Study of d^*(2380) in a chiral quark model

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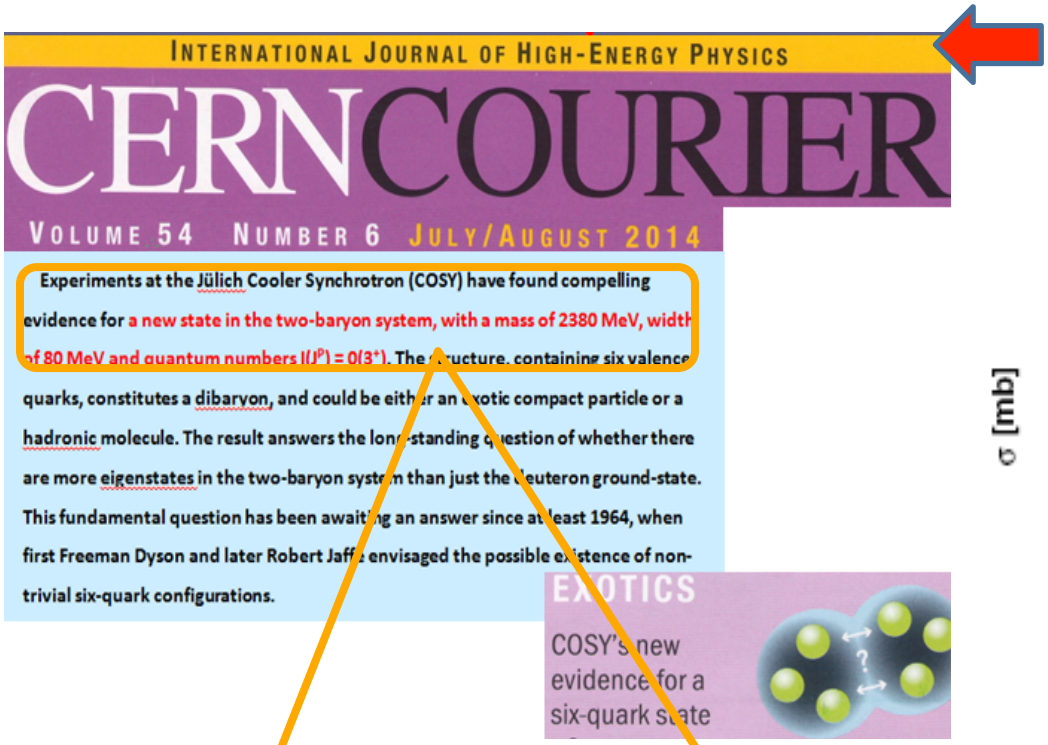
1、Observation of d*(2380)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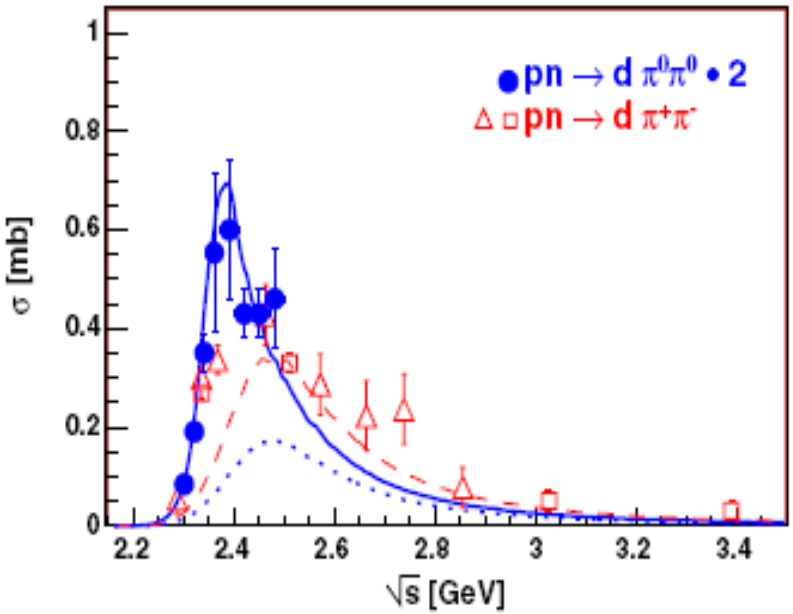
Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum numbers $I(J^P) = 0(3^+)$. The structure, containing six valence quarks, constitutes a dibaryon, and could be either an exotic 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-trivial six-quark configurations.

EXOTICS

COSY's new evidence for a six-quark state

cerncourier.com/cws/article/cern/57836

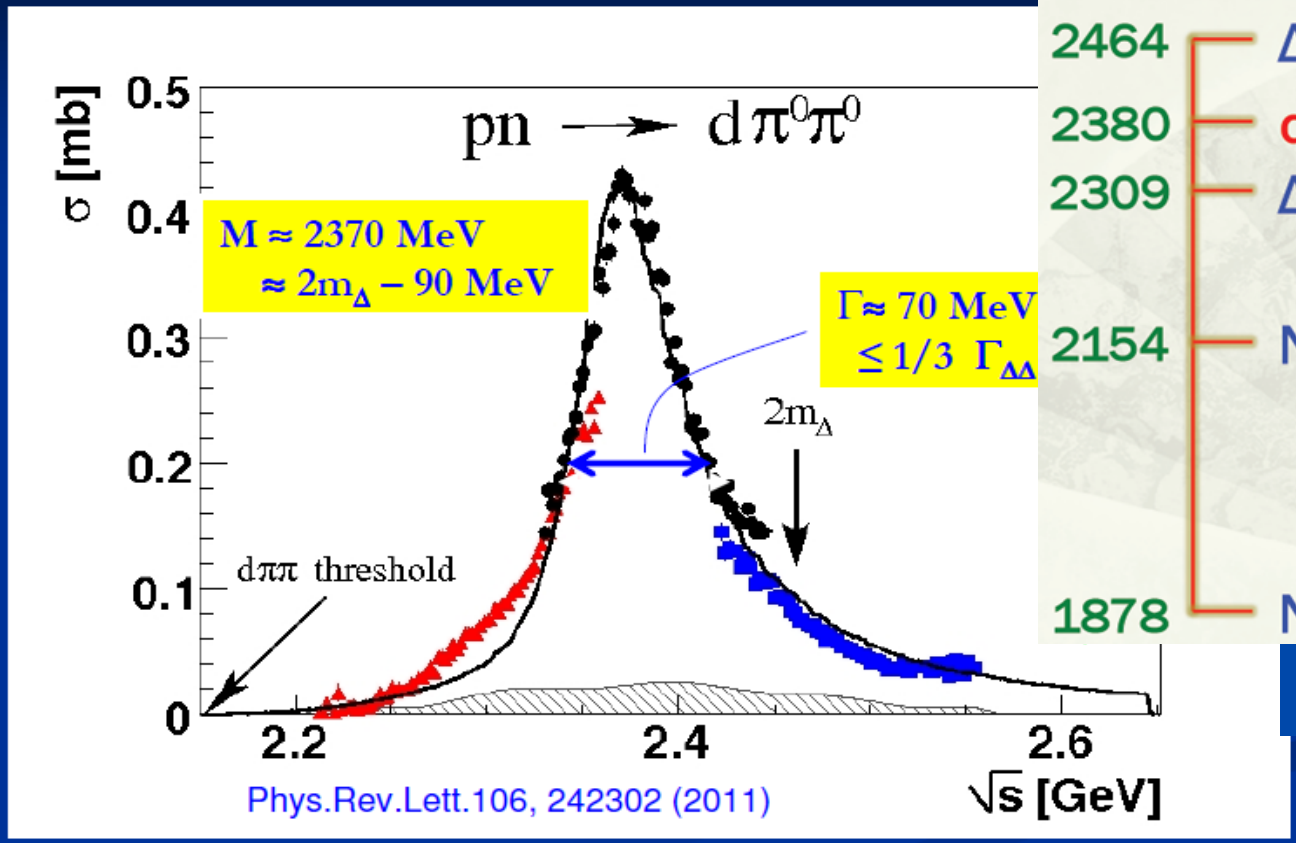
PRL 112 (2014) 202301

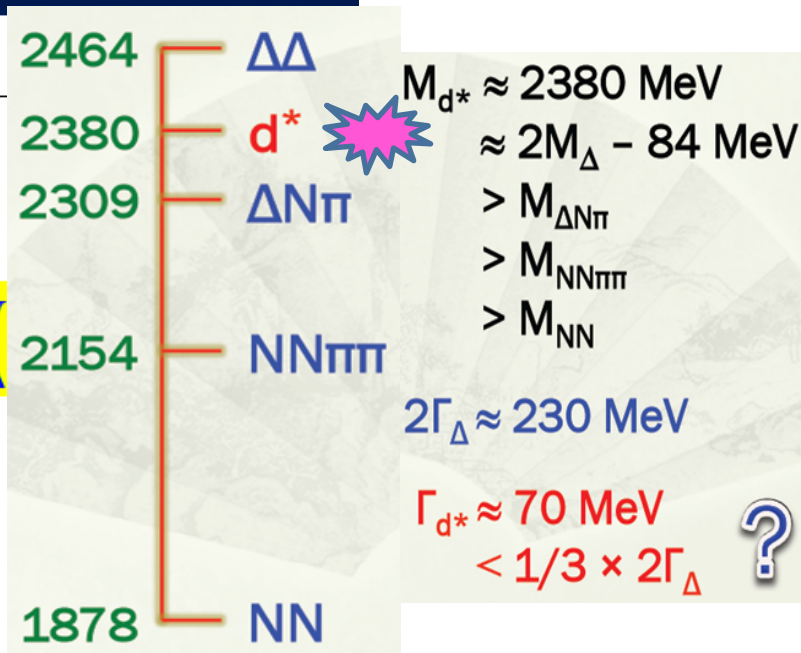


Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum numbers $I(J^P) = 0(3^+)$。

The d* Resonance I (J^P) = 0 (3^+)

Unusual narrow width





Baryon number=2

$\Gamma_{d^*} \approx 70\text{MeV}$

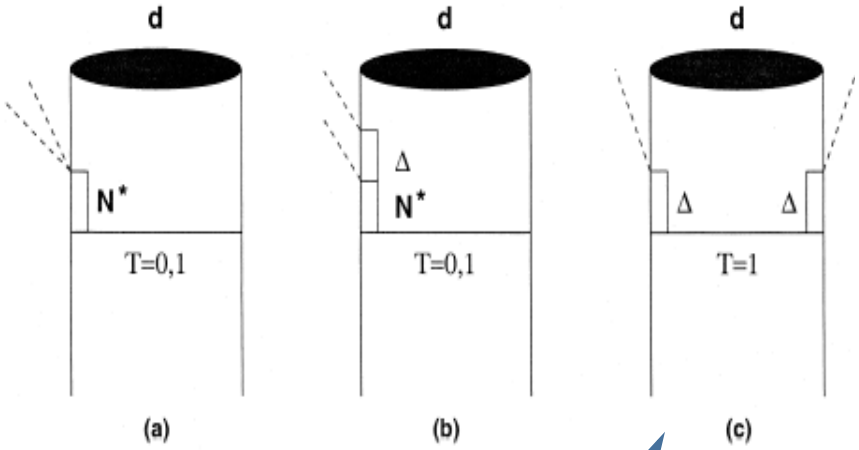
$M_{\Delta N\pi} = 2310\text{MeV}$ $M_{d^*} \approx 2380\text{MeV}$ $M_{\Delta\Delta} = 2464\text{MeV}$

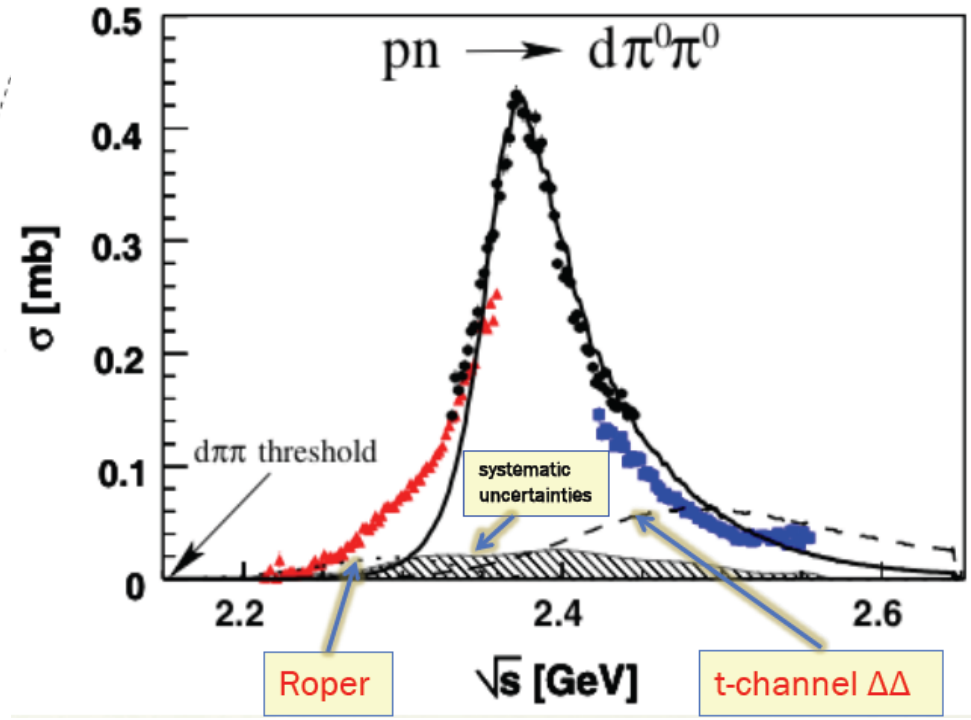
70MeV 70MeV

Fusion 2π production

$pd \rightarrow p_{spectator} d\pi^0\pi^0$ **Possible understandings**

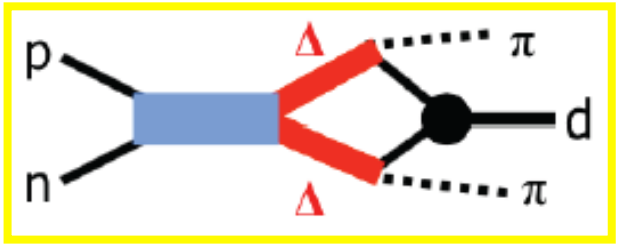
WASA-at-COSY: PRL106(2011)242302





Δ Δ resonance?

Neither NN (Roper), nor ΔΔ Intermediate state



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

$M \approx 2380 MeV$

$\Gamma \approx 70 MeV$

Signals in other reactions @ COSY

fusion 2π processes

Measured also in fusion reactions to helium isotopes:

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

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

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

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

Non-fusion 2π processes

$pn \rightarrow pn\pi\pi$

$pn \rightarrow pp\pi^-\pi^0$

$pn \rightarrow pn\pi^0\pi^0$

$pn \rightarrow pn\pi^+\pi^-$

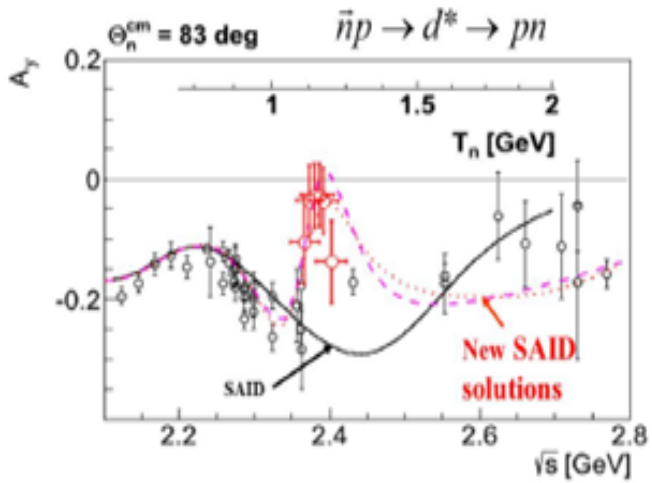
PRC88 (2013)055208

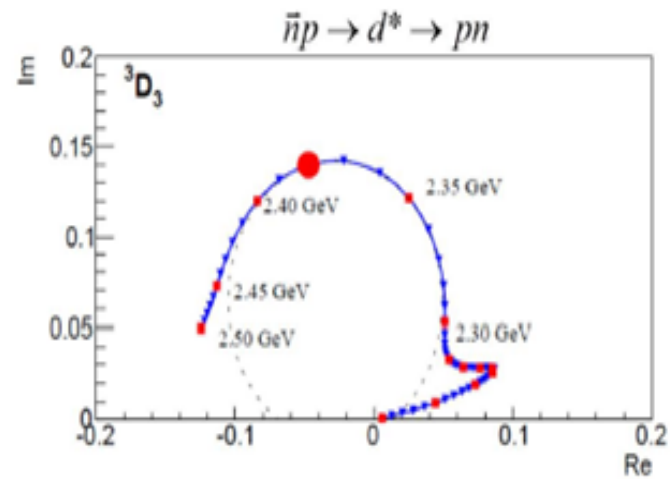
PLB 743 (2015) 325

Proc. STORI 2015

Scattering

$pn \rightarrow pn$



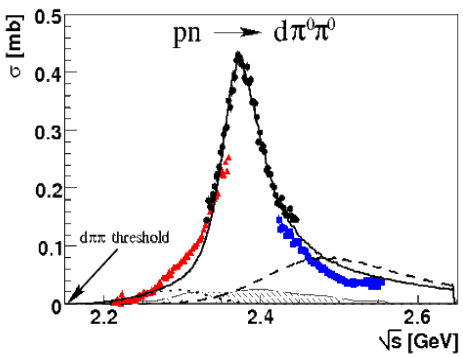


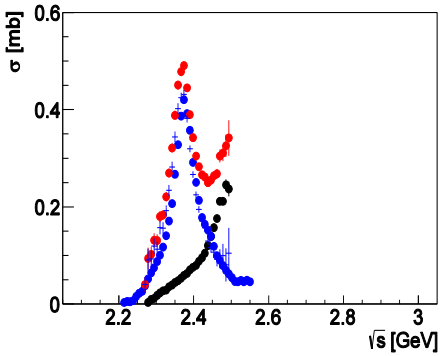
the Argand diagram of the 3D3 partial wave in pn scattering

WASA-at-COSY & SAID DAC, PRL112(2014)202301

d* Strong decays

PRL 106 (2011) 242302





PLB 721 (2013) 229

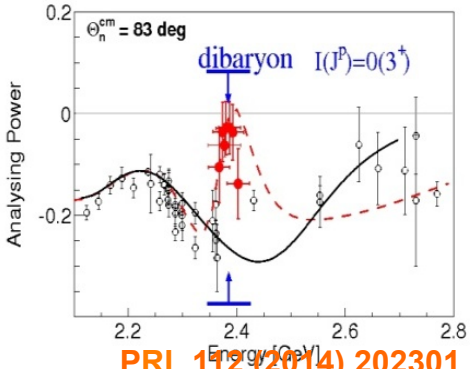
WASA data

$d\pi^0\pi^0$

$d\pi^+\pi^-$

pn → d*(2380)

pn

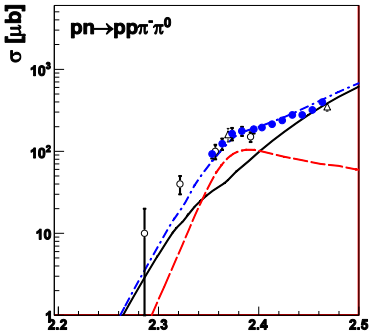


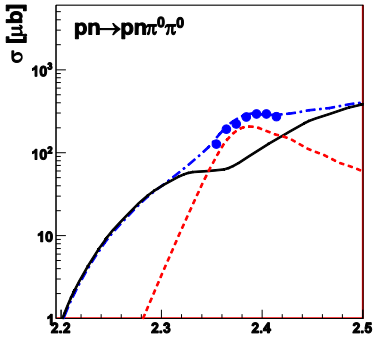
PRL 112 (2014) 202301

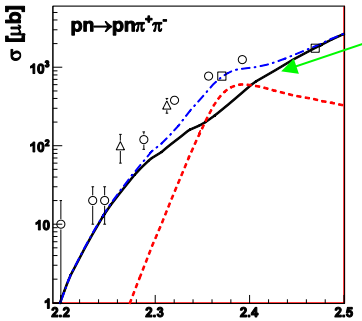
$pp\pi^-\pi^0$

$pn\pi^0\pi^0$

$pn\pi^+\pi^-$







HADES

PRC 88 (2013) 055208

PLB 743 (2015) 325

Proc. STORI 2015

d* Characters:

- d* mass locates between ΔΔ and ΔNπ
  Effect from threshold is expected small
- d* narrow width → Possible 6q structure might be different from normal hadrons

d*(2380) size

P.R.L.103(2009)162001

$$r \approx \frac{\hbar c}{\sqrt{2m\epsilon}}$$

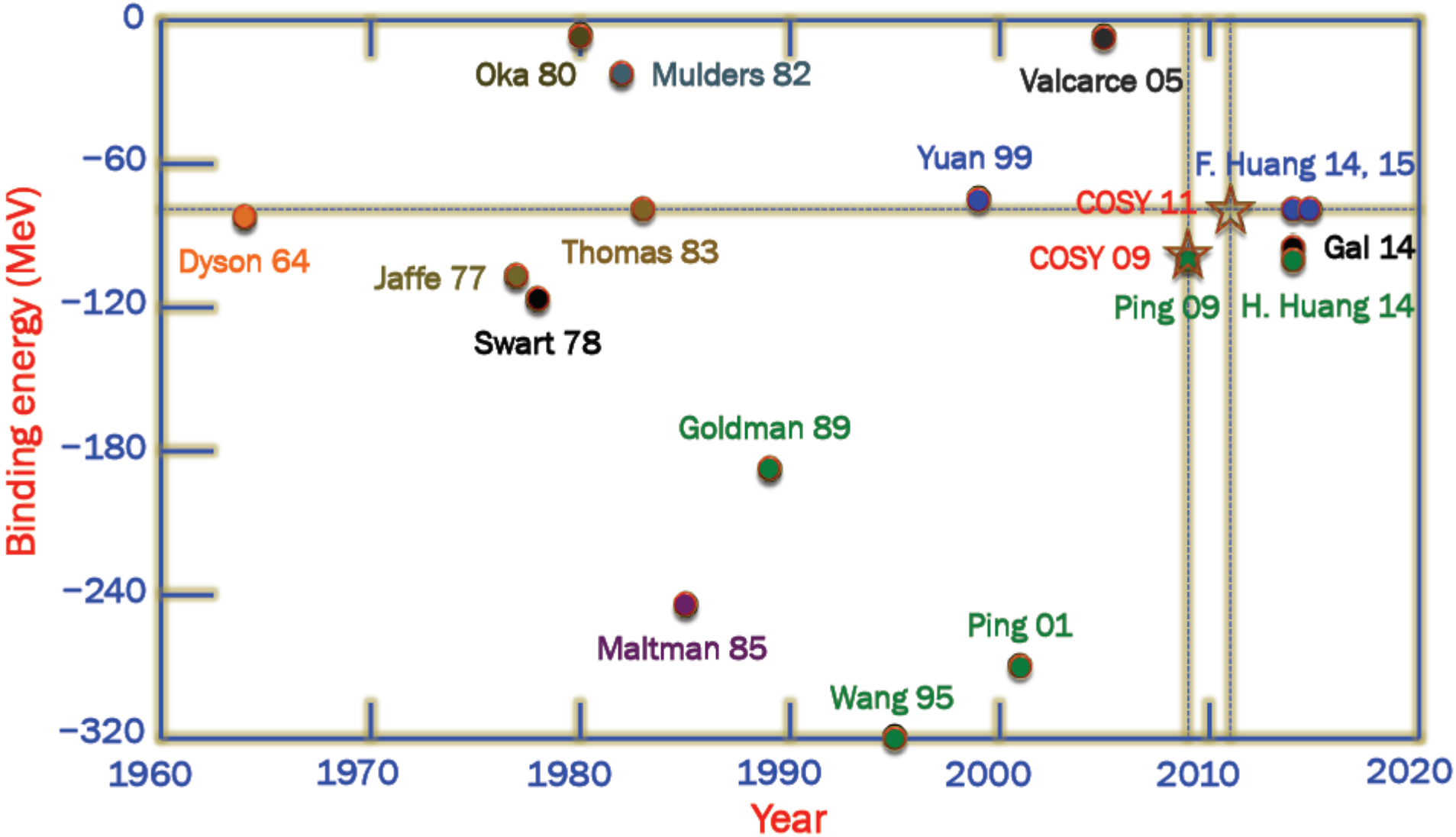
d* Binding energy ~ 80 MeV

→ d* rms is about 0.5fm ($m = m_{\Delta} = 1.232GeV$)

Probably a compact structure

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

2、Possible interpretations



Time

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

$$M = A + B'(T(T+1)) + B''(J(J+1))$$

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

Choose B = 50MeV, then, M_{d^*} = 2376MeV

• Chiral SU(3) Quark Model

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

ΔΔ + CC structures

√ Parameters: from NN phase shifts、YN cross sections、deuteron binding & radius

√ dynamical calculation for its binding d*(ΔΔ + CC (IS=03))

√ • predict: d* binding

BE ≅ 40—80 MeV [SU(3)]

(Present data: 84 MeV)

• Conclusions: CC channel is important, suppress the binding about 20MeV.

•WFs and decays not calculated.

TABLE III. Deltaron binding energy B(MeV) with different parameters. $B=-(E_{\text{deltaron}}-2M_{\Delta})$.

	$(\Delta\Delta+CC)$		$(L=0+L=2)$	
$B(\text{OGE}+\pi,\sigma)$	79.7	97.1	97.9	113.4
$B[\text{OGE}+\text{SU}(3)]$	37.3	64.2	52.4	79.2
b_N(fm)	0.505	0.60	0.505	0.60
m_σ(MeV)	625	625	550	550

- Binding energy: 40 ~ 80 MeV
- CC: 10 ~ 20 MeV increase in binding energy

Understanding d* after the discovery

- 6q dominant (quark-level)

* Argument

M.Bashkanov, S.J.Brodsky H.Clement, PLB727,438(2013)

* ΔΔ+CC Interpretations

a, arXiv: 1408.0458 [nucl-th] (CPC 39 (2015) 071001]

b, SCIENCE CHINA 59 (2016) 622002

c, PRC 91 (2015) 064002

d, arXiv: 1603.08748 [hep-ph], PRC 94, 014003 (2016)

Binding energy、wave functions, decays

Bashkanov, Brodsky, H.Clement Phys.Lett.B727(2013)438

We conclude from such observations that d^* must be of an unconventional origin, possibly indicating a genuine six-quark nature. With the predominant decay of d^* being $d^* \to \Delta\Delta$ ($BR(d^* \to \Delta\Delta)/BR(d^* \to pn) = 9:1$), one could naively expect d^* to be a so-called a "deltaron" denoting a deuteron-like bound state of two Δs. However, the narrow width of d^* contradicts this simple assumption. A deltaron would need to have 90 MeV binding energy, i.e. 45 MeV per Δ, which would lead to a reduction of width from $\Gamma_{\Delta\Delta} = 230$ MeV to $\Gamma_{\Delta\Delta} = 160$ MeV, using the known momentum dependence of the width of the Δ resonance. This is more than twice what is observed.

Ansatz

According to M. Harvey [66]

$$|\Psi_{d^*}\rangle = \sqrt{\frac{1}{5}}|\Delta\Delta\rangle + \sqrt{\frac{4}{5}}|6Q\rangle$$

$$|\Psi_{d^*}\rangle = \sqrt{\frac{4}{5}}|\Delta\Delta\rangle - \sqrt{\frac{1}{5}}|6Q\rangle.$$

Here $\Delta\Delta$ means the asymptotic $\Delta\Delta$ configuration and $6Q$ is the genuine "hidden color" six-quark configuration. The first solution denotes a S^6 quark structure (all six quarks in the S-shell).

$\Delta\Delta$ width:

$$\Gamma_{\Delta\Delta} = 230 MeV$$

Binding about 90MeV

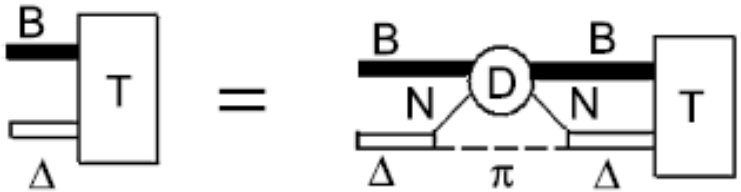
$$\Gamma_{\Delta\Delta} = 160 MeV$$

- d* narrow width

The observed d* must be of an unconventional origin, probably 6q structure。

- $\Delta N\pi$ 3-body bound state（π induced $D_{12}\pi$ scenario）

B =Δ' (Δ (Γ=0)) A. Gal et al. NPA 928, 73(2014)



S-matrix pole equation for $\mathcal{D}_{03}(2370)$ ΔΔ dibaryon

NΔ dibaryon's Lippmann–Schwinger equation

a). Δ' N is NNπ 3-body system:

Nπ Interaction: P33 channel separable potential (Δ')

By solving Faddeev eq. to obtain Δ' N interaction,

D_{12} -Pole : （2165~2174）- *i*（64~60） MeV

b). Take Δ'Δ as Δ' N π 3-body system:

Δ' N Interaction from solution a) , Nπ separable potential

Solving Faddeev eq. to get the Δ' N π resonance

$M_{\Delta' N\pi} = 2383$ MeV	Γ ≅ 82~94 MeV
$M_{\Delta' N\pi} = 2343$ MeV	Γ ≅ 48~62 MeV

$m_\Delta = (1211 + i\,X\,49.5)$ MeV

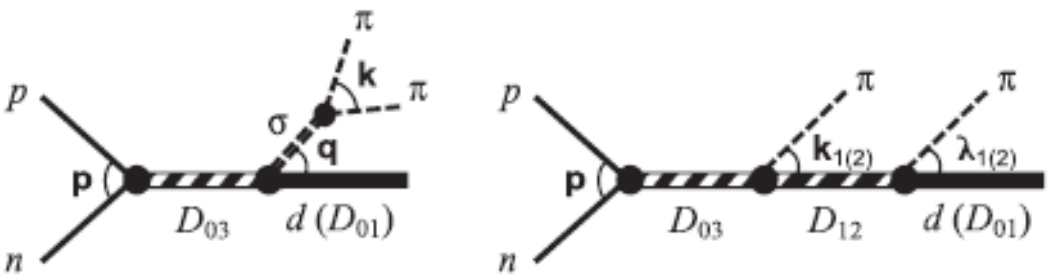
Where X = 1 或 2/3

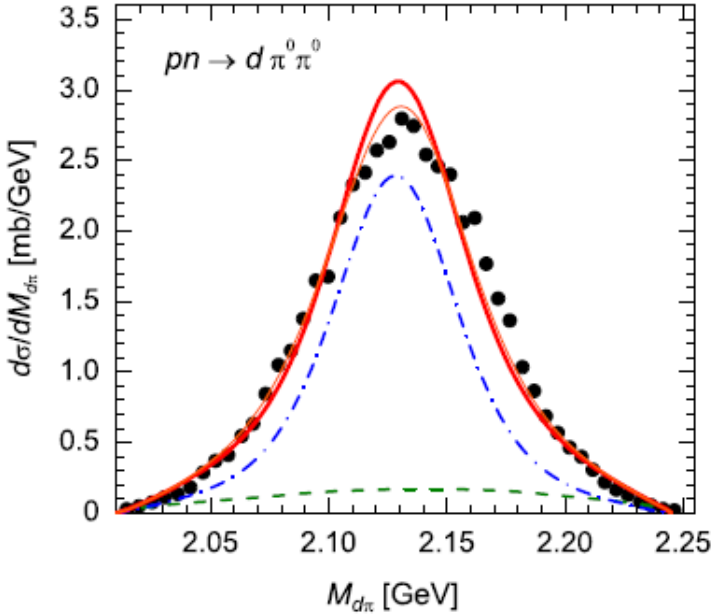
V. Kukulin et al. PRC87,025202(2013)

NPA 946,117(2016)

- $d\sigma$ & $D_{12}\pi$

Hadronic model





The dot-dashed line gives the "D12(2150) contribution to the two-body decay of D03(2380), and the dashed line gives a scalar-isoscalar sigma-meson emission contribution.

- QCD Sum rule (6q) H.X.Chen, PRC 91, 025204 (2015)

$$M_{d^*} = 2.4 \pm 0.2\,\mathrm{GeV}$$

. . . . . .

3、d* structures in chiral constituent quark model

q-q Interactions

$$V_{ij} = V_{ij}^{conf} + V_{ij}^{OGE} + V_{ij}^{ch} + V_{ij}^{chv}$$

$$V_{ij}^{ch} = \sum_{a} (V_{ij}^{s(a)} + V_{ij}^{ps(a)})$$

Scalar

Pseduoscalar

vector

Interactive Lagrangian

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

$b_{\mathbf{u}}, \ m_\sigma$ are determined by fitting to the experimental data for NN systems

$$\mathrm{BE}_d^{exp't} = 2.22\,\mathrm{MeV}$$

		SU(3)	**Ext. SU(3) (f/g=0)**	Ext. SU(3) (f/g=2/3)
Deuteron Binding energy(MeV)		2.09	**2.24**	2.20
Fraction of Wave Function (%)	NN (L=0)	93.68	**94.66**	94.71
	NN (L=2)	6.32	**5.34**	5.29

$b_{\mathbf{u}} = 0.5\,fm$ $\qquad$ $b_{\mathbf{u}} = 0.45\,fm$

$m_\sigma = 595\,\mathrm{MeV}$ $\qquad$ $m_\sigma = 535 \sim 547\,\mathrm{MeV}$

NN Phase shifts: Good

- **a, RGM method for WFs:** $I(J^P) = 0(3^+)$

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

$$\boxed{\begin{aligned} \Delta: &\quad (0s)^3\,[3]_{\rm orb}, S=3/2, I=3/2, C=(00), \\ C: &\quad (0s)^3\,[3]_{\rm orb}, S=3/2, I=1/2, C=(11), \end{aligned}}$$

$\mathcal{A}$: Anti-symmetrized operator

ϕ: Internal cluster WF

η: Relative WF from RGM with interactions

$\mathcal{A} = 1 - 9P_{36}$, P_{36} Quark Exchange Operator

• b, Hadronization

Due to the exchange operator, functions are not orthogonal

(1) (2)

$$\Psi_{6q} = (1 - 9P_{36})[\phi_\Delta \phi_\Delta \eta_{\Delta\Delta}(r)]_{SIC=30(00)}$$
$$+ (1 - 9P_{36})[\phi_C \phi_C \eta_{CC}(r)]_{SIC=30(00)}$$

(3) (4)

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

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

Relative Wave function (or Channel Wave function)

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

Contains (1), (2),(4) terms

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

Contains (3), (2),(4) terms

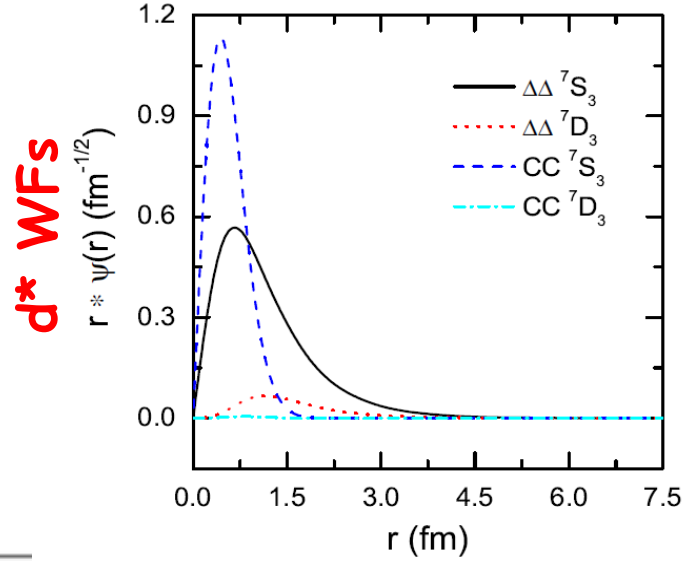
$$\Psi_{d^*} = |\Delta\Delta\rangle\, \chi_{\Delta\Delta}(r) + |CC\rangle\, \chi_{CC}(r)$$

$\chi_{\Delta\Delta}$ and χ_{CC} orthogonal

Quark exchange effect is included

- **Binding energy and relative wave function**

Parameters are determined by fitting to the data, then the binding and wave functions are calculated.



		SU(3)		Ext. SU(3) (f/g=0)		Ext. SU(3) (f/g=2/3)	
		ΔΔ (L=0,2)	ΔΔ-CC (L=0,2)	ΔΔ (L=0,2)	ΔΔ-CC (L=0,2)	ΔΔ (L=0,2)	ΔΔ-CC (L=0,2)
d^* Binding Energy(MeV)		28.9	47.9	62.3	83.9	47.9	70.3
Fraction of Wave Function (%)	ΔΔ (L=0)	97.18	33.11	98.01	31.22	97.71	32.51
	ΔΔ (L=2)	2.82	0.62	1.99	0.45	2.29	0.51
	CC (L=0)	0	66.25	0	68.33	0	66.98
	CC (L=2)	0	0.02	0	0.00	0	0.00

$$BE_{d^*}^{exp't} = 84MeV$$

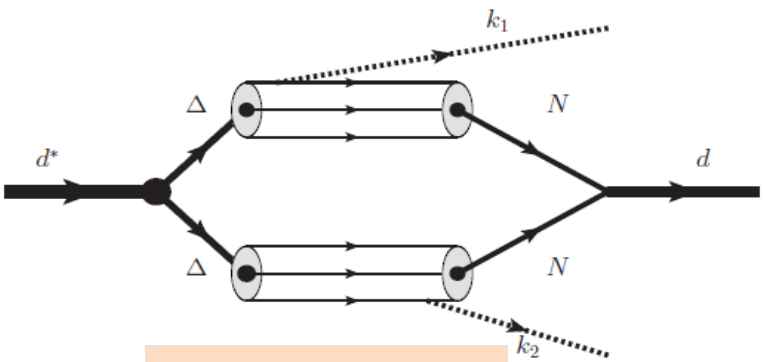
• d* decay widths

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

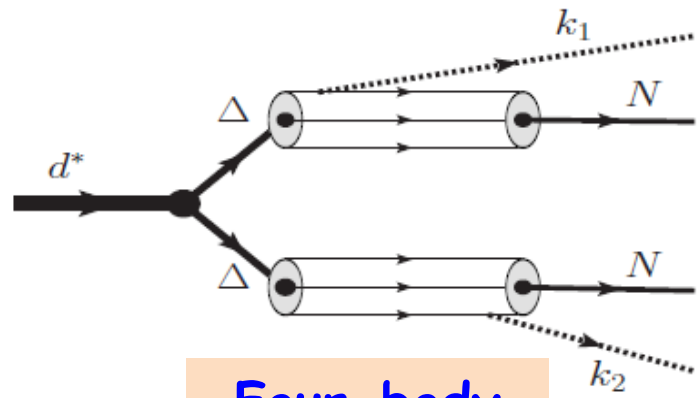
$d^* \to np\pi^0\pi^0\ (np\pi^+\pi^-)$

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

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



Three-body decay



Four-body decay

$qq\pi$ **Interaction**

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

Simon Capstick, PRD46,2864

$\Delta \to N\pi$ **Coupling & form factor**

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

Calculated widths: PRC91,064002; 94,014003

	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

Discussions:

*FSI is about 26~30%

*Total width is good

$$\Gamma^{exp't} = 70 \sim 75\, MeV$$

$$\Gamma^{th} \approx 72\, MeV$$

*Partial widths are good

*If only (ΔΔ) is considered, the widths are not good

M_{d^*}(MeV)	(100%)ΔΔ 2374	Expt 2375
Decay channel	Γ(MeV)	Γ(MeV)
$d^* \to d\pi^0\pi^0$	17.0	10.2
$d^* \to d\pi^+\pi^-$	30.8	16.7
Total	132.8	74.9

*Isospin breaking

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

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

Idearl

$$b_c = 0.45\, fm, \qquad \chi_{CC} = Ne^{-r^2/2b_c^2}$$

*The narrow width is due to large component CC

d*(2380) single-π decay: $d^*(2380) \dashrightarrow \pi NN$ PLB769, (2017) 223-226

This channel might provide a test for different interpretations.

Experiment gives 9% up-limit; the result of three-body (ΔπN) is about 18%.

Physics Letters B 769 (2017) 223–226

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Decay width of the $d^*(2380) \to NN\pi$ process in a chiral constituent quark model

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Single-pion decay

ABSTRACT

The width of three-body single-pion decay process $d^* \to NN\pi^{0,\pm}$ is calculated by using the d^* wave function obtained from our chiral SU(3) constituent quark model calculation. The effect of the dynamical structure on the width of d^* is taken into account in both the single $\Delta\Delta$ channel and coupled $\Delta\Delta + CC$ two-channel approximations. Our numerical result shows that in the coupled-channel approximation, namely, the hidden-color configuration being considered, the obtained partial decay width of $d^* \to NN\pi$ is about several hundred keV, while in the single $\Delta\Delta$ channel it is just about $2 \sim 3$ MeV. We, therefore, conclude that the partial width in the single-pion decay process of d^* is much smaller than the widths in its double-pion decay processes. Our prediction may provide a criterion for judging different interpretations of the d^* structure, as different pictures for the d^* may result quite different partial decay width.

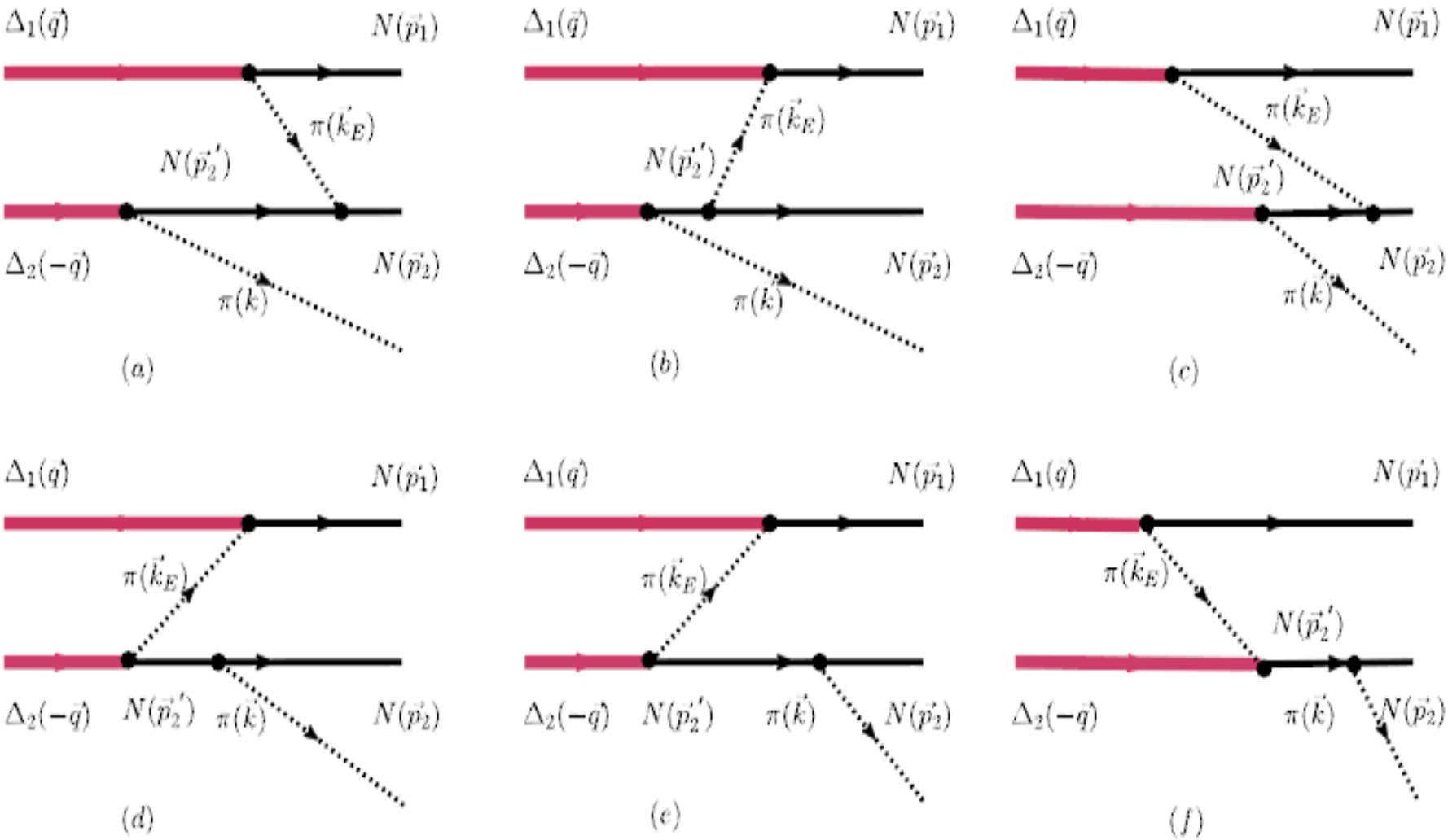


Fig. 1. Six possible ways to emit pion only from the $\Delta\Delta$ component of d^* in the $d^* \to NN\pi$ decay process. The outgoing pion with momenta $\vec{k}$ is emitted from Δ_2. The other six sub-diagrams with pion emitted from Δ_1 are similar, and then are not shown here for reducing the size of the figure.

$$L = L_{\pi NN} + L_{\Delta N\pi}$$

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

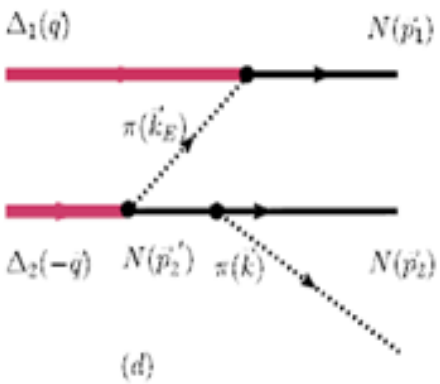
$$\Delta: \quad (0s)^3\,[3]_{\mathrm{orb}}, S = 3/2, I = 3/2, C = (00),$$

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

Intermediate states:

(N,N*,Δ,Δ*)

Low-lying resonances are considered



From quark model $\frac{g^2_{\pi\Delta\Delta}}{4\pi} = \frac{1}{25}\frac{M^2_\Delta}{M^2_N}\frac{g^2_{\pi NN}}{4\pi}$, $g_{\pi\Delta\Delta}$ *small*

1, C→Δ, interaction should be color and isospin-dependent

2, CC(SI=3,0)→NN*(1400), D-wave of OGE is required

The suppressions enable to ignore the contribution from the CC component in d*

Our prediction 1%

Table 1
The calculated decay width of the $d^* \to NN\pi$ process and the widths contributed individually from the (a)-, (b)-, (c)-, (d)-, (e)-, and (f)-type diagrams (in units of MeV).

Case	Total width	(a)	(b)	(c)	(d)	(e)	(f)	sum of (a)–(f)
One ch. ($\Delta\Delta$ *only*)	2.276	0.550	0.306	0.267	0.0963	0.209	0.233	1.661
Two chs. ($\Delta\Delta + \mathrm{CC}$)	0.670	0.154	0.0884	0.0789	0.0279	0.0687	0.0847	0.503

Recently Gal(arXiv:1612.05092)

In order to match the up-limit

Of exp.

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

4、Summary

•Our understanding:

d* with CC component dominant (~ 66-68%)

M ≈ 2380 MeV Γ ≈ 72 MeV

($M^{exp't}$ ≈ 2380 MeV $\Gamma^{exp't}$ ≈ 70-75 MeV)

- Other experimental measurements

$$e^+ + e^- \rightarrow \bar{d}^* + p + n \quad \Upsilon \rightarrow \bar{d} + d^*, \quad d + \bar{d}^*, \quad \bar{d}^* + d^*$$

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

- Short range interaction

If it is 6q dominant, one can get more information

Effective Δ-Δ short range interaction induced by OGE (VM) are attractive

q-q short range int.

One-gluon-exchange (OGE)

Vector meson exchange (VME)

Thanks !

If the d* is further confirmed by other experiments, we believe that our interpretation is reasonable. Thus, it is a resonance state with 6q structure dominant and moreover, the more information about the short range interaction is expected.

$\langle P_{36}^{sfc} \rangle$ exchange effect in spin-flavor-color spaces

Reason for the large component of CC (67%)

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

$P_{36} = P_{36}^{r} \; P_{36}^{sfc}$ if it large

$\langle P_{36}^{r} \rangle$: 1 should also large

$\langle P_{36}^{r} \rangle$ 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 attractive.

⟶ Two clusters ΔΔ closer, $\langle P_{36}^{r} \rangle$ 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 —— Model dependent

P_{36} Effect large, large CC componet

d* might be a 6q dominant state

⟶ d* deep bounded and narrow width

Analysis: Large component of CC (67%) in d* ?

(1) (2)

$$\Psi_{6q} = (1 - 9P_{36})[\phi_\Delta \phi_\Delta \eta_{\Delta\Delta}(\mathbf{r})]_{SIC=30(00)}$$
$$+ (1 - 9P_{36})[\phi_C \phi_C \eta_{CC}(\mathbf{r})]_{SIC=30(00)}$$

(3) (4)

$$\chi_{\Delta\Delta}(\boldsymbol{r}) \equiv \langle \phi_\Delta(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\, \phi_\Delta(\boldsymbol{\xi}_4, \boldsymbol{\xi}_5) \,|\, \Psi_{6q} \rangle\,,$$ (1) (2) (4) terms

$$\chi_{CC}(\boldsymbol{r}) \equiv \langle \phi_C(\boldsymbol{\xi}_1, \boldsymbol{\xi}_2)\, \phi_C(\boldsymbol{\xi}_4, \boldsymbol{\xi}_5) \,|\, \Psi_{6q} \rangle\,,$$ (3) (4) (2) terms

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

χ_{CC} contains the contri. From (2), from ΔΔ exchanged terms。

Thus P_{36} Exchange is important!

$P_{36} = P_{36}^{r}\, P_{36}^{sfc}$ d* has ΔΔ and CC components

- $\Delta\Delta$+coupled channels (in quark level)

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ChQM (10 channles with hidden-color ones)

$IJ^P = 03^+$	1	2	3	4		
	$\Delta\Delta(^7S_3)$	$NN(^3D_3)$	$\Delta\Delta(^3D_3)$	$\Delta\Delta(^7D_3)$		
	5	6	7	8	9	10
	$^2\Delta_8\ ^2\Delta_8(^3D_3)$	$^4N_8\ ^4N_8(^3D_3)$	$^4N_8\ ^2N_8(^3D_3)$	$^2N_8\ ^2N_8(^3D_3)$	$^4N_8\ ^4N_8(^7S_3)$	$^4N_8\ ^4N_8(^7D_3)$

BE= 71 MeV Γ = 150 MeV

QDCSM (4 coupled channels)

$$\Delta\Delta^7S_3, NN^3D_3, \Delta\Delta^3D_3, \Delta\Delta^7D_3$$

BE= 107 MeV Γ = 110 MeV

TABLE III. $\Delta\Delta$ or resonance mass M and decay width Γ, in MeV, in two quark models for the $IJ^P = 03^+$ state.

	QDCSM		ChQM		
	sc	4 cc	sc	4 cc	10 cc
M	2365	2357	2425	2413	2393
Γ_{NN}	–	14	–	14	14
Γ_{inel}	103	96	177	161	136
Γ	103	110	177	175	150

On the charge distribution of d*

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

Nucleon(1/2):

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

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

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):

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

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

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

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

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

d*(3):

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

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

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

$$G_E^{d^*}(Q^2) = \frac{1}{7} \sum_{m_{d^*}=-3}^{3} < p', m_{d^*} \mid J^0 \mid p, m_{d^*} >$$

$$J^0 = \sum_{i=1}^{6} e_i \bar{q}_i \gamma^0 q_i = \sum_{i=1}^{6} j_i^0 .$$

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