A study of $d^*(2380)$ resonance

Yubing Dong
Institute of High Energy Physics (IHEP),
Chinese Academy of Sciences

Collaborators: Qifang Lyu, Pengnian Shen, Fei Huang, Zongye Zhang

IV International conference of particle physics and astrophysics
Content

1. Observation

2. Interpretations

3. Compact 6-quark dominated structure in chiral constituent quark model
   (A) Mass and wave function
   (B) Strong decays
   (C) Charge distribution

4. Summary and remarks
Ordinary or exotic

Baryon

- proton, neutron, ...

Meson

- pion, kaon, ...

Tetraquark

- quark, antiquark, ...

Pentaquark

- quark, antiquark, ...

Dibaryon

- quark, antiquark, ...

Glueball

- hadron, quark, antiquark, ...

Hybrid
Charmonium-like particles - Exotic XYZ states

Example from Barnes, Godfrey, Swanson:

\[ V_0(r) = -\frac{4\alpha_s}{3r} + br + \frac{32\pi\alpha_s}{9m_c^2} \delta_\sigma(r) \vec{S}_c \cdot \vec{S}_\bar{c} \]

(Coulomb + Confinement + Contact)

\[ V_{\text{spin-dep}} = \frac{1}{m_c^2} \left[ \left( \frac{2\alpha_s}{r^3} - \frac{b}{2r} \right) \vec{L} \cdot \vec{S} + \frac{4\alpha_s}{r^3} T \right] \]

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)
(New resonances, Five-Quark)

Pentaquark states \( P_c(4380)^+ \), & \( P_c(4450)^+ \)

Observation of \( J/\psi p \) resonances consistent with pentaquark states

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

\[ \Lambda_b \rightarrow K \rightarrow p + J/\psi \rightarrow \mu^- \mu^+ \]

\[ b \rightarrow c + \bar{c}s \]
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 $I(J^P) = 0(3^+)$...Since 2009.
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 processes @ COSY

2π production processes

Fusion

\( np \rightarrow d^*(2380) \)

Non-fusion

\( pp\pi^-\pi^0 \)

\( pn\pi^0\pi^0 \)

\( pn\pi^+\pi^- \)

np scattering process

PRL 106 (2011) 242302
PLB 721 (2013) 229
PLB 743 (2015) 325
Proc. STORI 2015

PRL 112 (2014) 202301
PRC 88 (2013) 055208

WASA data

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

\[
\begin{align*}
M_{\Delta N\pi} &= 2310\text{MeV} \\
M_{d^*} &\approx 2380\text{MeV} \\
M_{\Delta\Delta} &= 2464\text{MeV} \\
\Gamma_{d^*} &\approx 70\text{MeV}
\end{align*}
\]

- $d^*$ narrow width
  - Possible 6$q$ structure might be different from normal hadrons

Signals in other reactions @ COSY

- fusion $2\pi$ processes

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) ΔΔ+CC quark cluster model

▲ 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
  - A. Compact 6q dominated exotic state
- Hadronic model
  - Gal (14) - ΔNπ
  - Kukulin (15, 16) - D_{12π}
  - B. ΔNπ (or D_{12π}) resonant state

\[ d^*(2380) \]
\[ I(J^p) = 0 (3^+) \]

• Other predictions
  - Jaffe(77)
  - Swart(78)
  - Oka(80)
  - Maltman(85)
  - Goldman(89)
  - Wang(95)
3. Compact 6q dominated d\(^*\) (2380) in chiral constituent quark model

(A)Mass and wave function

SU(3) chiral QM + RGM approach

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

\[ \text{BE}^{\exp}_d = 2.22 \text{ MeV} \]

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

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

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

Trial wavefunction: \( I(J^P) = 0(3^+) \)

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

Hadronization---Channel wave function:

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

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

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

The two components are orthogonal due to the quark exchange effect
**Results:**

Wave function

CPC 39 (2015) 071001

- **Binding energy**

\[ \text{BE}^{\text{th}}_{d^*} = 84 \text{MeV} \]

\[ \text{BE}^{\text{exp}/t}_{d^*} = 84 \text{MeV} \]

**d* WFs**

![Graph showing wave functions]

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

\( C \) : \((0s)^3 [3]_{\text{orb}}, S = 3/2, I = 1/2, C = (11) \)
Reason for the large component of CC (68%)

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

1). Intrinsic character of \( d^* \) -----

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

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

▲ 2π decay widths

Three-body decay

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

Four-body decay

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

Typical diagrams

Parameter:

\[ qq\pi \]

Interaction

\[ \Delta \rightarrow N\pi \]

Coupling & form factor

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

\[ \mathcal{H}_{qq\pi} = g_{qq\pi} \vec{\sigma} \cdot \vec{k}_\pi \tau \cdot \phi \frac{1}{(2\pi)^{3/2} \sqrt{2\omega_\pi}}, \]

PRC91, (2015) 064002
PRC94, (2016) 014003
### Discussions:

* FSI is about 26~30%

* Isospin breaking factor

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

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

* Too large width for (ΔΔ) component only

* All partial and total widths agree with data

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

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

The narrow width is due to large CC component
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 $d^*(2380) \rightarrow NN\pi$ is 9%.

This channel might serve as a test for different interpretations, since the result of the $\Delta\pi N$ (or $D_{12}\pi$) is about 18%.
Theoretical status

- 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.
Our prediction, 1% is compatible with the Exp’t upper-limits
2S+1=7 form factors

Compact ΔΔ+CC

Scenario A
- Single channel
- Coupled-channel
  - ΔΔ
  - CC

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

<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 and Remarks

d*: Hexaquark dominated state:

(CC component ~ 66-68% in ΔΔ+CC)

**Compact 6q dominated**

PLB769 (2017) 223

**ΔNπ (or D_{12}π) system**

A.Gal, PLB769 (2017) 436

**Mass**

Double-pion strong decays

Good

Exp't BR ≤ 9% \( d^*(2380) \rightarrow NN\pi \)

Good

**d*(2380) single-\(\pi\) decay**

the resultant BR for \(\Delta N\pi\) (or \(D_{12}\pi\)) is about 18%.

in the mixing case

\[
\alpha \Gamma_\langle + (1 - \alpha) \Gamma_\rangle = \Gamma_{NN\pi\pi}^{d^*}
\]

\(\Gamma_\rangle = 100\) MeV

\(\Gamma_{NN\pi\pi}^{d^*} = 60\) MeV

if \(\Gamma_\langle = 44\) MeV

\(\alpha = \frac{5}{7}\)

BR can be 9%

our predicted BR of 1% is compatible with the exp't upper limit of 9%
If the d* is further confirmed by experiments, we believe that our interpretation is reasonable. Thus, it is a state with 6q structure dominant and moreover, the more information about the short range interaction is expected.

Thanks!
Decay widths

Three-body decay

\[ \Gamma_{d^* \rightarrow d\pi^0\pi^0} = \frac{1}{2!} \int d^3k_1 d^3k_2 d^3p_d (2\pi)^3 \delta^3(k_1 + k_2 + p_d) \times \delta (\omega_{k_1} + \omega_{k_2} + E_{p_d} - M_{d^*}) |\mathcal{M}_{if}^{\pi^0\pi^0}|^2 \]

\[ \mathcal{M}_{if}^{\pi^0\pi^0} = \frac{1}{\sqrt{3}} \sum F_1 F_2 k_{1,\mu} F_2 k_{2,\nu} I_{1,1}^0 I_{1,1}^0 C_{1,1,\mu} C_{1,1,\mu} C_{1,1,\mu} C_{1,1,\mu} \]

\[ \times \int d^3q \left[ \frac{\chi_d^*(\vec{q} - \frac{1}{2}\vec{k}_{12})}{E_{\Delta}(q) - E_N(q - k_1) - \omega_1} + \frac{\chi_d^*(\vec{q} + \frac{1}{2}\vec{k}_{12})}{E_{\Delta}(q) - E_N(q - k_2) - \omega_2} \right. \]

\[ + \frac{\chi_d^*(\vec{q} + \frac{1}{2}\vec{k}_{12})}{E_{\Delta}(-q) - E_N(-q - k_1) - \omega_1} \]

\[ \left. + \frac{\chi_d^*(\vec{q} - \frac{1}{2}\vec{k}_{12})}{E_{\Delta}(-q) - E_N(-q - k_2) - \omega_2} \right] \chi_d^*(\vec{q}) \]

Four-body decay

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

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

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

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

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

\[ d^* \rightarrow np\pi^0\pi^0 \ (np\pi^+\pi^-) \]
C, Form factors (charge distributions)

Form factors: $2S+1$ relative to size  

arXiv:1704.01253

Nucleon(1/2): 

\[
\langle N(p') \mid J_N^\mu \mid N(p) \rangle = U_N(p') \left[ F_1(Q^2) \gamma^\mu + i \frac{\sigma^{\mu\nu} q_\nu}{2M_N} F_2(Q^2) \right] U(p),
\]

\[
G_E(Q^2) = F_1(Q^2) - \eta F_2(Q^2), \quad G_M(Q^2) = F_1(Q^2) + F_2(Q^2),
\]

Breit frame

\[
\langle N(\bar{q}/2) \mid J_N^0 \mid N(-\bar{q}/2) \rangle = \left( 1 + \eta \right)^{-1/2} \chi_s^+ \chi_s G_E(Q^2)
\]

\[
\langle N(\bar{q}/2) \mid J_N^- \mid N(-\bar{q}/2) \rangle = \left( 1 + \eta \right)^{-1/2} \chi_s^+ \frac{\vec{\sigma} \times \vec{q}}{2M_N} \chi_s G_M(Q^2).
\]

Deuteron(1):

\[
J_{jk}^\mu(p', p) = \epsilon_{j^*}^\alpha(p') S_{\alpha\beta}^\mu \epsilon_k^\beta(p)
\]

\[
S_{\alpha\beta}^\mu = - \left[ G_1(Q^2) g_{\alpha\beta} - G_3(Q^2) \frac{Q_\alpha Q_\beta}{2m_D^2} \right] P^\mu - G_2(Q^2) (Q_\alpha g_\beta^\mu - Q_\beta g_\alpha^\mu),
\]

\[
G_C(Q^2) = G_1(Q^2) + \frac{2}{3} \eta_D G_2(Q^2), \quad G_M(Q^2) = G_2(Q^2),
\]

\[
G_Q(Q^2) = G_1(Q^2) - G_2(Q^2) + (1 + \eta_D) G_3(Q^2)
\]

Breit frame

\[
G_C(Q^2) \quad \rightarrow \quad \frac{1}{3} \sum_\lambda \langle p', \lambda \mid J^0 \mid p, \lambda \rangle.
\]
For a spin=3 system:

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

Wave Function

Charge Distribution

rms

Compact ΔΔ+CC

Scenario A (d*)

Scenario A (Single channel)

Coupled-channel

ΔΔ

CC

Total

r_{rms} (fm)

<table>
<thead>
<tr>
<th>Cases</th>
<th>A1</th>
<th>A2</th>
</tr>
</thead>
<tbody>
<tr>
<td>d*(2380)</td>
<td>1.09</td>
<td>0.72</td>
</tr>
</tbody>
</table>