in obtaining a relatively small width for $\mathcal{D}_{03}$ [11].

Finally, straightforward extensions of $\mathcal{S} = 0$ pion-assisted dibaryon phenomenology to strangeness $\mathcal{S} = -1$ and to charm $\mathcal{C} = +1$ were briefly discussed, particularly in connection to recent searches of kaonic nuclear clusters [8].

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