Study of D_{03} and D_{30} dibaryons in a SU(3) chiral constituent quark model

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Refs.

1. A series papers
2. PPNP 131, 104045
3. Sci. China Phys. Mech. Astron. 68, 232011

Outline

1, Introduction: Exotic states & d*(2380)--D_{03} dibaryon

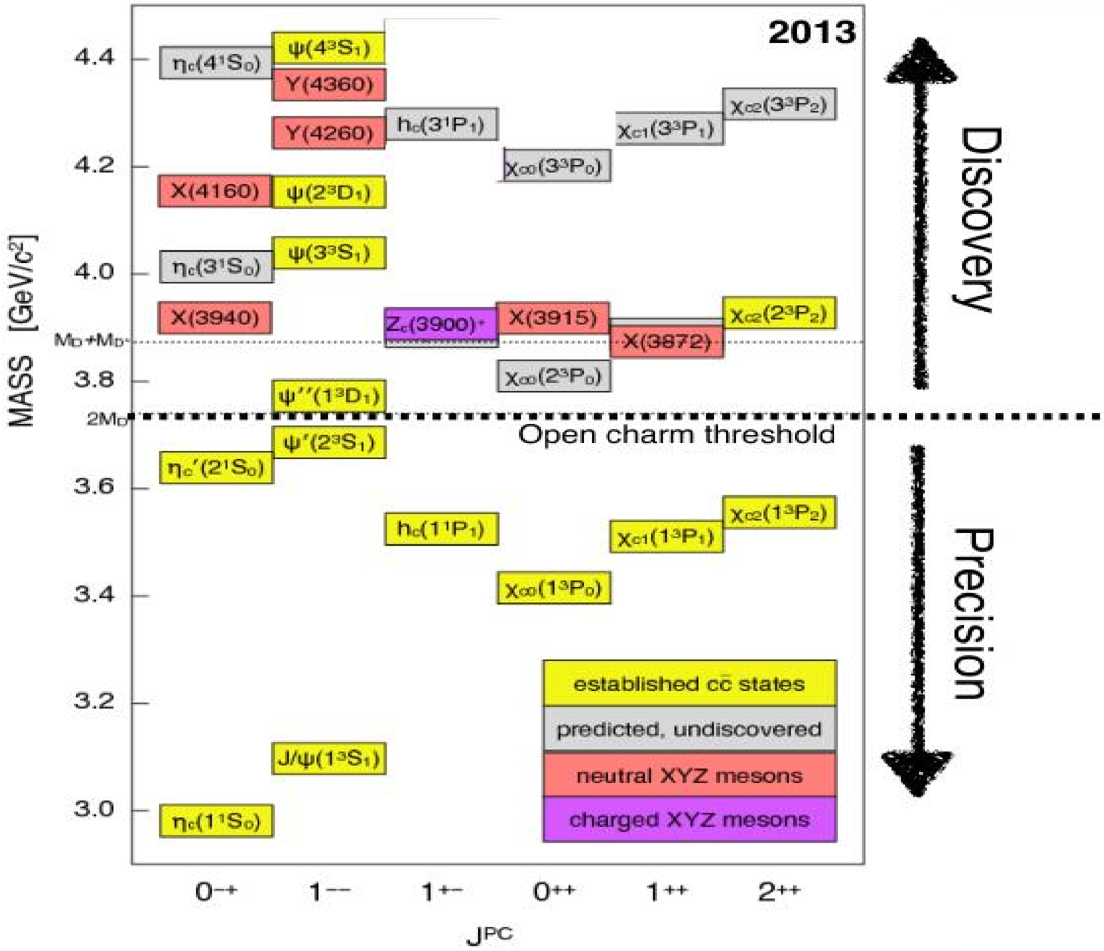
2, ★SU(3) chiral constituent quark model … …

3, ●Calculated properties of d*(2380): Mass, wave function, decays, FFs……

4, Other possible dibaryons: like D_{30}

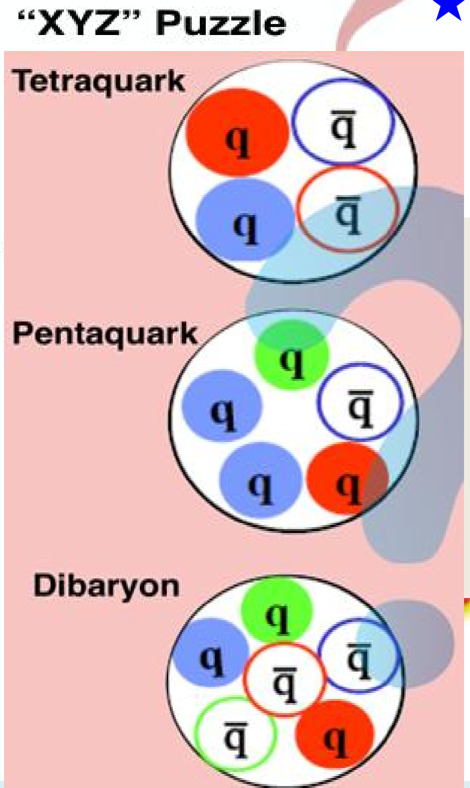
5, Summary and discussions

1, Introduction: Recent studies on exotic particles_((4,5), 6)



XYZ states 类粲介子

★Near threshold,
★Narrow width



Normal hadrons mesons($q\bar{q}$) & baryons(qqq)

Courtesy of Messchendorp

Dibaryons: deuteron

- Binding energy ~2.2MeV, or 1.1MeV/A

  Which has to be compared to the averaged binding energy of 8 MeV/A in Nuclei

- Its charge radius of 2.1fm (loosely bounded)

  The centers of the proton and neutron are far apart from each other than the pion exchange range $r \sim hc/m_\pi \sim 1.4$fm

- Proton-neutron (dominated),

  six-quark content (2-3% or 0.15-0.3%)+ $\Delta\Delta$(0.4%)

<u>Summarizing</u>: in the baryon-baryon system, we have so far clear-out experimental evidence a bound state: <u>deuteron, 1932</u>

Beginning: (★Dyson and Xuong, 1964)

1964, when quarks were still perceived as merely mathematical entities
SU(6) multiplet in 56×56 product : contains the SU(3) \bar{10} and 27;
Deuteron D_{01} and NN virtual state D_{10}➔D_{12}(NΔ) and D_{03}(ΔΔ)

$M \sim A + B\left[I(I+1) + S(S+1) - 2\right]$ *with the NN threshold mass 1878MeV,*
a value $B \sim 47MeV$ *was reached by assigning* D_{12} *to* $pp \leftrightarrow \pi^{+}d$ *resonance*
at $\sqrt{s} = 2160$ *MeV (near the* $N\Delta$ *threshold)*

D_{IS}

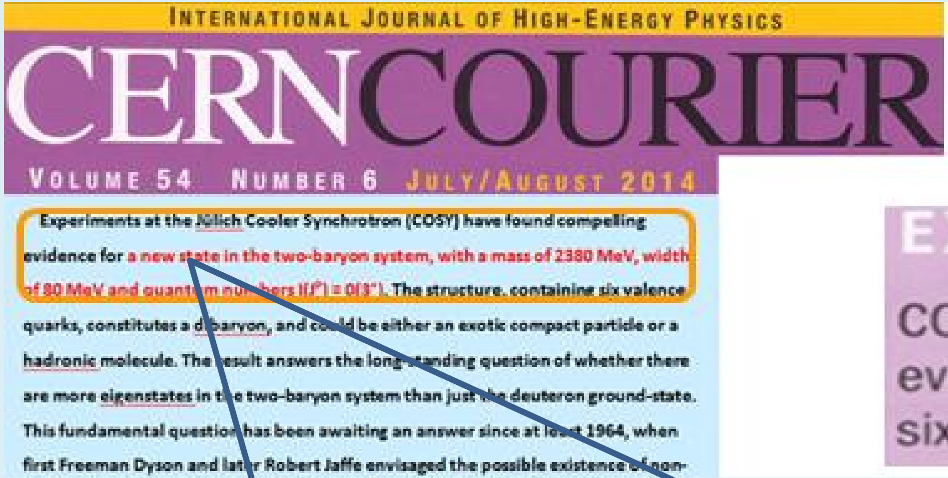
➔$M(D_{03}) = 2350MeV$. This dibaryon has been the subject of several quark-based model calculations since 1980 by A. Gal

Nonstrange s-wave dibaryon SU(6) predictions

D_{IS}

Mass$_{MeV}$	dibaryon	I	S	SU(3)	legend	mass
1876	$\mathcal{D}_{01}$	0	1	$\overline{10}$	deuteron	A
1876	$\mathcal{D}_{10}$	1	0	27	nn	A
2160	$\mathcal{D}_{12}$	1	2	27	$N\Delta$	$A + 6B$
2160	$\mathcal{D}_{21}$	2	1	35	$N\Delta$	$A + 6B$
2350	$\mathcal{D}_{03}$	0	3	$\overline{10}$	$\Delta\Delta$	$A + 10B$
2350	$\mathcal{D}_{30}$	3	0	28	$\Delta\Delta$	$A + 10B$

observation: d*(2380) (D_{03})—light flavor dibaryon


INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

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VOLUME 54 NUMBER 6 JULY/AUGUST 2014

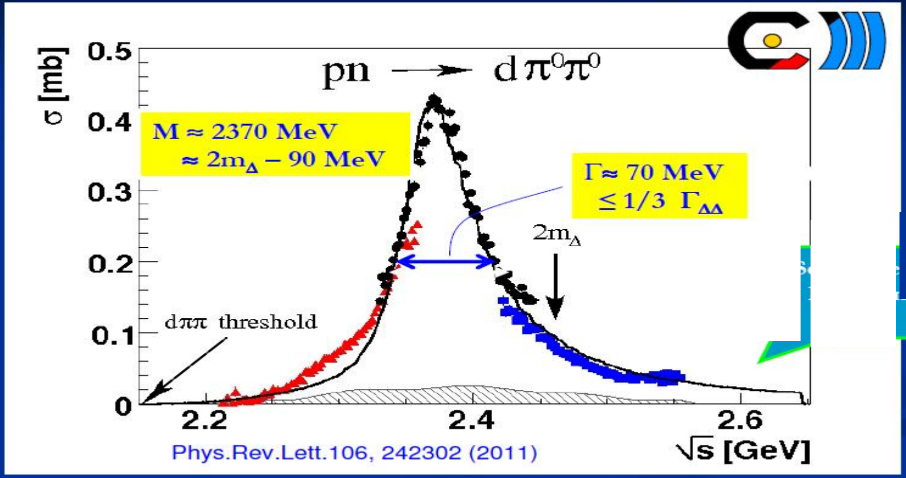
Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum numbers $I(J^P) = 0(3^+)$. The structure, containing six valence quarks, constitutes a dibaryon, and could be either an exotic compact particle or a hadronic molecule. The result answers 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-

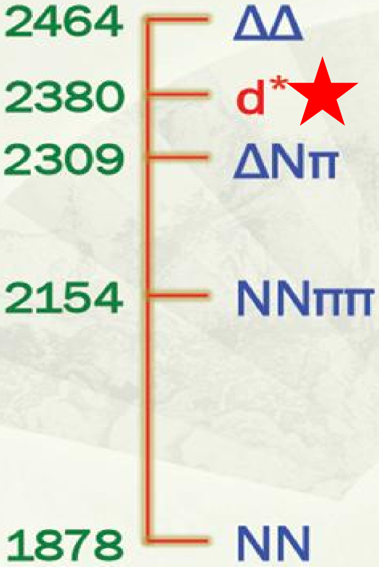
cerncourier.com/cws/article/cern/57836

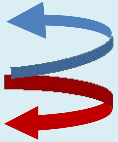
(2014)

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^+)







84MeV

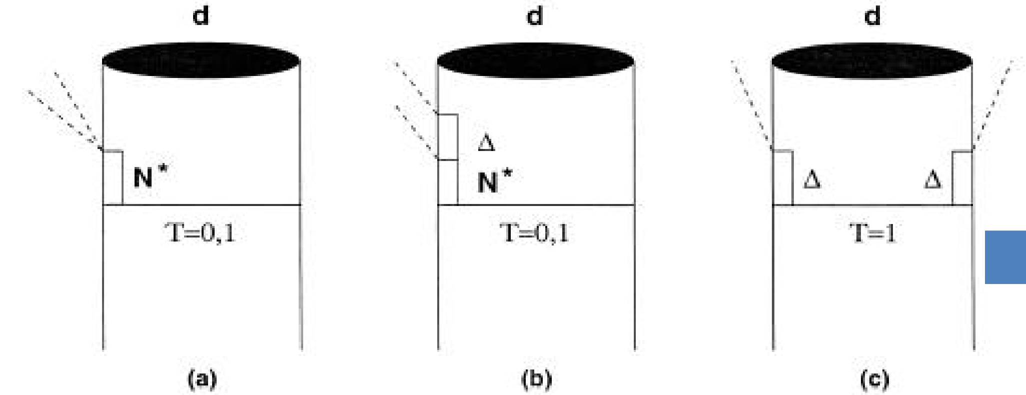
71MeV

effect from threshold

$$M_{d^*} \approx 2380 MeV$$
$$\approx 2M_\Delta - 84 MeV$$
$$> M_{\Delta N\pi}$$
$$> M_{NN\pi\pi}$$
$$> M_{NN}$$
$$2\Gamma_\Delta \approx 230 MeV$$
$$\Gamma_{d^*} \approx 70 MeV \quad ?$$
$$< \frac{1}{3} \times (2\Gamma_\Delta) \quad narrow$$

★Baryon number=2

★ Unusual narrow width



neither N*N (Roper),

nor ΔΔ

Intermediate state

They need this d*(2380)

★ Possible interpretation of d*(2380)
compact 6q dominated d*(2380)

▲ After COSY's observations

- **Quark model**

J.Ping (09/14)-10 coupled channels QM
★ F.Huang, YBD, Zhang. (14-18)--ΔΔ+CC QM
Bashkanov, Brodsky, Clement (13) -- ΔΔ+CC

A), a compact 6q dominated exotic state

- **Hadronic model**

Gal (14) ---ΔNπ
Kukulin (15,16) - $D_{12}\pi$

B), a ΔNπ (or $D_{12}\pi$) resonant state

- Some Other interpretations

2, ★SU(3) chiral constituent quark model: SU(3) CCQM

- **Quark model framework**

PRC 60 (1999) 045203
CPC 39 (2015) 071001

SU(3) chiral QM + RGM approach (light flavor)

▲ **Interactions:** $V_{ij} = V_{ij}^{Conf.} + V_{ij}^{OGE} + V_{ij}^{ch} + V_{ij}^{chv}$

q-q potentials $V_{ij}^{ch} = \sum_a (V_{ij}^{s(a)} + V_{ij}^{ps(a)})_{scalar+PS}$

Interactive Lagrangian

$$\mathcal{L}_I = -g_{ch}\bar{\Psi}\left(\sum_a^8 \sigma_a \lambda^a + i\sum_a^8 \pi_a \lambda^a \gamma_5\right)\Psi$$

$$\begin{cases} \sigma_a : \text{scalar nonet fields} \\ \pi_a : \text{psudoscalar nonet fields} \end{cases}$$

★Extended SU(3) chiral constituent quark model: SU(3) ECCQM

$$\mathcal{L}_I = -\bar{\Psi}(g_{chv}\gamma_\mu \sum_a^8 \rho_a^\mu \lambda^a + \frac{f_{chv}}{2M_N}\sum_a^8 \sigma_{\mu\nu}\partial^\mu \rho_a^\nu \lambda^a)\Psi,$$

ρ_a : *vector nonet fields*

★Model parameters:

could well-reproduce and match the experimental data for N-N scatterings

---NN phase shifts

& hyper-nucleon interaction

+deuteron properties: $\begin{cases} \textit{bingding} \\ \textit{size} \end{cases}$

Binding Energy $(BE)_d^{Expt} = 2.22\,MeV$

Values of model parameters in *SU*(3)CCQM and *SU*(3)ECCQM

	SU(3)CCQM	*SU*(3)ECCQM	
		Set I	Set II
b_u (fm)	0.5	0.45	0.45
$g_{NN\pi}$	13.67	13.67	13.67
g_{ch}	2.621	2.621	2.621
g_{chv}	0	2.351	1.973
f_{chv}/g_{chv}	0	0	2/3
m_σ (MeV)	595	535	547
g_u	0.875	0.237	0.363
α_s (g_u^2)	0.766	0.056	0.132
a_{uu}^c (MeV/fm^2)	46.6	44.5	39.1
a_{uu}^{c0} (MeV)	−42.4	−72.3	−62.9
$B_{deuteron}$ (MeV)	2.09	2.24	2.20

▲ Trial wave function of d* $[I(J^P)=0(3^+)]_{B=2}$

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

★ 6-quark two clusters + RGM

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

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

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

▲ Hadronization---channel wave function:

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

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

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

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

● the two components orthogonal

★ the quark exchange effect included

Reason for large component of CC (67%)

Due to quark exchange effect

$P_{36} = P^{r}_{36} \; P^{sfc}_{36}$: $\langle P^{sfc}_{36} \rangle$

exchange effect in spin-flavor-color spaces

intrinsic	$(\Delta\Delta)_{SI=30}$ $(\Delta\Delta)_{SI=30}$	$(\Delta\Delta)_{SI=30}$ $(CC)_{SI=30}$	$(CC)_{SI=30}$ $(CC)_{SI=30}$
$\langle P^{sfc}_{36} \rangle$	$-\frac{1}{9}$	$-\frac{4}{9}$	$-\frac{7}{9}$

$\langle P^{r}_{36} \rangle$ is determined by the dynamical wave function

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

→ Two clusters ΔΔ closer, $\langle P^{r}_{36} \rangle \sim 1$

1) d* special characters

spin-flavor-color spaces exchange effect

should also large

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

d* might be a 6q dominant state

Dynamical effect ⟷ Model independent

P_{36} Effect large, large CC component

$[I(J^{P})=0(3^{+})]_{B=2}$

→ d* *deep bounded and narrow width*

3, Calculated properties of d*(2380)$_{model}$

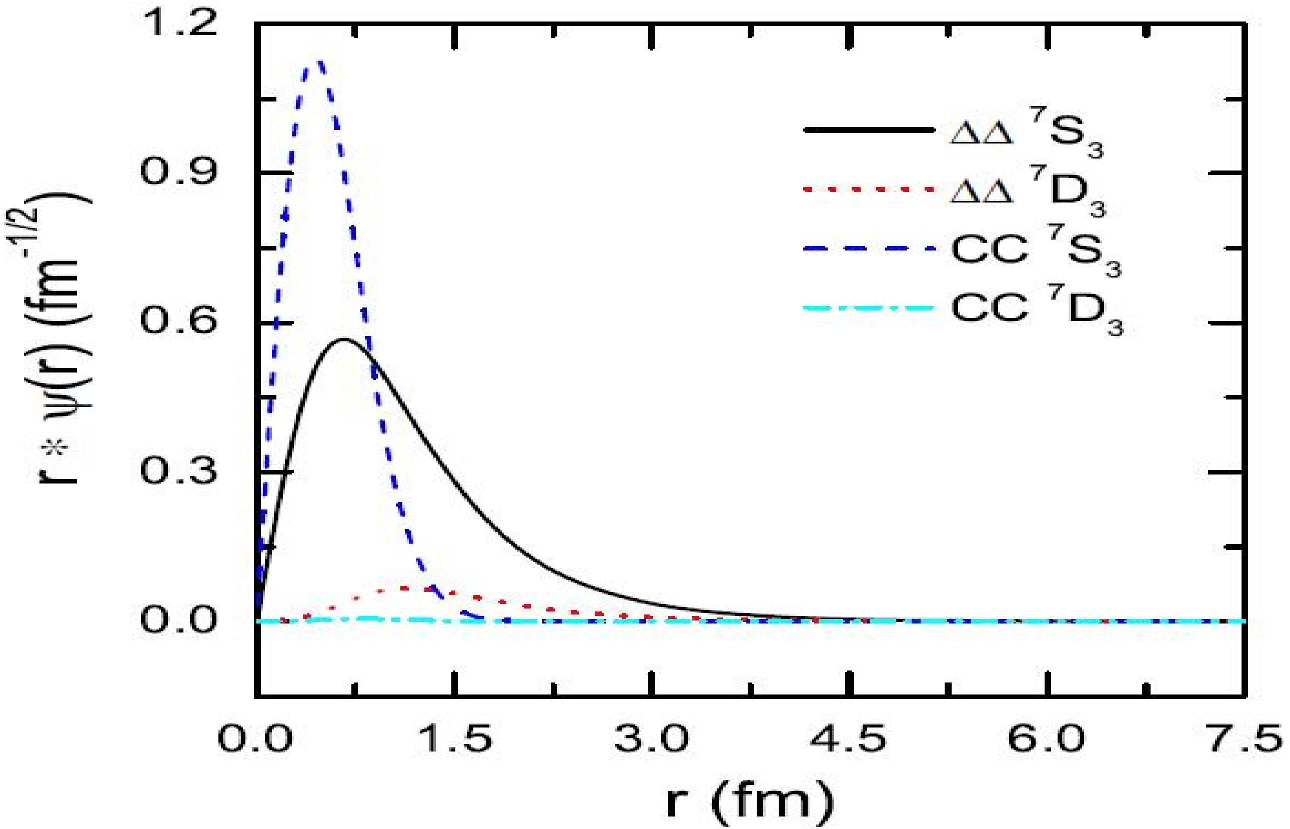
a, Mass & wave function of d*(2380)

PRC 60 (1999) 045203
CPC 39 (2015) 071001

▲ Results:

$I(J^P) = 0(3^+)$

d* (WFs)



- **Binding energy (BE)**

$$(BE)_{d^*}\begin{cases}Expt.\sim\ 84\,MeV\\ Theor.\sim 84\,MeV\end{cases}$$

PRC 60 (1999) 045203		Ext. SU(3) (f/g=0)	
$I(J^P)=0(3^+)$		ΔΔ S (L=0,2)	ΔΔ-CC (L=0,2)
d^* Binding Energy(MeV)		62.3	83.9
Fraction of Wave Function (%)	ΔΔ (L=0)	98.01	31.22
	ΔΔ (L=2)	1.99	0.45
	CC (L=0)	0	68.33
	CC (L=2)	0	0.00

■1, Intrinsic character of d*

quark exchange effect of sfc large (negative: -4/9)

2, Dynamical effect

(SI=30), OGE & vector meson exchange induced Δ-Δ short range interaction is attractive

*** d* is deeply bounded & narrow

b, Strong decay$_I$: ▲ 2π decay widths

PRC91 064002, PRC94 014003

Three-body decay

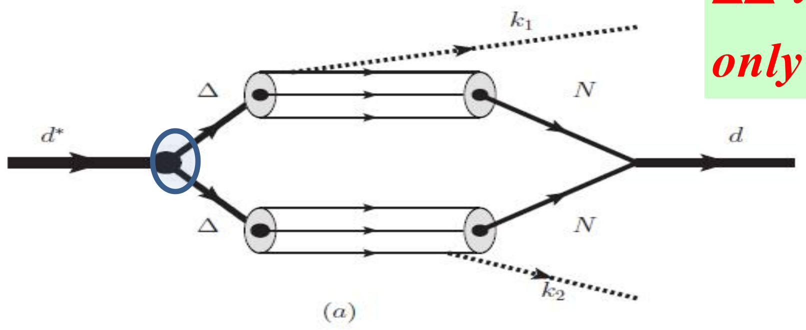
$I(J^P) = 0(3^+)$

$d^* \to d\pi^0\pi^0$

$d^* \to d\pi^+\pi^-$

Typical diagram

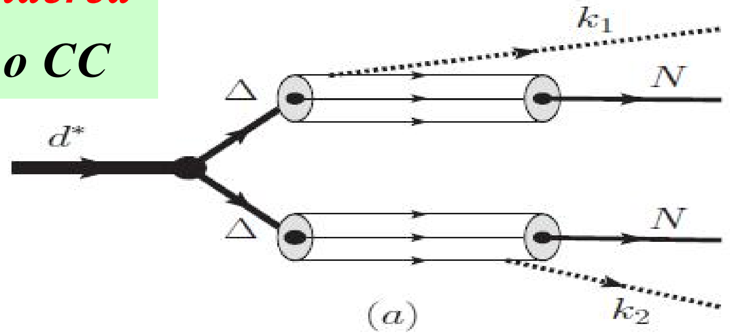
ΔΔ is considered only and ***no CC***



Four-body decay

$d^* \to pn\pi^0\pi^0(pn\pi^+\pi^-)$

$d^* \to nn\pi^0\pi^+(pp\pi^0\pi^-)$



Parameters:

$\Delta \to N\pi$

Interaction

Coupling & form factor

$qq\pi$

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

$$\Gamma_{\Delta\to\pi N} = \frac{4}{3\pi}k_\pi^3(g_{qq\pi}I_o)^2\frac{\omega_N}{M_\Delta},$$

Our interpretation of d*_Compact 6q dominated exotic state

(wave function of SU(3) (CQM+ECQM))

* All partial and total widths agree with data reasonably

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

$$\begin{cases} \Gamma^{Expt} = 70 \sim 75\,MeV \\ \Gamma^{Theor.} \approx 72\,MeV \end{cases}$$

PRC91,064002(15), PRC94,014003(16)

$I(J^P) = 0(3^+)$

	Theor.(MeV)	Expt.(MeV)
$d^* \to d\pi^+\pi^-$	16.8	16.7
$d^* \to d\pi^0\pi^0$	9.2	10.2
$d^* \to pn\pi^+\pi^-$	20.6	21.8
$d^* \to pn\pi^0\pi^0$	9.6	8.7
$d^* \to pp\pi^0\pi^-$	3.5	4.4
$d^* \to nn\pi^0\pi^+$	3.5	4.4
$d^* \to pn$	8.7	8.7
Total	71.9	74.9

▲ 2π decay widths

The narrow width is due to large CC component

①, *Compact structure:*
size~~0.8fm

②, *Components*

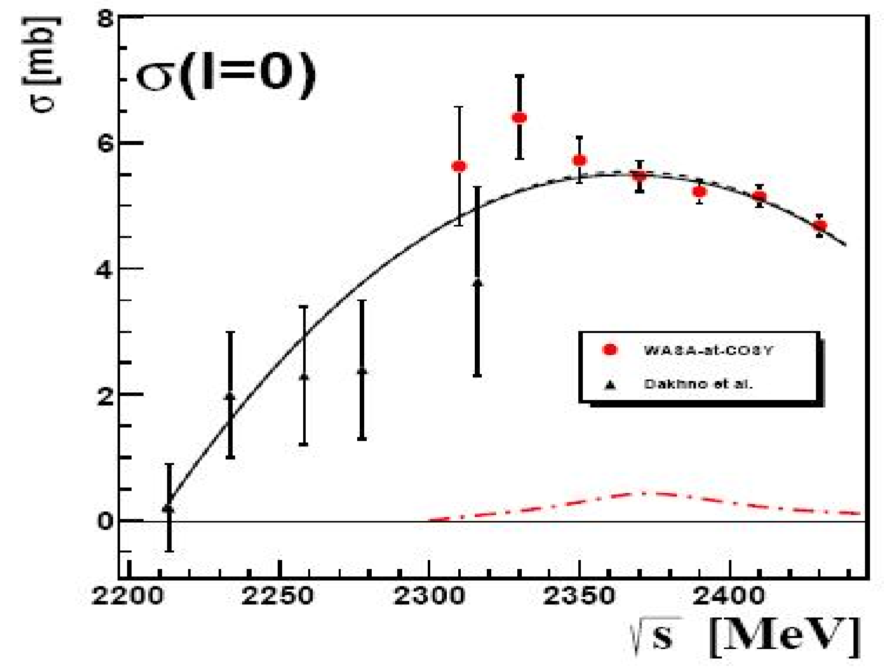
$$|d^*>\sim\sim \sqrt{\frac{1}{3}}\,|\Delta\Delta> + \sqrt{\frac{2}{3}}\,|CC>$$

③, ΔΔ component plays of the *most important role in the calculations*

c, Strong decay$_{II}$: Single-pion decay

$I(J^P) = 0(3^+)$

$$\sigma_{NN\to NN\pi}(I=0) = 3(2\sigma_{np\to pp\pi^-} - \sigma_{pp\to pp\pi^0})$$



- **Experimental status**

The WASA-@-COSY Collaborations,

PLB774 (2017)$_{Gal}$, 599-607

Dash-dotted line illustrates a 10% d* resonance contribution

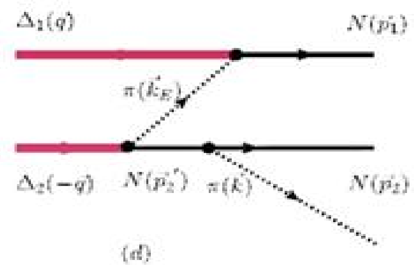
Upper limit of branching ratio for "d*(2380)→NNπ" is 9%.

This channel might serve as a test!

Our prediction, 1%, is compatible with the Exp't upper-limit: PLB769,223-226

Typical diagram

ΔΔ is considered only and no CC

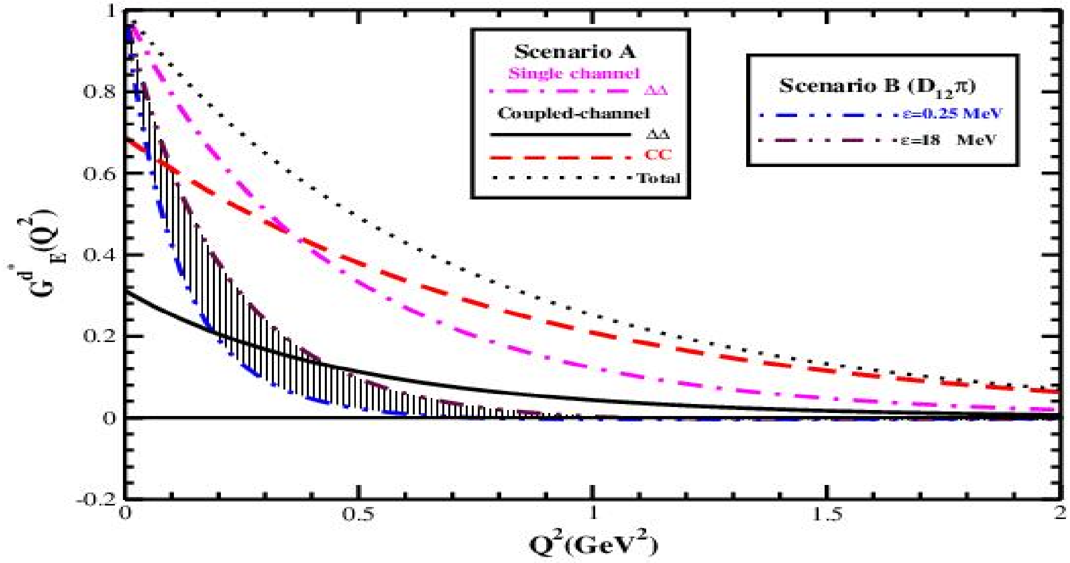


d, Form factors of d* and charge radii

d*(2380) charge distributions

$[I(J^p)=0(3^+)]_{B=2}$

Cases	$d^*(2380)$		D_{12}
	A1	A2	
$rms \quad (fm)$	1.09	0.78	2.39



Magnetic Moment

Naïve quark model

Nucleon $\frac{\mu_p}{\mu_n} = -\frac{3}{2} \to -\frac{2.79}{1.91}_{EXPT.}$

d*(2380) ΔΔ+CC $\mu_{d^*} = \frac{M_{d^*}}{m_q} \approx 7.6$

d*(2380) $D_{12}\pi$ $\mu_{d^*} = \frac{2M_{d^*}}{3m_q} \approx 5.1$

4, Other possible dibaryons: like $D_{IS}=D_{30}$_Results

- The mirror state D_{30} is a weakly bound state.
- It also has a significant hidden color component.
- Only *S*-wave channels exist in this system.
- No signal of D_{30} is observed (Near threshold?)

Properties of those systems

	NN	D_{03}	D_{30}		D_{03} (%)	D_{30} (%)
$\mathcal{E}_b$	2.25	80.1_{25}	6.00_{12}			
Expt.	2.2	~80	***(no seen)			
$\mathcal{R}_{AB}$	2.45	0.73	1.94	ΔΔ	32	74
$\mathcal{R}_{6q}$	1.33	0.77	1.25	CC	68	26

$$\begin{cases} \mathcal{R}_{AB} = \sqrt{< r_{AB}^2 >} \\ \mathcal{R}_{6q} = \sqrt{\frac{1}{6}\sum_{i=1} < \left(\vec{r}_i - \vec{R}_{cm}\right)^2 >}, \end{cases}$$

Consequence: consistent with the observations √

★ The short range quark-quark interaction induced by vector meson exchange is important

5, Summary and discussions

★ ① **Our SU(3)(CCQM & ECCQM) approaches for the mass & wave function of [d*(2380), 3^+]. They could well reproduce the experimental data for the N-N scatterings as well as the properties of deuteron and hyperon-nucleon interaction, and thus, the model parameters are fixed.**

★② **Within the approaches and by employing the same set of parameters, the mass of d*(2380) is well-reproduced and its wave function is expressed as ΔΔ+CC, hidden color parts dominated, and vector meson exchange dominates the short range interactions between quarks.**

$$|d^*>\sim\sim\sqrt{\frac{1}{3}}|\Delta\Delta>+\sqrt{\frac{2}{3}}|CC>$$

novel

$[I(J^P)=0(3^+)]_{B=2}$

★③ **It is a compact 6-quark state with some large-portion |ΔΔ> component, due to its spin and quark exchange effect+short-range interactions, and vector meson exchange is important for the correct binding energies**

★ ④ **We calculate the strong decays of d*(2380),**

a, double pion decays are reproduced;

b, the single pion decay is expected to be much small.

★⑤ **The electromagnetic form factors of d*(2380) are also calculated and its charge radius, magnetic moments, quadupole moments are obtained.**

★⑥ **The predicting the mirror state D_{30}, which is a weakly bound state. The short-range interaction with vector-meson exchanges plays important role, and hidden-color component is sizeable.**

★⑦ **More experimental information of those dibaryons is necessary to confirm their existence.**

The study of dibaryons is not a new, it opens a window of multi-quark states.

Further investigations

- **Other possible channels for *dibaryons:*** $\gamma d \rightarrow d\pi\pi$, e^+e^-, Υ **decay, collisions,**

  --- ELPH, *BGooD*, *JLab.*, BEPC$_{up}$, BELLII, NICA, Heavy-Ion, Panda, ...

- **The D_{30} state can be searched for in the $pp \rightarrow pp\pi^+\pi^+\pi^-\pi^-$ reaction**
- **Possible nonstrange D_{12} and D_{21} states which are composed of ΔN and hidden color components** Ishikawa, Phys. Rev. C 104, L052201; 105, 045201 [ELPH].
- **Systems like $NN^*(1535)$, $\Delta N^*(1440)$, ηd, ...**
- **Systems with strange, charm, and bottom quarks**

Thanks for your attention!

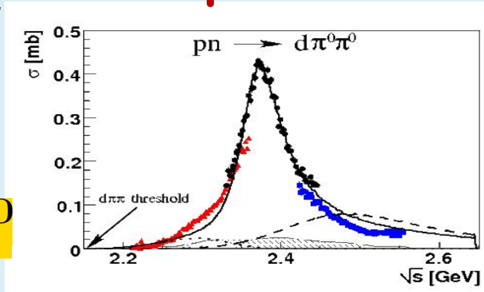
Backup

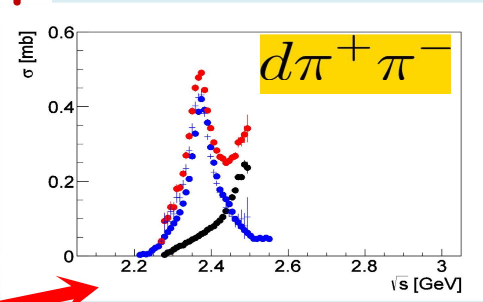
Signals in np processes WASA @ COSY

PRL 106 (2011) 242302
PLB 721 (2013) 229

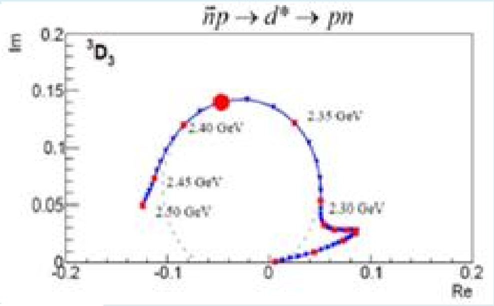
WASA data

2π production processes





np scattering process

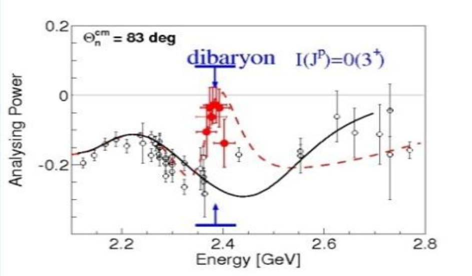


Fusion $d\pi^0\pi^0$

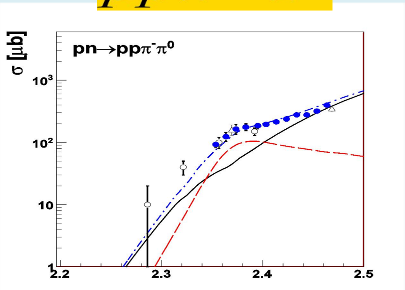
pn → d*
→d(pn)+2 π

Non-fusion

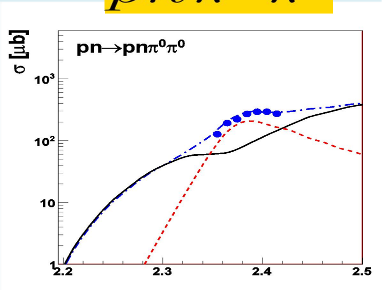
pn



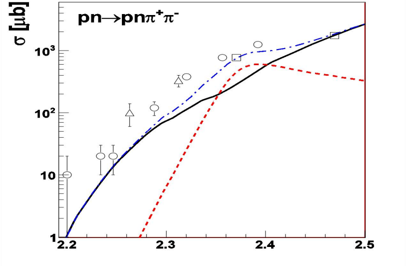
$pp\pi^-\pi^0$



$pn\pi^0\pi^0$



$pn\pi^+\pi^-$



fusion 2π processes

Measured also in fusion reactions to helium isotopes:

$p + d \to {}^3He + \pi^0 + \pi^0$

$p + d \to {}^3He + \pi^+ + \pi^-$

$d + d \to {}^4He + \pi^0 + \pi^0$

$d + d \to {}^4He + \pi^+ + \pi^-$

Characters of d*(2380)

- d* <u>mass</u> locates between ΔΔ and ΔNπ thresholds

<u>the effect from threshold is expected small</u>

$M_{\Delta N\pi} = 2310 MeV$

$M_{d^*} \approx 2380 MeV$

$\Gamma_{d^*} \approx 80 MeV$

$M_{\Delta\Delta} = 2460 MeV$

70MeV

80MeV

- d* narrow width

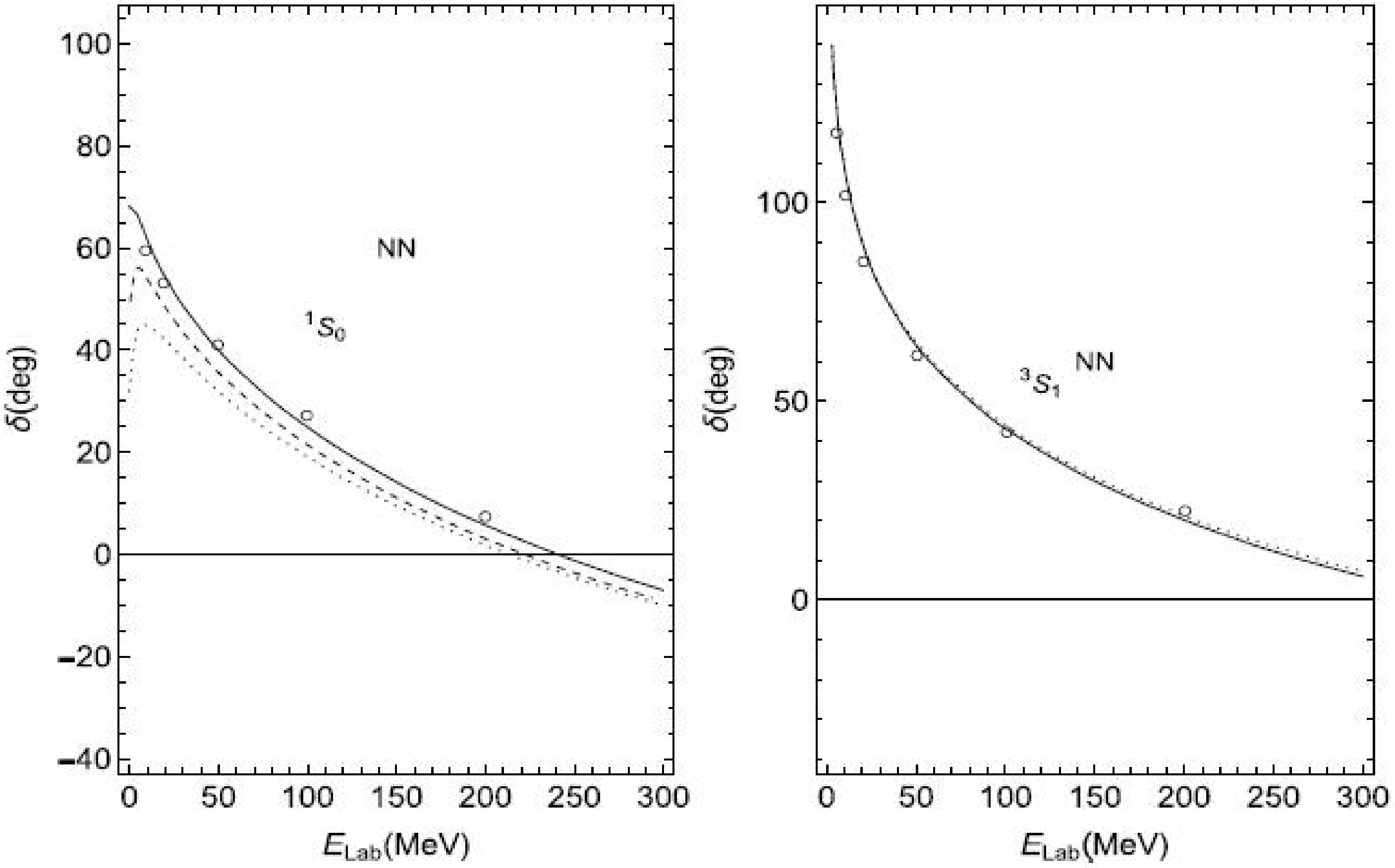
Possible 6q structure

⇒ be different from normal hadrons

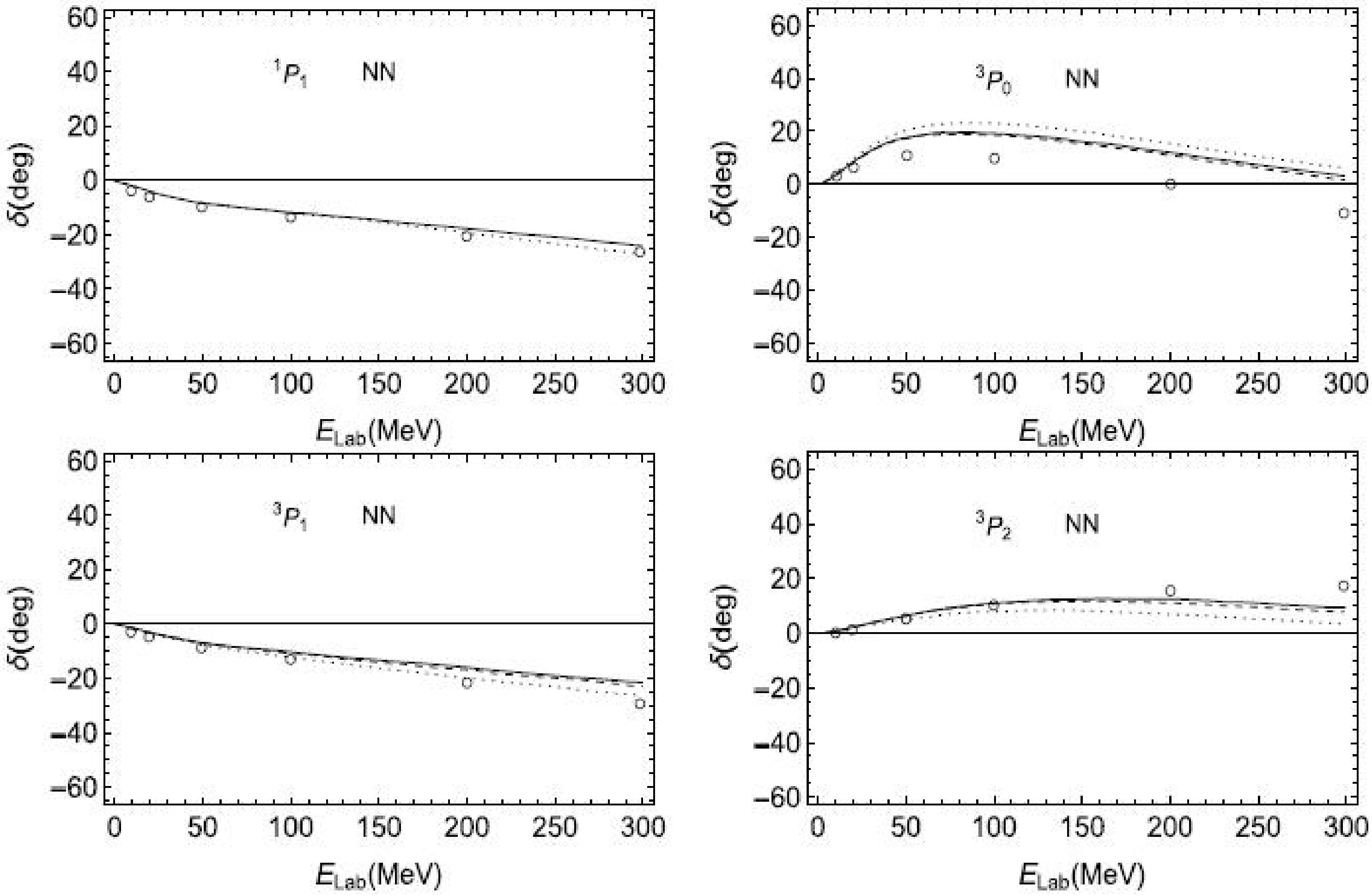
Review article: by Heinz Clement,

Progress in Particle and Nuclear Physics,

93 (2017), 195-142



The S-Wave phase shifts of the N-N scattering in SU(3)CCQM and SU(3) ECCQM. Dotted, dashed and solid curves: (f/g=0, 2/3).



The P-wave phase shifts of the $N-N$ scattering in $SU(3)$CCQM and $SU(3)$ECCQM approaches.

Comparison of two interpretations

(A) Compact quark model: (deeply)   (B) ΔπN three-body system: (loosely)

Good √ Quarks ⟵ **Mass, energy and Double-pion strong decays** ⟶ Good √ Hadrons

d*(2380) single-π decay

Our prediction 1% which is compatible with the experimental up-limits

$I(J^P) = 0(3^+)$

The result of three-body (ΔπN) scenario is about 18%.

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

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

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

Exp. gives 9% up-limit

Recently Gal (PLB769)
In order to match the up-limit of exp.

EM Form Factors：

More sophisticated admixture

Photo-absorption on deuteron by *d*(2380)*

Cloud

$$|\,d^* > \approx \sqrt{\frac{5}{7}}\,|\Delta\Delta > + \sqrt{\frac{2}{7}}\,|\,N\Delta\pi >$$

● **Suggest other possible experimental searching for it**

and study for possible dibaryon signals (non-strange):

① Process (Mainz, Jlab., ELPH, BGOOD): $\gamma + d$

② Process (Belle), Y-decays: $\Upsilon \to \bar{d}^* + X$

$BR(\Upsilon \to \bar{d} + X)_{已知} \sim 2.9 \times 10^{-5}$

③ Processes (BEPC, Babar, Belle?): $e^+ + e^- \to \bar{d}^* + p + n$

④ Processes (Panda): $p + \bar{p} \to \bar{d}^* d^* + X$

Other Than

WASA@COSY

NICA

$p + n$

$p + d$

$d + d$

ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

FONDAZIONE BRUNO KESSLER

Tensor spin observables

2023年7月10日至14日

ECT*

Europe/Rome 时区

● **Theoretical study of other dibaryon candidates:**

[★ $d_{(S=3,I=0)}{}^*(2380)$: $|d^*> \sim \sqrt{\frac{1}{3}}|\Delta\Delta> + \sqrt{\frac{2}{3}}|CC>$, $d_{(S=0,I=3)}{}^*(2380)$],

[$D_{(S=2,I=1)}$, $D_{(S=1,I=2)}$], [Roper+Δ]_Wasa@Cosy

On the possibility of observing weakly excited 6-quark states in

d-d → 6q+d

processes at the NICA SPD

B.F. Kostenko

JINR LIT

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

d, Productions at other facilities

other than $p + n$, $p + d$, $d + d$

▲ *Suggest other experimental search and study for possible dibaryon signals:*

● $\gamma + d$ *Process (Mainz, Jlab., ELPH, BGOOD)* Int.J.Mod.Phys.A34,1950100(2019)

◆ $\Upsilon \rightarrow \bar{d}^{*} + X$ Process (Belle) PRD99 036015 (2019) CPC42 064012 (2018)

[BR($\Upsilon \rightarrow \bar{d} + X$) ~ 2.86 ×10 $^{-5}$]

■ $e^{+} + e^{-} \rightarrow \bar{d}^{*} + p + n$ *Processes (BEPC, Babar, Belle)*

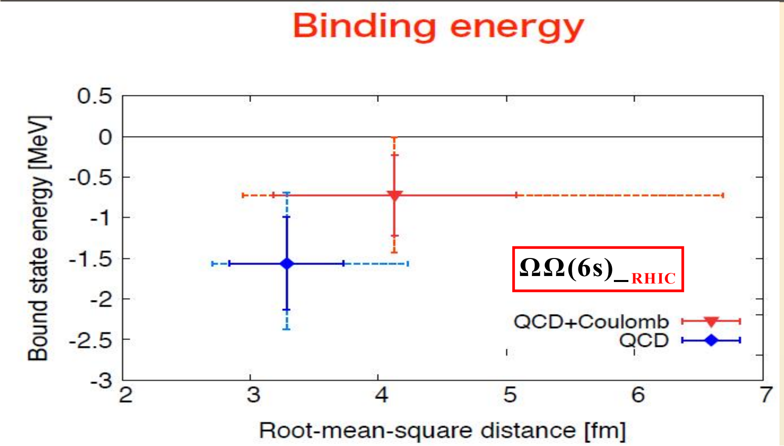
★ $p + \bar{p} \rightarrow \bar{d}^{*} d^{*} + X \rightarrow d^{*} + \bar{p}\bar{n}$ *Processes (Panda)* CPC46 113102(2022) CPC45 023105(2022)

Theoretical study of other dibaryon candidates:

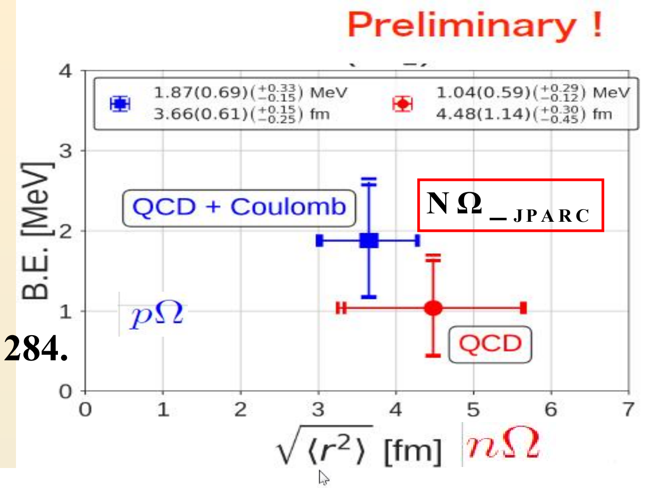
$$|d^{*}> \sim \sqrt{\frac{1}{3}}|\Delta\Delta> + \sqrt{\frac{2}{3}}|CC>,$$

[d*$_{(S=3,I=0)}$(2380), d*$_{(S=0,I=3)}$], [D$_{(S=2,I=1)}$, D$_{(S=1,I=2)}$]

♣Some Lattice Calculations (HALQCD)



Other Di-baryons$_{Lattice}$

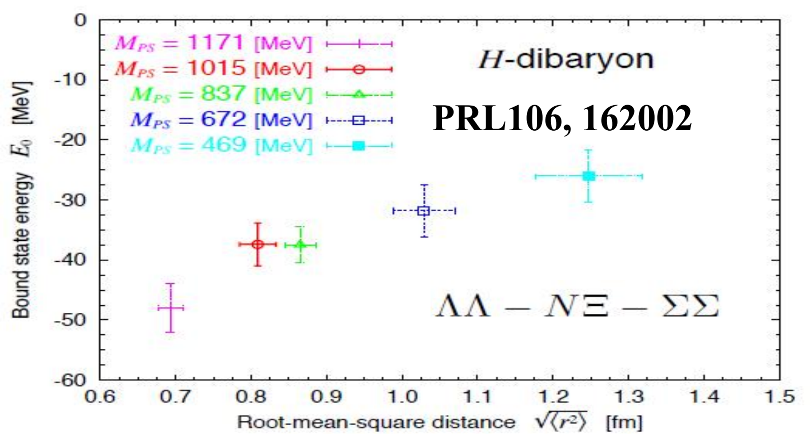


PLB 792, 284.

Dibaryon with Highest Charm Number near Unitarity from Lattice QCD

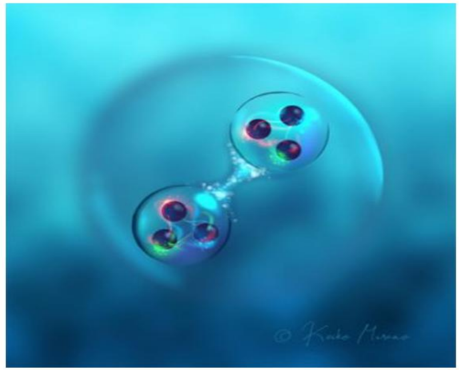
Yan Lyu, Hui Tong, Takuya Sugiura, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Jie Meng, and Takaya Miyamoto

Phys. Rev. Lett. **127**, 072003 – Published 11 August 2021



PRL106, 162002

An H-dibaryon exists in the flavor SU(3) limit.
Binding energy = 25-50 MeV at this range of quark mass.
A mild quark mass dependence.



チャームダイオメガ（ΩcccΩccc）のイメージ図

Some others:
deuteron-like (shallow bounded)
heavy dibaryons, PRL123,162003

Summarizing, in the baryon-baryon (BB) system we have so far clear-cut experimental evidence only for a single boundstate, which is the deuteron groundstate known since 1932. In particular, there is no boundstate in the hyperon-nucleon system with strangeness $S = -1$. In the strangeness $S = -2$ sector the existence of a possible boundstate, the H dibaryon, has not yet been ruled out completely at present.

d, Form factors of d*

Form factors: 2S+1 relative to size arXiv:1704.01253, PRD96,094001

Nucleon(1/2):

$$< N(p') \mid J_N^\mu \mid N(p) >= \bar{U}_N(p')\left[F_1(Q^2)\gamma^\mu + i\frac{\sigma^{\mu\nu}q_\nu}{2M_N}F_2(Q^2)\right]U(p),$$

$$G_E(Q^2) = F_1(Q^2) - \eta F_2(Q^2), \qquad G_M(Q^2) = F_1(Q^2) + F_2(Q^2),$$

Breit frame

$$< N(\vec{q}/2) \mid J_N^0 \mid N(-\vec{q}/2) > \; = \; (1+\eta)^{-1/2}\chi_{s'}^+\chi_s G_E(Q^2)$$

$$< N(\vec{q}/2) \mid \vec{J}_N \mid N(-\vec{q}/2) > \; = \; (1+\eta)^{-1/2}\chi_{s'}^+\frac{\vec{\sigma}\times\vec{q}}{2M_N}\chi_s G_M(Q^2).$$

Deuteron(1):

$$J_{jk}^\mu(p',p) = \epsilon_j^{\prime *\alpha}(p')S_{\alpha\beta}^\mu\epsilon_k^\beta(p)$$

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

$$G_C(Q^2) = G_1(Q^2) + \frac{2}{3}\eta_D G_2(Q^2), \qquad G_M(Q^2) = G_2(Q^2),$$

$$G_Q(Q^2) = G_1(Q^2) - G_2(Q^2) + (1+\eta_D)G_3(Q^2),$$

Breit frame

$$G_C(Q^2) \longrightarrow \frac{1}{3}\sum_\lambda < p', \lambda \mid J^0 \mid p, \lambda >.$$

EM current (7 form factors, S=3)

$$\mathcal{J}^{\mu} = (\epsilon^{*})^{\alpha'\beta'\gamma'}(p')\mathcal{M}^{\mu}_{\alpha'\beta'\gamma',\alpha\beta\gamma}\epsilon^{\alpha\beta\gamma}(p)$$

$$\begin{aligned}\mathcal{M}^{\mu}_{\alpha'\beta'\gamma',\alpha\beta\gamma} = {} & [G_1(Q^2)\mathcal{P}^{\mu}[g_{\alpha'\alpha}(g_{\beta'\beta}g_{\gamma'\gamma} + g_{\beta'\gamma}g_{\gamma'\beta}) + \text{permutations}] \\ & + G_2(Q^2)\mathcal{P}^{\mu}[q_{\alpha'}q_{\alpha}[g_{\beta'\beta}g_{\gamma'\gamma} + g_{\beta'\gamma}g_{\gamma'\beta}] + \text{permutations}]/(2M^2_{d^*}) \\ & + G_3(Q^2)\mathcal{P}^{\mu}[q_{\alpha'}q_{\alpha}q_{\beta'}q_{\beta}g_{\gamma'\gamma} + \text{permutations}]/(4M^4_{d^*}) \\ & + G_4(Q^2)\mathcal{P}^{\mu}q_{\alpha'}q_{\alpha}q_{\beta'}q_{\beta}q_{\gamma'}q_{\gamma}/(8M^6_{d^*}) + G_5(Q^2)[(g^{\mu}_{\alpha'}q_{\alpha} - g^{\mu}_{\alpha}q_{\alpha'})(g_{\beta'\beta}g_{\gamma'\gamma} + g_{\beta'\gamma}g_{\beta'\gamma}) + \text{permutations}] \\ & + G_6(Q^2)[(g^{\mu}_{\alpha'}q_{\alpha} - g^{\mu}_{\alpha}q_{\alpha'})(q_{\beta'}q_{\beta}g_{\gamma'\gamma} + q_{\gamma'}q_{\gamma}g_{\beta'\beta} + q_{\beta'}q_{\gamma}g_{\gamma'\beta} + q_{\gamma'}q_{\beta}g_{\gamma\beta'}) + \text{permutations}]/(2M^2_{d^*}) \\ & + G_7(Q^2)[(g^{\mu}_{\alpha'}q_{\alpha} - g^{\mu}_{\alpha}q_{\alpha'})q_{\beta'}q_{\beta}q_{\gamma'}q_{\gamma} + \text{permutations}]/(4M^4_{d^*})],\end{aligned}$$

$$q_{\mu}\mathcal{M}^{\mu}_{\alpha'\beta'\gamma',\alpha\beta\gamma} = 0$$

Electric multi-poles

$$G^E_l(Q^2) = \frac{(2M_{d^*})^l}{e}\sqrt{\frac{4\pi}{2l+1}}\frac{(2l+1)!!}{l!Q^l}\mathcal{I}_{El}(Q^2),$$

with e being the unit of charge and

$$\begin{aligned}\mathcal{I}_{El}(Q^2) &= \langle d^*|\sum_{i=1}^{6}\int d^3r[d^3X]e_i j_l(Q|\vec{r}_i - \vec{R}|)Y_{l0}(\Omega_{r_i})|d^*\rangle \\ &= 3\langle d^*|\int d^3r[d^3X][e_3 j_l(Q|\vec{r}_3 - \vec{R}|)Y_{l0}(\Omega_{\vec{r}_3-\vec{R}}) \\ &\quad + e_6 j_l(Q|\vec{r}_6 - \vec{R}|)Y_{l0}(\Omega_{\vec{r}_6-\vec{R}})]|d^*\rangle,\end{aligned}$$

Magnetic multi-poles

$$\langle d^*|\rho^M(\vec{q})|d^*\rangle = e\sum_{l=0}^{+\infty} i^l\tau^{l/2}\frac{l+1}{C^{l-1}_{2l-1}}G_{Ml}(Q^2)Y_{l0}(\Omega_q), \quad (10)$$

where $\rho^M(\vec{q})$ denotes the magnetic density of the system with $\tau = \frac{Q^2}{4M^2_{d^*}}$, and

If we only consider the quark-photon coupling, we can write the magnetic density as $\rho^M(\vec{r}) = \sum_{i=1}^{6}\vec{\nabla}\cdot(\vec{j}_i(r)\times\vec{r}_i)$ with $\vec{j}_i(r)$ and $\vec{r}_i$ being the current and position vectors for the ith quark in the coordinate space, and $\rho^M(\vec{q}) = \sum_{i=1}^{6}\vec{\nabla}\cdot[(e_i\vec{\sigma}_i\times\vec{q})\times\vec{q}] = 2\sum_{i=1}^{6}e_i\vec{\sigma}_i\cdot\vec{q}$ with $\vec{\sigma}_i$, e_i, and $\vec{q}$ being the Pauli matrix, the charge for the ith quark and the transferred momentum, respectively.

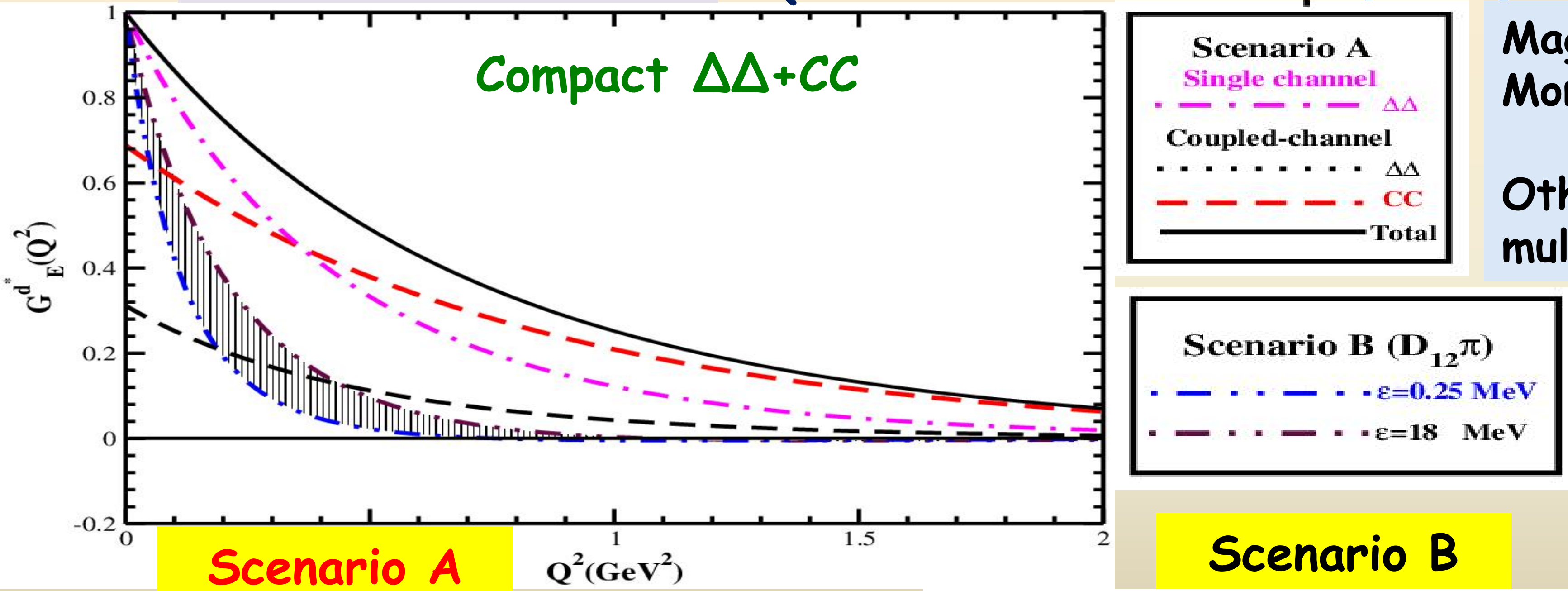
c, Form factors of d*(2380)

$I(J^P) = 0(3^+)$, *high spin*

PRD96 094001 (2017)
PRD97 114002 (2018)

spin=<u>3</u> system, 2S+1=7 form factors

Charge Distributions (related to the size of system)



Magnetic Moment

Other multipoles

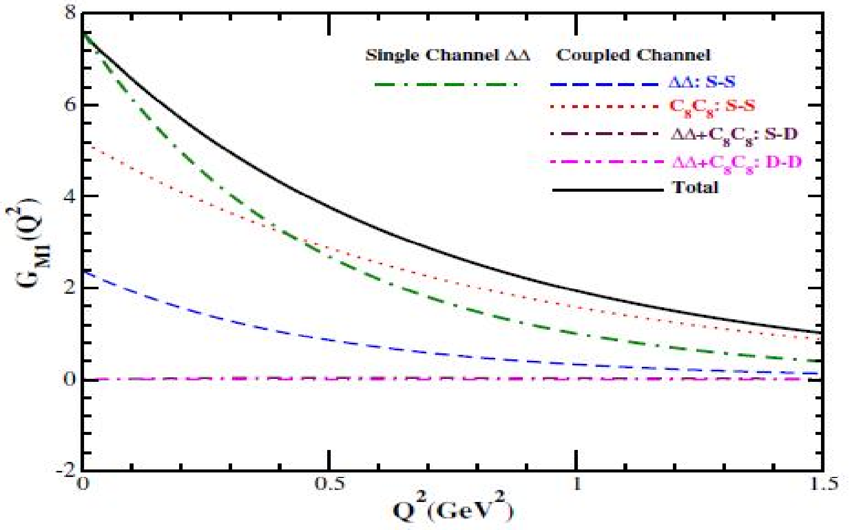
Scenario A

Scenario B

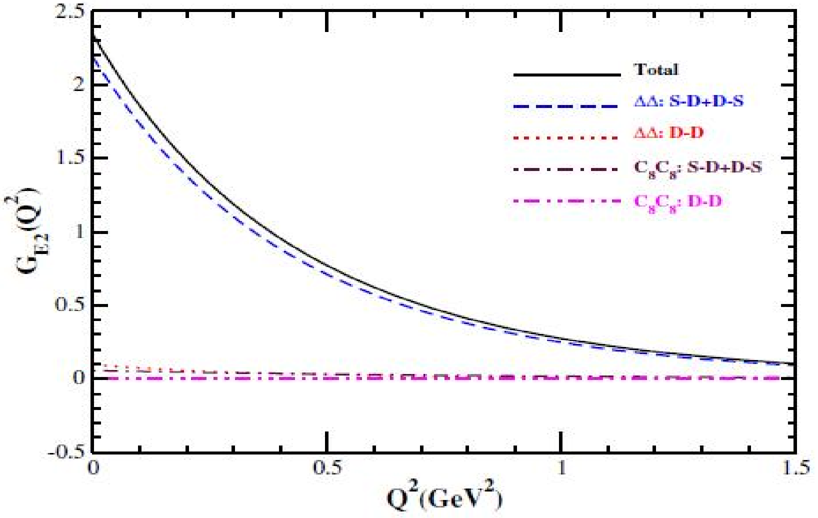
rms

$d^*(2380)$		
Cases	A1	A2
rms (fm)	1.09	0.72

D_{12}		
Cases	B1	B2
rms (fm)	2.64	1.87



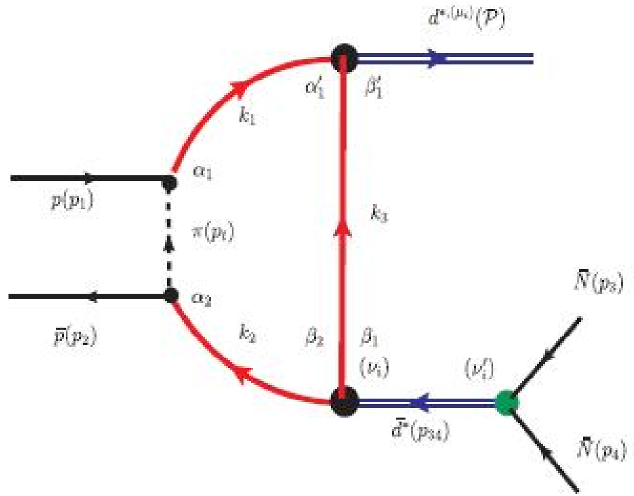
The magnetic dipole form factor $M1$ of d^*.

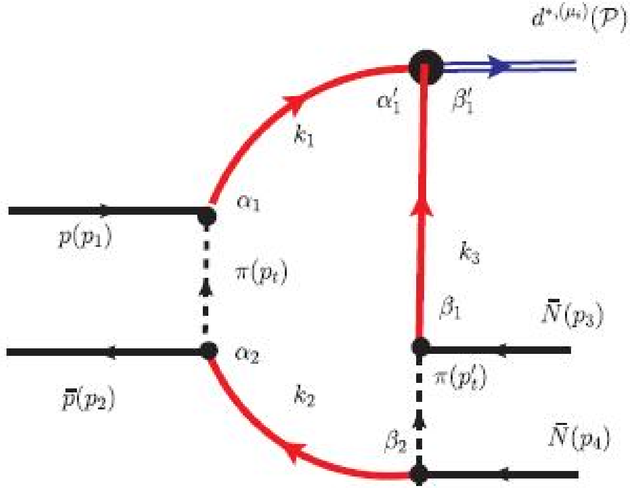


The quadrupole form factor of d^*.

e, Productions at other facilities

$$p+\bar{p}\to d^*(2380)+(\bar{p}+\bar{n})$$





$$\mathcal{L}_{d^*pn} = g_{d^*pn} q^{(pn)}_{\mu_1} q^{(pn)}_{\mu_2} \bar{\psi}_N \gamma_{\mu_3} \psi_N^C \times (d^*(\mathcal{P}))^{(\mu_i)} + \text{h.c.},$$

★1, ΔΔ Contribution
★2, Compact system
★3, Breit-Wigner form considered

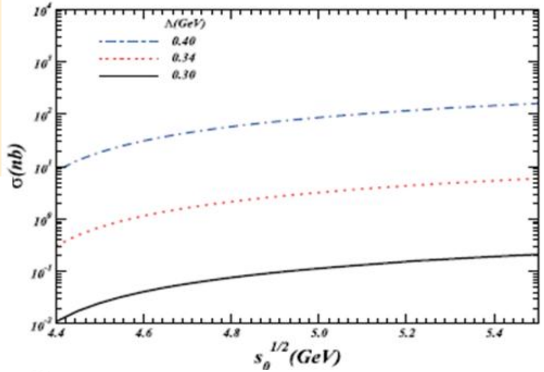
Panda

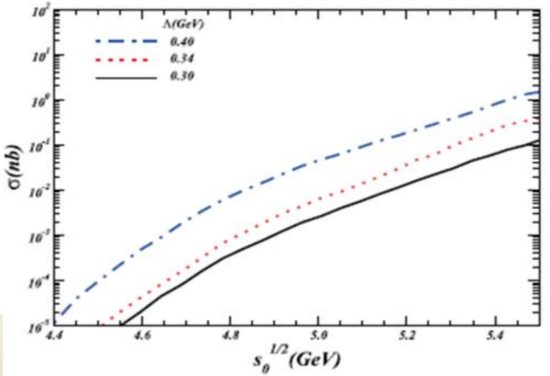
亮度:$2\times10^{32}cm^{-2}/s$

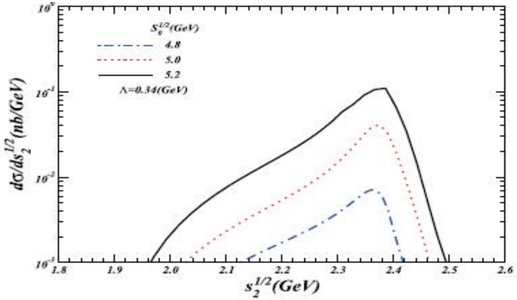
$\sqrt{s_0}=(4.8,5.0,5.2,5.4)GeV$

$(3.6,5.6,7.2,9.3)\times10^4{}_{evens}$

$(20,100,600,3200)_{evens}$







Results for D_{03} [d^*(2380)] and D_{30}

Set II	D_{03}				D_{30}			
	SU(3)	Ext. SU(3) ($f/g = 0$)	Ext. SU(3) ($f/g = 2/3$)	Ext. SU(3) (no OGE)	SU(3)	Ext. SU(3) ($f/g = 0$)	Ext. SU(3) ($f/g = 2/3$)	Ext. SU(3) (no OGE)
Binding energy	25.09	80.08	66.40	91.21	12.30	6.00	11.65	5.28
$\mathcal{R}_{\Delta\Delta/CC}$	1.04	0.73	0.77	0.71	1.50	1.94	1.67	2.01
$\mathcal{R}_{6q}$	0.94	0.77	0.79	0.76	1.10	1.25	1.14	1.27
Fraction of $(\Delta\Delta)_{L=0}$	42.07	31.91	33.41	30.90	61.29	74.30	68.31	76.19
Fraction of $(\Delta\Delta)_{L=2}$	1.59	0.49	0.57	0.41	–	–	–	–
Fraction of $(CC)_{L=0}$	56.34	67.60	66.02	68.68	38.71	25.70	31.69	23.81
Fraction of $(CC)_{L=2}$	0.00	0.00	0.00	0.00	–	–	–	–

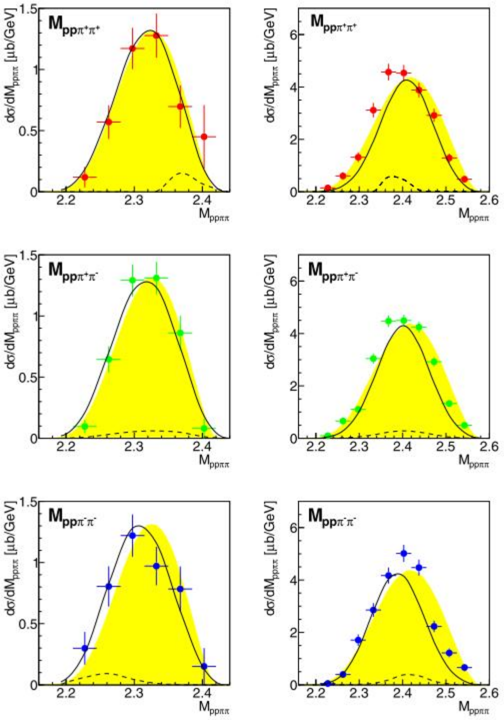
- Vector meson exchange is essential for the correct binding energies
- Compact nature of the D_{03} state
- The D_{30} state is a weekly bound state (about 5~12 MeV)

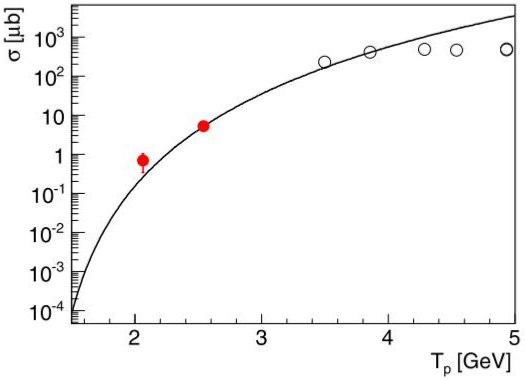
Symmetry analysis

	$\langle P_{36}^{sfc} \rangle$	$\langle \mathcal{A}^{sfc} \rangle$
deuteron	$-\frac{1}{81}$	$\frac{10}{9}$
$(\Delta\Delta)_{ST=03}$	$-\frac{1}{9}$	2
$(\Delta\Delta)_{ST=30}$	$-\frac{1}{9}$	2
$(\Sigma^*\Delta)_{ST=0\frac{5}{2}}$	$-\frac{1}{9}$	2
$(\Sigma^*\Delta)_{ST=3\frac{1}{2}}$	$-\frac{1}{9}$	2
$(\Xi^*\Omega)_{ST=0\frac{1}{2}}$	$-\frac{1}{9}$	2
$(\Omega\Omega)_{ST=00}$	$-\frac{1}{9}$	2

When antisymmetrizer A^{sfc} is large enough, the system is very possible to become a bound state. More systems like ΔΔ?

Searching for the D_{30} state





Invariant masses for *ppππ* and the total cross section. Limited data.

P. Adlarson et al. (WASA-at-COSY Collaboration), Phys. Lett. B 762, 455-461 (2016).