**NΔ & ΔΔ dibaryons revisited**

Hadron2013, Nara, Japan, Nov. 4–8 2013

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- Quark-based expectations for dibaryons.
- Non-strange dibaryons, from Dyson & Xuong (1964) to Oka & Yazaki (1980) & to Goldman et al. (1989): the INEVITABLE ΔΔ dibaryon.
- Experimental searches: COSY recent news.
- Long-range dynamics of pions, nucleons & Δ’s: 3-body calculations of NΔ & ΔΔ dibaryons.

A. Gal, H. Garcilazo, PRL 111, 172301 (2013)
Dibaryons as six-quark configurations
Color Magnetic (CM) gluon exchange interaction

For orbitally symmetric color-singlet $n$-quark cluster:

$$V_{CM} \approx \sum_{i<j} -(\lambda_i \cdot \lambda_j)(s_i \cdot s_j)M_0 \rightarrow \left[ -\frac{n(10-n)}{4} + \Delta P_f + \frac{S(S+1)}{3} \right] M_0$$

where $M_0 \sim 75$ MeV, $P_f = \pm 1$ for any symmetric/antisymmetric flavor pair, $\Delta P_f$ means with respect to the SU(3)$_f$ 1 antisymmetric representation of $n$ quarks, $n = 3$ for a baryon (B) and $n = 6$ for BB.

For $n = 6$, SU(3)$_f$ 1 [2,2,2] is Jaffe’s $H$ [PRL 38 (1977) 195]:

$$H \sim A[\sqrt{1/8} \Lambda \Lambda + \sqrt{1/2} N \Xi - \sqrt{3/8} \Sigma \Sigma,] \quad S = -2, \quad I = S = L = 0$$

$$< V_{CM} >_H = -2 < V_{CM} >_\Lambda = -2M_0$$

$$< V_{CM} >_H = -6M_0 = -\frac{3}{2}(< V_{CM} >_\Delta - < V_{CM} >_N) \sim -450 \text{ MeV}$$

<table>
<thead>
<tr>
<th>$S$</th>
<th>SU(3)$_f$</th>
<th>$I$</th>
<th>$J^\pi$</th>
<th>BB structure</th>
<th>$\Delta &lt; V_{CM} &gt;$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>[3,3,0] 10</td>
<td>0</td>
<td>3$^+$</td>
<td>$\Delta\Delta$</td>
<td>0</td>
</tr>
<tr>
<td>−1</td>
<td>[3,2,1] 8</td>
<td>1/2</td>
<td>2$^+$</td>
<td>$\sqrt{1/5} (N\Sigma^* + 2 \Delta\Sigma)$</td>
<td>$-M_0$</td>
</tr>
<tr>
<td>−2</td>
<td>[2,2,2] 1</td>
<td>0</td>
<td>0$^+$</td>
<td>$\sqrt{1/8} (\Lambda\Lambda + 2 N\Xi - \sqrt{3} \Sigma\Sigma)$</td>
<td>$-2M_0$</td>
</tr>
<tr>
<td>−3</td>
<td>[3,2,1] 8</td>
<td>1/2</td>
<td>2$^+$</td>
<td>$\sqrt{1/5} [\sqrt{2} N\Omega - (\Lambda\Xi^* - \Sigma^<em>\Xi + \Sigma\Xi^</em>)]$</td>
<td>$-M_0$</td>
</tr>
</tbody>
</table>

- Table suggests that the $S = −2$ H is the most bound. However, thresholds & other SU(3) breaking effects abort binding.
- Coupled-channel H near ΞN threshold, $\approx 26$ MeV above ΛΛ.
- Let’s focus on the nonstrange $\Delta\Delta$ dibaryon candidate.
Nonstrange s-wave dibaryon SU(6) predictions
F.J. Dyson, N.-H. Xuong, PRL 13 (1964) 815

<table>
<thead>
<tr>
<th>dibaryon</th>
<th>$I$</th>
<th>$S$</th>
<th>SU(3)</th>
<th>legend</th>
<th>mass</th>
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</thead>
<tbody>
<tr>
<td>$\mathcal{D}_{01}$</td>
<td>0</td>
<td>1</td>
<td>$\bar{10}$</td>
<td>deuteron</td>
<td>$A$</td>
</tr>
<tr>
<td>$\mathcal{D}_{10}$</td>
<td>1</td>
<td>0</td>
<td>$27$</td>
<td>$nn$</td>
<td>$A$</td>
</tr>
<tr>
<td>$\mathcal{D}_{12}$</td>
<td>1</td>
<td>2</td>
<td>$27$</td>
<td>$N\Delta$</td>
<td>$A + 6B$</td>
</tr>
<tr>
<td>$\mathcal{D}_{21}$</td>
<td>2</td>
<td>1</td>
<td>$35$</td>
<td>$N\Delta$</td>
<td>$A + 6B$</td>
</tr>
<tr>
<td>$\mathcal{D}_{03}$</td>
<td>0</td>
<td>3</td>
<td>$\bar{10}$</td>
<td>$\Delta\Delta$</td>
<td>$A + 10B$</td>
</tr>
<tr>
<td>$\mathcal{D}_{30}$</td>
<td>3</td>
<td>0</td>
<td>$28$</td>
<td>$\Delta\Delta$</td>
<td>$A + 10B$</td>
</tr>
</tbody>
</table>

Assuming ‘lowest’ SU(6) multiplet, 490, within $56 \times 56$.

$M = A + B[I(I + 1) + S(S + 1) - 2]$, $A = 1878$ MeV from $M(d) \approx M(v)$.

$B = 47$ MeV from $M(\mathcal{D}_{12}) \approx 2160$ MeV observed in $\pi^+d \rightarrow pp$.

Hence, $M(\mathcal{D}_{03}) = M(\mathcal{D}_{30}) \approx 2350$ MeV.
Quark-based model calculations of $\mathcal{D}_{03}$ & $\mathcal{D}_{12}$

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>$\mathcal{D}_{03}$ ($\Delta\Delta$)</td>
<td>2.35</td>
<td>2.36</td>
<td>2.46</td>
<td>2.38</td>
<td>2.20</td>
<td>$\leq2.26$</td>
<td>2.43</td>
<td>2.46</td>
<td>2.37</td>
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<tr>
<td>$\mathcal{D}_{12}$ ($N\Delta$)</td>
<td>2.16*</td>
<td>2.36</td>
<td>–</td>
<td>2.36</td>
<td>–</td>
<td>–</td>
<td>2.34*</td>
<td>2.17</td>
<td>$\approx2.17$</td>
<td></td>
</tr>
</tbody>
</table>

1. Dyson-Xuong, PRL 13 (1964) 815; *input.
Recent news from WASA@COSY
Evidence for $D_{03}(2370)$ $\Delta\Delta$ dibaryon, $B \sim 90$ & $\Gamma \sim 70$ MeV

$^3D_3 - ^3G_3$ pn resonance?

Adlarson et al. (WASA@COSY), PRL 106, 242302 (2011)

Total cross section from $pd \rightarrow d\pi^0\pi^0 + p_s$ at several energies, seen also in $pd \rightarrow d\pi^+\pi^- + p_s$. What makes it that narrow?
Pair correlations and particle distributions

Dalitz plot $M_{d\pi^0}^2$ vs. $M_{\pi^0\pi^0}^2$

$\cos(\Theta_d^*)$
d cm angular distribution: $J^P=3^+$ (solid), $J^P=1^+$ (dash)

Plots at $\sqrt{s}=2.38$ GeV

from Adlarson et al. (WASA@COSY), PRL 106, 242302 (2011)
Dalitz plot projections at $\sqrt{s}=2.38$ GeV

$M_{d\pi}^2$ at $\sqrt{s}=2.38$ GeV

$M_{\pi\pi}^2$ at $\sqrt{s}=2.38$ GeV

from Adlarson et al. (WASA@COSY), PRL 106, 242302 (2011)

Curves denote calculations for a $s$-channel resonance decaying to $\Delta\Delta$ with $J^P=3^+$ (solid) & $J^P=1^+$ (dash). Shaded areas denote phase-space distributions.
Long-range dynamics of dibaryons

A.Gal, H.Garcilazo, PRL 111, 172301 (2013)
$D_{12}$ $N\Delta$ dibaryon candidate

$\Delta N \quad I(J^P) = 1(2^+) \text{ Dibaryon}$

$NN \ ^1D_2 \text{ amplitude}$
$1880 < W < 2260$ MeV.
Hoshizaki resonance at
$W = 2144 - i55$ MeV

$NN \leftrightarrow \pi d$ reactions resonate near $N\Delta$ threshold at 2.17 GeV.
$D_{12}(2150)$ $N\Delta$ dibaryon near threshold (2.17 GeV)

- Long ago established in coupled-channel $pp(^1D_2) \leftrightarrow \pi^+d(^3P_2)$ scattering & reactions. Hoshizaki’s & Arndt et al’s analyses: $M \approx 2.14 - 2.17$ GeV, $\Gamma \approx 115$.

- Nonrelativistic $\pi NN$ Faddeev calculation, Ueda (1982): $M = 2.12$ GeV, $\Gamma = 120$ MeV.

- Our relativistic-kinematics calculation gives $M \approx 2.15$ GeV, $\Gamma \approx 120$ MeV.

- $M$ & $\Gamma$ robust to variations of $NN$ & $\pi N$ input.
For separable interactions, Faddeev equations reduce to one effective 2-body scattering equation. Solve homogeneous part for resonance poles.

- Given this $D_{12}(2150) \, N\Delta$ dibaryon, how does one find a related $N\Delta$-isobar form factor?
Construction of $N\Delta$ form factor

- Construct $(NN)_{\ell=2} - (NN')_{\ell=0} - (N\Delta')_{\ell=0}$ separable potential. $N'$—fictitious $P_{13}$ baryon with $m_{N'} = m_\pi + m_N$ to generate $\pi NN$ inelastic cut. $\Delta'$—stable $\Delta$ with $m_{\Delta'} = 1232$ MeV.

- No ad-hoc pole is introduced into $(N\Delta')_{\ell=0}$.

- Require form-factor cutoff momenta $\leq 3$ fm$^{-1}$ to be consistent with long-range physics e.g. no $\pi N \rightarrow \rho N$.

- Fitting $NN \delta^{(1D_2)}$ & $\eta^{(1D_2)}$ determines the $D_{12}(2150)$-isobar $(N\Delta')_{\ell=0}$ form factor.
Fitting $NN \delta^{(1D_2)}$ & $\eta^{(1D_2)}$

$NN^{1D_2}$ phase shift fit

$NN^{1D_2}$ inelasticity fit

Dashed: gwdac.phys.gwu.edu [SAID], Solid: best fit
Calculation of $D_{03}(2370) \Delta\Delta$ dibaryon in terms of $\pi$’s, $N$’s & $\Delta$’s

- Approximate $\pi\pi NN$ problem by $\pi N\Delta'$ problem.
- Separable pair interactions: $\pi N \Delta$-isobar form factor by fitting $\delta(P_{33})$; $N\Delta'$ $D_{12}(2150)$-isobar form factor by fitting $NN(1D_2)$ scattering.
- 3-body $S$-matrix pole equation reduces to effective $\Delta\Delta'$ diagram:
• Searching numerically for $S$-matrix resonance poles by going complex, $q_{j} \to q_{j} \exp(-i\phi)$, thus opening sections of the unphysical Riemann sheet to accommodate poles of the form $W = M - i\Gamma/2$.

• In the $\pi N$ propagator, where $\Delta'$ is a spectator, replace real mass $m_{\Delta'} = 1232$ MeV by $\Delta$-pole complex mass $m_{\Delta} = 1211 - i49.5 \times (2/3)$ MeV, factor $2/3$ accounting for quantum-statistics correlations between decay products of the two $I(J^P) = 0(3^+)$ $\Delta$’s, assuming $s$-wave decay nucleons.
Results & Discussion

- Using two different $P_{33}$ form factors, with spatial size 0.9 & 1.3 fm, we get $M = 2363 \pm 20$, $\Gamma = 65 \pm 17$ MeV, in good agreement with WASA@COSY.

- Although bound w.r.t. $\Delta\Delta$, $D_{03}(2370)$ is resonating w.r.t. the $\pi - D_{12}(2150)$ threshold. The subsequent decay $D_{12}(2150) \rightarrow \pi d$ is seen in the $\pi d$ Dalitz plot projection.

- Search for other, $NN$-decoupled dibaryon resonances: $D_{21}$ and $D_{30}$, arXiv:1308.6404 Bashkanov-Brodsky-Clement: Novel Six-Quark Hidden-Color Dibaryon States in QCD.
Summary

• The two experimentally established nonstrange (s-wave ?) dibaryons $D_{12}(2150)$ and $D_{03}(2370)$ are quantitatively derived from long range physics description requiring only pions, nucleons and $\Delta$’s for input.

• Search for other, in particular $D_{21}$ & $D_{30}$ dibaryon candidates.

• Develop EFT description for these dibaryons.

• Does $\Sigma(1385)$ play the role of $\Delta(1232)$ for strange dibaryon candidates?

Special thanks to my collaborator Humberto Garcilazo