On the new resonance d*(2380) --- calculations in a chiral quark model

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2. Possible interpretations

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   (B) Strong decays
   (C) Charge distribution

4. Summary, remarks and outlook
1 Observations of exotic

Ordinary versus “exotic” matter

- Baryon (proton, neutron, ...)
- Meson (pion, kaon, ...)
- Tetraquark
- Pentaquark
- Dibaryon
- Glueball
- Hybrid

Courtesy of J. Messchendorp
Charmonium-like particles - XYZ states

Near threshold, narrow width

“XYZ” Puzzle

XYZ states

11/14/2018
Observation of $J/\psi p$ resonances consistent with pentaquark states

Exotic Hadron Spectroscopy at LHCb:
Candidates for Tetra- and Pentaquark States

$\Lambda_b \rightarrow J/\psi K^- p$ decays

The LHCb Collaboration

Abstract
Observations of exotic structures in the $J/\psi p$ channel, that we refer to as pentaquark-charmonium states, in $\Lambda_b \rightarrow J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb$^{-1}$ acquired with the LHCb detector from 7 and 8 TeV $pp$ collisions. An amplitude analysis is performed on the three-body final-state that reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $380 \pm 8$ MeV and a width of $305 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4149.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred $J^P$ assignments are of opposite parity, with one state having spin $3/2$ and the other $5/2$.

Five-quark

$\Sigma_c \bar{D}, \Sigma_c^* \bar{D}, \Sigma_c \bar{D}^*, \Sigma_c^* \bar{D}^*, p \chi_c, \psi(2S)p$

$3^- / 2$, $5^+ / 2 (J^P \ ?)$

$P_c(4380), P_c^\prime(4449)$
Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum numbers \( I(J^P) = 0(3^+) \). The structure, containing six valence quarks, constitutes a dibaryon, and could be either an exotic compact particle or a hadronic molecule. The results answer the long-standing question of whether there are more eigenstates in the two-baryon system than just the deuteron ground-state. This fundamental question has been awaiting an answer since at least 1964, when first Freeman Dyson and later Robert Jaffe envisaged the possible existence of non-
The $d^*$ Resonance $I (J^P) = 0 (3^+)$

Baryon number = 2

Unusual narrow width

Neither NN (Roper), nor $\Delta\Delta$

Intermediate state

d*(2380)
Signals in np procese @ COSY

2π production processes

\[ \text{pn} \rightarrow d^*(2380) \]

Fusion

Non-fusion

PRL 106 (2011) 242302
PLB 721 (2013) 229
PRL 112 (2014) 202301
PRC 88 (2013) 055208
PLB 743 (2015) 325
Proc. STORI 2015
Characters of $d^*(2380)$

- $d^*$ mass locates between $\Delta\Delta$ and $\Delta N\pi$ thresholds
  
  Effect from threshold is expected small

  $$M_{\Delta N\pi} = 2310\text{MeV}$$
  $$M_{\Delta\Delta} = 2464\text{MeV}$$
  $$M_{d^*} \approx 2380\text{MeV}$$

- $d^*$ narrow width

  Possible 6q structure might be different from normal hadrons

Signals in other reactions @ COSY

**fusion $2\pi$ processes**

Review article: by Heinz Clement, Progress in Particle and Nuclear Physics, 93 (2017), 195-142

Measured also in fusion reactions to helium isotopes:

- $p + d \rightarrow ^3\text{He} + \pi^0 + \pi^0$
- $p + d \rightarrow ^3\text{He} + \pi^+ + \pi^-$
- $d + d \rightarrow ^4\text{He} + \pi^0 + \pi^0$
- $d + d \rightarrow ^4\text{He} + \pi^+ + \pi^-$
2、Possible interpretations

▲ Before COSY's observation

- Consists with COSY's measurement

Dyson(64) ------- symmetry analysis

Thomas(83) ------ bag model

Yuan(99) ------- $\Delta\Delta+CC$ quark cluster model

Jaffe(77)

Swart(78)

Oka(80)

Maltman(85)

Goldman(89)

Wang(95)......
After COSY's observation

- **Quark model**
  
  J. Ping (09/14) - 10 coupled channels QM
  
  F. Huang, Y. B. Dong et al. (14–18) -- ΔΔ + CC QM
  
  Bashkanov, Brodsky, Clement (13) -- ΔΔ + CC

- **Hadronic model**
  
  Gal (14) -- ΔNπ
  
  Kukulin (15, 16) -- D_{12π}

A. Compact 6q dominated exotic state

B. ΔNπ (or D_{12π}) resonant state
3. Compact 6q dominated $d^*$ (2380) in a chiral constituent quark model (A), Mass and wave function

SU(3) chiral QM + RGM approach

\[ V_{ij} = V_{ij}^{\text{conf}} + V_{ij}^{\text{OGE}} + V_{ij}^{\text{ch}} + V_{ij}^{\text{chv}} \]

\[ V_{ij}^{\text{ch}} = \sum_a (V_{ij}^{s(a)} + V_{ij}^{ps(a)}) \]

Interactive Lagrangian

\[ \mathcal{L}_I = -g_{ch} \bar{\Psi} \left( \sum_{a=0}^{8} \sigma_a \lambda_a + i \sum_{a=0}^{8} \pi_a \lambda_a \gamma_5 \right) \Psi \]

Model parameters: reproduce experimental data for NN systems---NN phase shifts,

\[ \text{BE}^{exp}_{d} = 2.22 \text{ MeV} \]
### Trial wavefunction:

\[ \Psi_{6q} = A \left[ \phi_{\Delta}(\xi_1, \xi_2) \phi_{\Delta}(\xi_4, \xi_5) \eta_{\Delta\Delta}(r) + \phi_{C}(\xi_1, \xi_2) \phi_{C}(\xi_4, \xi_5) \eta_{CC}(r) \right]_{S=3,I=0,C=(00)} \]

- **\(\Delta\):** \((0s)^3 [3]_{\text{orb}}, S = 3/2, I = 3/2, C = (00)\)
- **\(C\):** \((0s)^3 [3]_{\text{orb}}, S = 3/2, I = 1/2, C = (11)\)

\[ I(J^P) = 0(3^+) \]

### Hadronization---Channel wave function:

Using the projection method to integrate out the internal coordinates inside the clusters (or Hadronization approach)

\[ \Psi_{d*} = |\Delta\Delta\rangle \chi_{\Delta\Delta}(r) + |CC\rangle \chi_{CC}(r) \]

- \(\chi_{\Delta\Delta}(r) \equiv \langle \phi_{\Delta}(\xi_1, \xi_2) \phi_{\Delta}(\xi_4, \xi_5) | \Psi_{6q} \rangle\),
- \(\chi_{CC}(r) \equiv \langle \phi_{C}(\xi_1, \xi_2) \phi_{C}(\xi_4, \xi_5) | \Psi_{6q} \rangle\),

\(\eta_{\Delta\Delta}(r)\) and \(\eta_{CC}(r)\) are not orthogonal

The two components are orthogonal due to the quark exchange effect
(A), Mass and wave function

Results:

\( d^* \) WFs

CPC 39 (2015) 071001
- Binding energy

\[ BE_{d^*}^{th} = 84 \text{MeV} \quad \text{BE}_{d^*}^{exp/'} = 84 \text{MeV} \]

<table>
<thead>
<tr>
<th>( d^* ) Binding Energy (MeV)</th>
<th>Ext. SU(3) (f/g=0)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( \Delta \Delta )</td>
</tr>
<tr>
<td></td>
<td>(L=0,2)</td>
</tr>
<tr>
<td>62.3</td>
<td>83.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fraction of Wave Function (%)</th>
<th>( \Delta \Delta ) (L=0)</th>
<th>( \Delta \Delta ) (L=2)</th>
<th>( \text{CC} ) (L=0)</th>
<th>( \text{CC} ) (L=2)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>98.01</td>
<td>1.99</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>31.22</td>
<td>0.45</td>
<td>68.33</td>
<td>0.00</td>
</tr>
</tbody>
</table>
Reason for the large component of CC (68%)

\[ P_{36} = P_{36}^r P_{36}^{sfc} \]

\[ I(J^P) = 0(3^+) \]

1). Intrinsic character of \( d^* \) ------ \( <P_{36}^{sfc}> \)
   quark exchange effect of sfc large (negative: -4/9)

2). Dynamical effect------
   (SI=30), OGE and vector meson exchange induced \( \Delta - \Delta \) short range interaction is attractive

Two cluster closer \( \rightarrow \) large CC component

\( d^* \) deep bound and narrow width

\( d^* \) might be a 6q dominant state!
(B), Strong decays

2\pi decay widths

Three-body decay

\[ d^* \rightarrow d\pi^0\pi^0 (d\pi^+\pi^-) \]
\[ d^* \rightarrow pp\pi^-\pi^0 \]

Four-body decay

Typical diagrams

\[ d^* \rightarrow np\pi^0\pi^0 (np\pi^+\pi^-) \]
\[ d^* \rightarrow nn\pi^0\pi^+ \]

Parameter:

qq\pi Interaction

\[ \Delta \rightarrow N\pi \]

Coupling & form factor

\[ \Gamma_{\Delta\rightarrow\pi N} = \frac{4}{3\pi} k_\pi^3 (g_{qq\pi} I_0)^2 \frac{\omega_N}{M_\Delta}, \]

PRC91, (2015) 064002
PRC94, (2016) 014003
<table>
<thead>
<tr>
<th>Decay channel</th>
<th>Theor.(MeV)</th>
<th>Expt.(MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d^* \rightarrow d\pi^+\pi^-$</td>
<td>16.8</td>
<td>16.7</td>
</tr>
<tr>
<td>$d^* \rightarrow d\pi^0\pi^0$</td>
<td>9.2</td>
<td>10.2</td>
</tr>
<tr>
<td>$d^* \rightarrow p\pi^+\pi^-$</td>
<td>20.6</td>
<td>21.8</td>
</tr>
<tr>
<td>$d^* \rightarrow p\pi^0\pi^0$</td>
<td>9.6</td>
<td>8.7</td>
</tr>
<tr>
<td>$d^* \rightarrow p\pi^0\pi^-$</td>
<td>3.5</td>
<td>4.4</td>
</tr>
<tr>
<td>$d^* \rightarrow n\pi^0\pi^+$</td>
<td>3.5</td>
<td>4.4</td>
</tr>
<tr>
<td>$d^* \rightarrow pn$</td>
<td>8.7</td>
<td>8.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>71.9</strong></td>
<td><strong>74.9</strong></td>
</tr>
</tbody>
</table>

**Discussions:**

* FSI is about 26~30%

* Isospin breaking factor

\[
\frac{\Gamma(d^* \rightarrow d\pi^+\pi^-)}{\Gamma(d^* \rightarrow d\pi^0\pi^0)} \sim 1.8 \ (1.6, \ 2.0)
\]

\[
\frac{\Gamma(d^* \rightarrow p\pi^+\pi^-)}{\Gamma(d^* \rightarrow p\pi^0\pi^0)} \sim 2.2 \ (2.5, \ 2.5)
\]

* All partial and total widths agree with data

\[
\Gamma^{exp'} = 70 \sim 75 \, MeV
\]

\[
\Gamma^{th} \approx 72 \, MeV
\]

Idearl!

* Too large width for $(\Delta\Delta)$ component only

<table>
<thead>
<tr>
<th>Decay channel</th>
<th>$M_{d^*}$ (MeV)</th>
<th>$(100%)\Delta\Delta$</th>
<th>Expt</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2374</td>
<td>2375</td>
<td></td>
</tr>
<tr>
<td>Decay channel</td>
<td>$\Gamma$(MeV)</td>
<td>$\Gamma$(MeV)</td>
<td></td>
</tr>
<tr>
<td>$d^* \rightarrow d\pi^0\pi^0$</td>
<td>17.0</td>
<td>10.2</td>
<td></td>
</tr>
<tr>
<td>$d^* \rightarrow d\pi^+\pi^-$</td>
<td>30.8</td>
<td>16.7</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>132.8</strong></td>
<td><strong>74.9</strong></td>
<td></td>
</tr>
</tbody>
</table>

The narrow width is due to large CC component
Single-$\pi$ decay

\[ \sigma_{NN\to NN\pi}(I = 0) = 3(2\sigma_{n p\to pp\pi^-} - \sigma_{p p\to pp\pi^0}) \]

- **Experimental status**
  The WASA-@-COSY Collaborations, arXiv:1702.07212v1 [nucl-ex]
  PLB774 (2017), 599-607
  Dash-dotted line illustrates a 10% $d^*$ resonance contribution

**Upper limit of branching ratio for** $d^*(2380) \to NN\pi$
**is 9%.**

This channel might serve as a test
compact 6q dominated case:

Typical diagrams: pion emitted from cluster II

Fig. 1. Six possible ways to emit pion only from the $\Delta\Delta$ component of $d^*$ in the $d^* \rightarrow NN\pi$ decay process. The outgoing pion with momenta $\vec{k}$ is emitted from $\Delta_2$. The other six sub-diagrams with pion emitted from $\Delta_1$ are similar, and then are not shown here for reducing the size of the figure.
\[ \Psi_{d^*} = |\Delta\Delta\rangle \chi_{\Delta\Delta}(r) + |CC\rangle \chi_{CC}(r) \]

Intermediate states: \((N,N^*,\Delta,\Delta^*)\)
Low-lying resonances need to be considered

From quark model

\[ \frac{g_{\pi\Delta}}{4\pi} = \frac{1}{25} \frac{M_{\Delta}^2}{M_N^2} \frac{g_{\pi NN}^2}{4\pi}, \quad g_{\pi\Delta} \text{ small} \]

1. \(C \rightarrow \Delta\), interaction should be color and isospin-dependent
2. \(CC(SI=3,0) \rightarrow NN^*(1400)\), D-wave of OGE is required

The suppressions enable to ignore the contribution from the CC component in \(d^*\)

Our prediction, 1% is compatible with the Exp’t upper-limits
(C), Charge distribution of $d^*(2380)$

For a spin=3 system:

$2S+1=7$ form factors (related to the size of system)

<table>
<thead>
<tr>
<th>$d^*(2380)$</th>
<th>Cases</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$rms$ (fm)</td>
<td>1.09</td>
<td>0.72</td>
<td></td>
</tr>
</tbody>
</table>
Charge Distributions

Compact $\Delta\Delta + CC$

Scenario A
Single channel
- $\Delta\Delta$
Coupled-channel
- $\Delta\Delta$
- CC
Total

Scenario B ($D_{12}\pi$)
- $\epsilon = 0.25$ MeV
- $\epsilon = 18$ MeV

Scenarios A and B

<table>
<thead>
<tr>
<th>$d^*(2380)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cases</td>
</tr>
<tr>
<td>$rms$ (fm)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$D_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cases</td>
</tr>
<tr>
<td>$rms$ (fm)</td>
</tr>
</tbody>
</table>
4. Summary, Remarks, and outlook

\textbf{d*: Hexaquark dominated state:}

\((CC \text{ component } \sim 66-68\% \text{ in } \Delta\Delta + CC)\)

\textbf{Compact 6q dominated}  \hspace{1cm}  \Delta N\pi \text{ (or } D_{12}\pi) \text{ system}  \hspace{1cm}  \text{A. Gal, PLB769 (2017) 436}

\textbf{Good}  \hspace{1cm} \text{Mass}  \hspace{1cm} \textbf{Good}

\textbf{Double-pion strong decays}

\textbf{d*(2380) single-}\pi\textbf{ decay}  \hspace{1cm} \text{Exp}'t \text{ BR } \leq 9\%  \hspace{1cm} d^*(2380) \rightarrow NN\pi

\text{our predicted BR of 1}\%

\text{the BR for } \Delta N\pi \text{ (or } D_{12}\pi) \text{ is large}

in the mixing case
Suggest other experimental searches

- $\gamma + d$  
  Process (Mainz, Jlab.)

- $\gamma \rightarrow \bar{d}^* + X$  
  Process (Belle)

\[
\text{[ BR}(\gamma \rightarrow \bar{d} + x) \sim 2.86 \times 10^{-5} \text{ ]}
\]

- $e^+ + e^- \rightarrow \bar{d}^* + p + n$  
  Processes (Belle?)

If the $d^*$ is further confirmed by experiments, our interpretation looks reasonable. Thus, it might be a state with $6q$ structure dominant and moreover, the more information about the short range interaction is expected.

Thanks!
BACKUP SLICES
Analysis: Large component of CC (67%) in $d^*$?

\[ \Psi_{6q} = (1 - 9P_{36})[\phi_\Delta \phi_\Delta \eta \Delta \Delta (r)] \text{SIC}\,=\,30(00) \]

\[ + (1 - 9P_{36})[\phi_C \phi_C \eta CC (r)] \text{SIC}\,=\,30(00) \]

(1) (2) (3) (4)

\[ \chi_{\Delta \Delta} (r) \equiv \langle \phi_\Delta (\xi_1, \xi_2) \phi_\Delta (\xi_4, \xi_5) | \Psi_{6q} \rangle, \quad (1) (2) (4) \text{ terms} \]

\[ \chi_{CC} (r) \equiv \langle \phi_C (\xi_1, \xi_2) \phi_C (\xi_4, \xi_5) | \Psi_{6q} \rangle, \quad (3) (4) (2) \text{ terms} \]

\[ \Psi_{d^*} = |\Delta \Delta\rangle \chi_{\Delta \Delta} (r) + |CC\rangle \chi_{CC} (r) \]

\[ \chi_{CC} \] contains the contri. From (2), from $\Delta \Delta$ exchanged terms.

Thus \( P_{36} \) Exchange is important!

\[ P_{36} = P_{36}^{r} P_{36}^{sfc} \] \( d^* \) has $\Delta \Delta$ and CC components
Before the discovery of d*

- A pioneer discussion from symmetry: J. Dyson, PRL 13, 815 (1964)

Two baryon systems
SU(6) classification:

Anti-symmetric representations:
Non-strange states

(I, J) = (3,0)(2,1)(1,0)(1,2)(0,1)(0,3) 6 states

Casmir operator reduced
a mass formula

If B' = B'' = B, the obtained deuteron mass
1876 MeV, and then, obtain A,

Choose B = 50 MeV, Then, $M_{d^*} = 2376$ MeV
<P_{36}^{sfc}> exchange effect in spin-flavor-color spaces

<table>
<thead>
<tr>
<th>intrinsic</th>
<th>(ΔΔ)_{SI=30}</th>
<th>(ΔΔ)_{SI=30}</th>
<th>(CC)_{SI=30}</th>
</tr>
</thead>
<tbody>
<tr>
<td>(ΔΔ)_{SI=30}</td>
<td>(ΔΔ)_{SI=30}</td>
<td>(CC)_{SI=30}</td>
<td>(CC)_{SI=30}</td>
</tr>
</tbody>
</table>

\[
\begin{array}{c}
<\mathbf{P}_{36}^{sfc}> \\
\frac{1}{9} & \frac{4}{9} & \frac{7}{9}
\end{array}
\]

\[P_{36}^{36} = P_{36}^{r} P_{36}^{sfc}\]

if it large

\[<P_{36}^{r}> \sim 1\]

should also large

\[<P_{36}^{r}>\]

is determined by the dynamical wave function

The effective Δ-Δ interaction induced by OGE and vector meson exchange enables the short range interaction attractive.

\[<\mathbf{P}_{36}>\]

For d*

\[\rightarrow \text{Two clusters } \Delta\Delta \text{ closer, } <\mathbf{P}_{36}^{r}> \text{ is not small}\]

1). d* special characters

spin-flavor-color spaces exchange effect: model independent

2). ΔΔ (SI=30), Δ-Δ short range interaction is attractive

Dynamical effect \[\rightarrow\] Model dependent

\[P_{36}\]

Effect large, large CC component

d* deep bounded and narrow width

Reason for the large component of CC (67%)
A. Compact 6q dominated exotic state

(a) In 1999, proposed d* with ΔΔ+CC structure

X.Q.Yuan, Z.Y.Zhang, Y.W.Yu, P.N.Shen, PRC 60 (1999) 045203

- d* binding energy: 40–80 MeV
- CC enhances binding energy by 20 MeV

(b) In 2013, proposed narrow d* width due to Harvey formula

\[ |\psi_{d^*}\rangle = \sqrt{\frac{1}{5}} |\Delta\Delta\rangle + \sqrt{\frac{4}{5}} |6Q\rangle \]


(c) In 2014, gave CC fraction of 68% in d*(ΔΔ+CC )

Decay widths

Three-body decay

\[ \Gamma_{d^* \rightarrow d\pi^0\pi^0} = \frac{1}{2!} \int d^3k_1 d^3k_2 d^3p_d (2\pi)^3 \delta^3(\vec{k}_1 + \vec{k}_2 + \vec{p}_d) \times \delta(\omega_{k_1} + \omega_{k_2} + E_{p_d} - M_{d^*}) |M_{if}^{\pi^0\pi^0}|^2 \]

\[ M_{if}^{\pi^0\pi^0} = \frac{1}{\sqrt{3}} \sum \frac{C_{1m_1} C_{2m_2} C_{3m_3} C_{4m_4} I_1 I_2}{\sqrt{f_{k_1} f_{k_2} f_{p_d}}} \times \int d^3q \frac{\chi_d^*(\vec{q} - \frac{1}{2}\vec{k}_1)}{E_{\Delta}(q) - E_N(q - k_1) - \omega_1} \]

\[ + \frac{\chi_d^*(\vec{q} + \frac{1}{2}\vec{k}_1)}{E_{\Delta}(q) - E_N(q - k_2) - \omega_2} \]

\[ + \frac{\chi_d^*(\vec{q} - \frac{1}{2}\vec{k}_1)}{E_{\Delta}(-q) - E_N(-q - k_1) - \omega_1} \]

\[ + \frac{\chi_d^*(\vec{q} + \frac{1}{2}\vec{k}_2)}{E_{\Delta}(-q) - E_N(-q - k_2) - \omega_2} \] \[ \times \chi_d^*(\vec{q}) \]

Four-body decay

\[ \Gamma_{d^* \rightarrow pn\pi^0\pi^0} = \frac{1}{2!2!} \int d^3k_1 d^3k_2 d^3p_1 (2\pi)^3 \delta(\Delta E) \times |M(k_1, k_2; p_1)|^2 \]

\[ M(k_1, k_2; p_1) = M^{\text{bare}}(k_1, k_2; p_1) \times \mathcal{I} \]

\[ \mathcal{I} = J^{-1}(k) = C(k^2) \frac{\sin \delta e^{i\delta}}{k} \]

\[ M^a(k_1, k_2; p_1) = \int d^3p_2 d^3q [\mathcal{H} S_f \mathcal{H}] \Psi_{d^*}(q) \times \delta^3(\vec{p}_1 + \vec{k}_1 - \vec{q}) \delta(\vec{p}_2 + \vec{k}_2 + \vec{q}) \]

\[ = \int d^3p_2 d^3\delta^3(\vec{p}_1 + \vec{p}_2 + \vec{k}_1 + \vec{k}_2)[\mathcal{H} S_f \mathcal{H}] \times \Psi_{d^*}(-\vec{p}_2 - \vec{k}_2) \]

\[ d^* \rightarrow np\pi^0\pi^0 \quad (np\pi^+\pi^-) \]
Naïve quark model

Nucleon

\[ \frac{\mu_p}{\mu_n} = -\frac{3}{2} \rightarrow -\frac{2.79}{1.91_{EXPT}}. \]

\[
\begin{align*}
d^*(2380) & \quad \Delta\Delta + CC & \quad \mu_{d^*} = \frac{M_{d^*}}{m_q} & \approx 7.6 \\
d^*(2380) & \quad D_{12}\pi & \quad \mu_{d^*} = \frac{2M_{d^*}}{3m_q} & \approx 5.1
\end{align*}
\]
Form factors: $2S+1$ relative to size \textit{arXiv:1704.01253}

**Nucleon(1/2):**

$$< N(p') | J_{N}^{\mu} | N(p) > = \bar{U}_{N}(p') \left[ F_{1}(Q^{2})\gamma^{\mu} + i\frac{\sigma^{\mu\nu}q_{\nu}}{2M_{N}}F_{2}(Q^{2}) \right] U(p),$$

$$G_{E}(Q^{2}) = F_{1}(Q^{2}) - \eta F_{2}(Q^{2}), \quad G_{M}(Q^{2}) = F_{1}(Q^{2}) + F_{2}(Q^{2}),$$

**Breit frame**

$$< N(\bar{q}/2) | J_{N}^{0} | N(-\bar{q}/2) > = (1+\eta)^{-1/2} \chi_{s'}^{+} \chi_{s} G_{E}(Q^{2})$$

$$< N(\bar{q}/2) | J_{N}^{\pm} | N(-\bar{q}/2) > = (1+\eta)^{-1/2} \chi_{s'}^{+} \sigma \frac{\bar{q}}{2M_{N}} \chi_{s} G_{M}(Q^{2}).$$

**Deuteron(1):**

$$J_{jk}^{\mu}(p', p) = \epsilon_{j}^{\star\alpha}(p') S_{\alpha\beta}^{\mu} \epsilon_{k}^{\beta}(p)$$

$$S_{\alpha\beta}^{\mu} = - \left[ G_{1}(Q^{2})g_{\alpha\beta} - G_{3}(Q^{2}) \frac{Q_{\alpha}Q_{\beta}}{2m_{D}^{2}} \right] P^{\mu} - G_{2}(Q^{2})(Q_{\alpha}g_{\beta}^{\mu} - Q_{\beta}g_{\alpha}^{\mu}),$$

$$G_{C}(Q^{2}) = G_{1}(Q^{2}) + \frac{2}{3}\eta_{D}G_{2}(Q^{2}), \quad G_{M}(Q^{2}) = G_{2}(Q^{2}),$$

$$G_{Q}(Q^{2}) = G_{1}(Q^{2}) - G_{2}(Q^{2}) + (1+\eta_{D})G_{3}(Q^{2}),$$

**Breit frame**

$$G_{C}(Q^{2}) \rightarrow \frac{1}{3} \sum_{\lambda} < p', \lambda | J^{0} | p, \tilde{\lambda} >.$$