A theoretical study of $d^*(2380) \to \mathrm{d}\,\pi\pi$ Decay width

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PRC91 064002(2015)

Contents

1, Introduction (Multiquark states)

The XYZ states

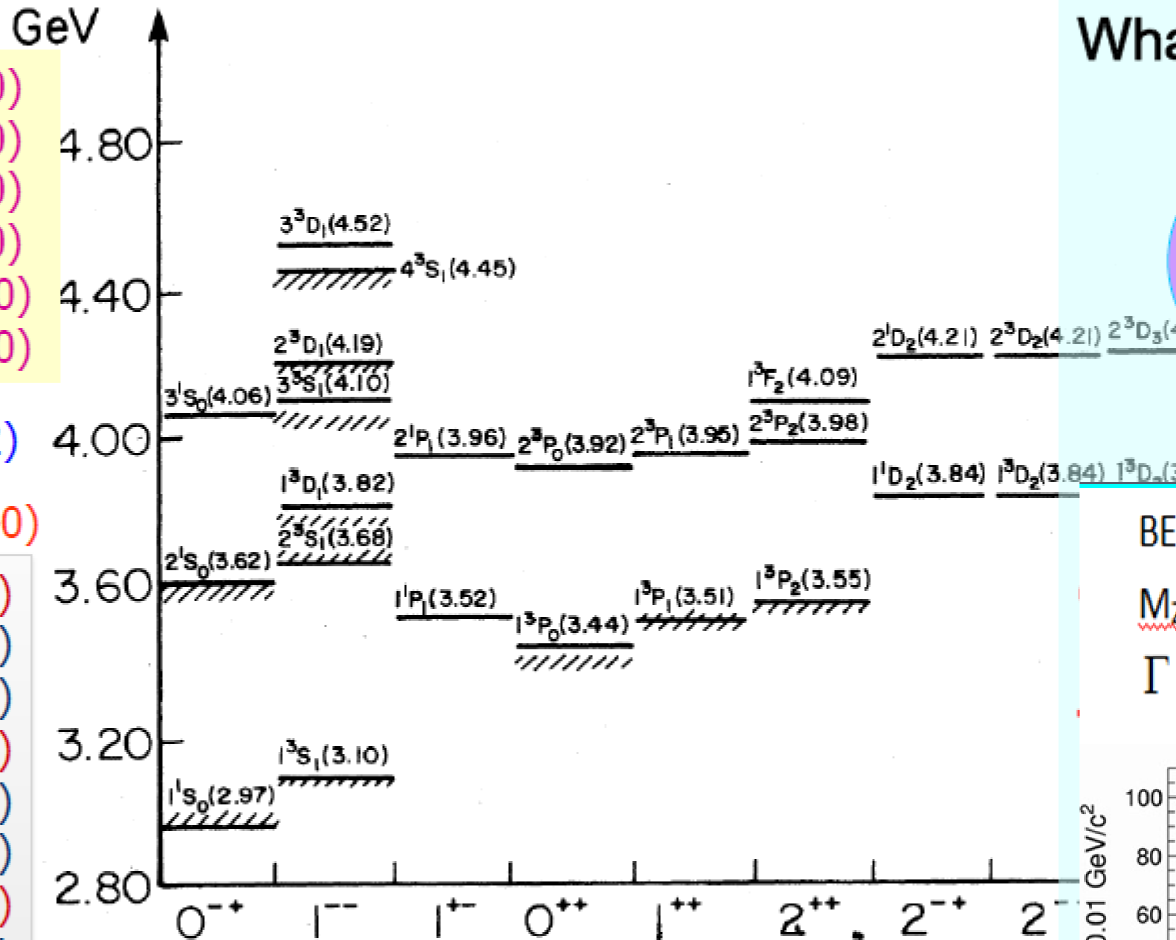
Four-quark

Z(4430)
Z(4250)
Z(4050)
Z(4200)
Zc(3900)
Zc(4020)

X(3872)

XYZ(3940)

X(3915)
X(4160)
Y(4008)
Y(4140)
Y(4260)
Y(4360)
X(4350)
Y(4660)



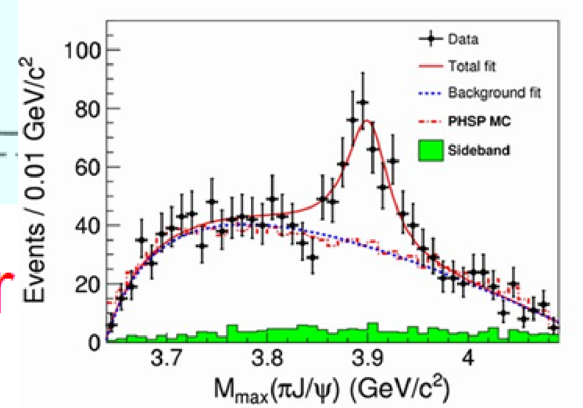
What are they ?

Potential models worked well for charmonium spectroscopy

BESIII, Belle and CLEO-c → $Z_c(3900)$

$M_{Zc(3900)} = (3899 \pm 3.6 \pm 4)$ MeV

$\Gamma_{Zc(3900)} = (46 \pm 10 \pm 20)$ MeV



Not all XYZ states are char

Courtesy of C. Z.Yuan

(New resonances, five-quark)

Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

The LHCb collaboration[†]

Abstract

Observations of exotic structures in the $J/\psi p$ channel, that we refer to as pentaquark-charmonium states, in $\Lambda_b^0 \to J/\psi K^- p$ 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 $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ 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

Five-quark

$\bar{D}\Sigma_c^*$, $\bar{D}^*\Sigma_c$, $\bar{D}^*\Sigma_c^*$ **bound states**

$3^- / 2, 5^+ / 2$

$P_c(4380), P_c'(4449)$

$\Lambda_c(2940)^+$

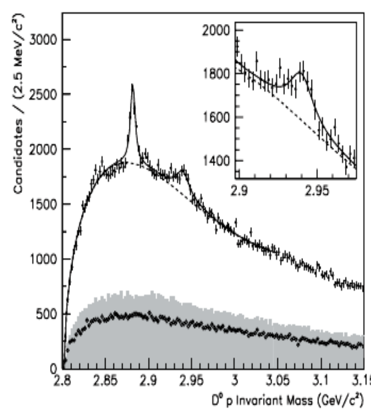
- Potential models
- Non relativistic QCD
- Heavy quark effective theory
- Heavy hadron chiral perturbation theor
- QCD sum rule
- Lattice calculations

- Molecule, baryonium
- tetraquark
- Hybrids
- Coupling channel…

PRL 98, 012001 (2007) PHYSICAL REVIEW LETTERS week ending 5 JANUARY 2007

Observation of a Charmed Baryon Decaying to $D^0 p$ at a Mass Near 2.94 GeV/c^2

(BABAR Collaboration)



The results for the $\Lambda_c(2940)^+$ baryon are

$$m = [2939.8 \pm 1.3(\mathrm{stat}) \pm 1.0(\mathrm{syst})]\ \mathrm{MeV}/c^2,$$

$$\Gamma = [17.5 \pm 5.2(\mathrm{stat}) \pm 5.9(\mathrm{syst})]\ \mathrm{MeV}.$$

For the $\Lambda_c(2880)^+$ baryon the results are

$$m = [2881.9 \pm 0.1(\mathrm{stat}) \pm 0.5(\mathrm{syst})]\ \mathrm{MeV}/c^2,$$

$$\Gamma = [5.8 \pm 1.5(\mathrm{stat}) \pm 1.1(\mathrm{syst})]\ \mathrm{MeV}.$$

d*(2380), six-quark

INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

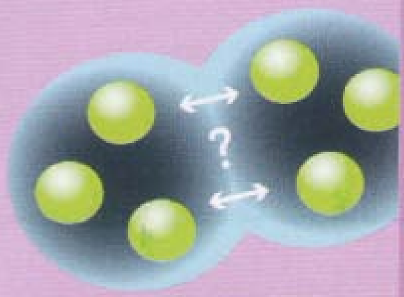
CERN COURIER

VOLUME 54 NUMBER 6 JULY/AUGUST 2014

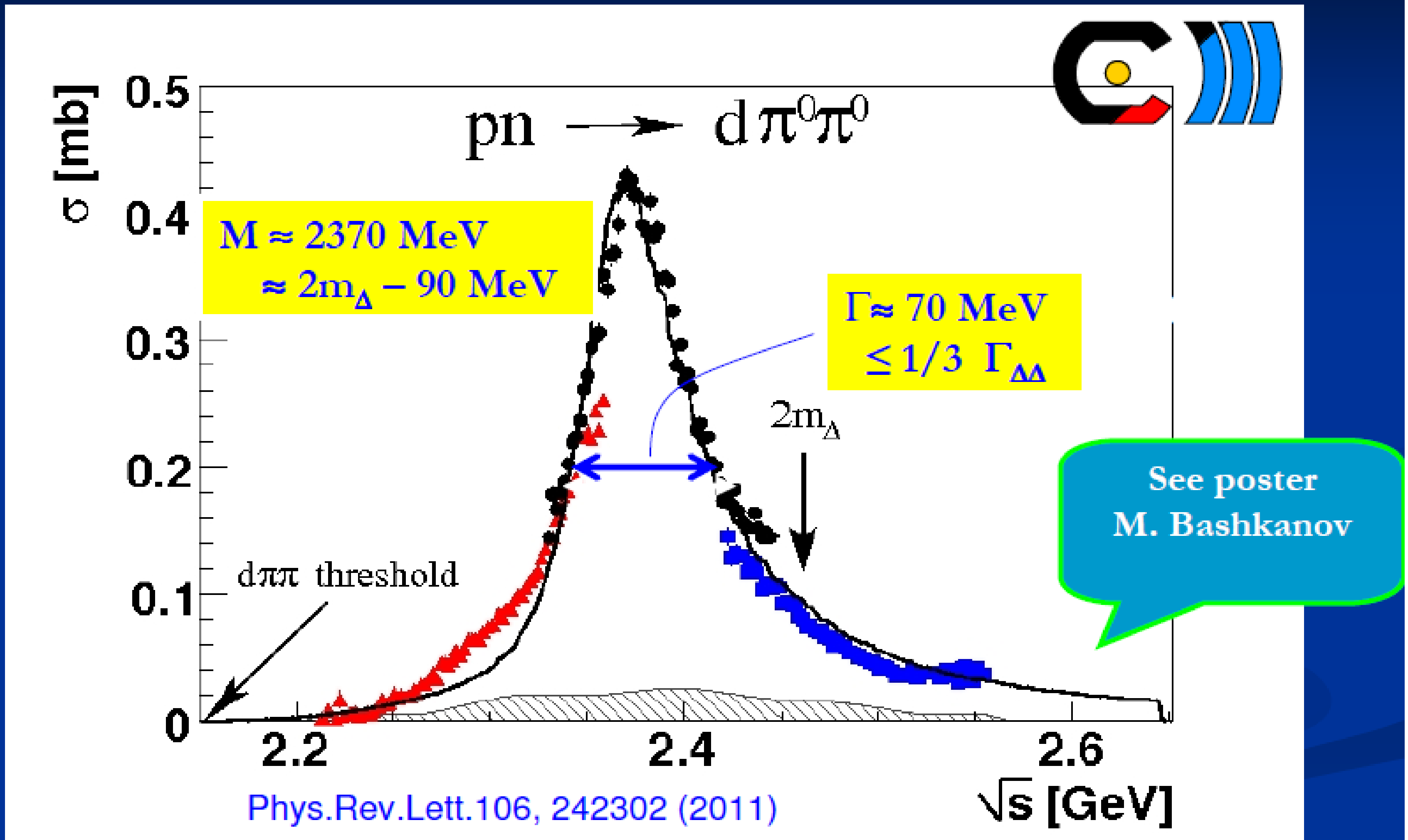
Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum numbers $I(J^P) = 0(3^+)$. The structure, containing six valence quarks, constitutes a dibaryon, and could be either an exotic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

EXOTICS

COSY's new evidence for a six-quark state



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



$M_{\Delta\Delta}$ = 2464 MeV

M_{d^*} ≈ 2380 MeV

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

Γ_{d^*} ≈ 70 MeV

???

Properties of the d*(2380)

- **Mass**

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

Far From threshold

$\Delta E \sim 84$ MeV $\Delta E \sim 70$ MeV

- **Width**

$\Gamma_{\Delta} = 116 \sim 120$ MeV

$\Gamma_{d^*} \approx 70$ MeV(narrow)

$< \frac{1}{3}(\Gamma_{\Delta} + \Gamma_{\Delta})$

- **Spin-parity**

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

Quantum numbers

$pn \to d\pi^0\pi^0$

2, Interpretations

- ***Many interpretations have been proposed***
- 1964 Dyson and Xiong: six non-strange states
- J.J. de Swart --- Phys. Rev. D17(1978)260
- M.Oka & K.Yazaki---PLB90(1980) 41
- A.W. Thomas---J.Phys.G9(1983)1159
- K.Maltman（Berkeley): Nucl.Phys.A438(1985)669
- T.Goldman ... F. Wang Phys.Rev. C39(1989)1889
- Zhang, and Shen et al., PRC60 (1999) 045203

Predictions

- AFTERWARDS

- Bashkanov, Brodsky, and Clement: arguments (2013)
- A. Gal et al. Nucl.Phys.A928(2014)73(Feddev+N+Δ+π)
- Kuklin—Russia (PRC87 (13) 025202: d*[d+σ(2pi)])
- +......

Interpretation (argument)

Novel six-quark hidden-color dibaryon states in QCD

M. Bashkanov[a,*], Stanley J. Brodsky[b], H. Clement[a]

PLB727, 438 (2013)

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

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

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), the second one a S^4P^2 configuration (4 quarks in the S-shell and 2 quarks in the P-shell). The quark structure with the large $\Delta\Delta$ coupling would correspond to a deltaron and can be excluded. Thus it is natural to assign the observed d^* resonance to the S^6 six-quark predominantly "hidden color" state, thus providing an explanation for its narrow decay width.

2, Chiral quark model

- X.Q.Yuan, Z.Y.Zhang …P.N.Shen: Phys.Rev.C60(1999)045203

Hamiltonian of the system:

$$H = \sum_i t_i - T_G + \sum_{i<j} V_{ij} \quad ,$$

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

$$V_{ij}^{ch} = \sum_a (V_{ij}^{s(a)} + V_{ij}^{ps(a)}) \quad .$$

ΔΔ+CC channel

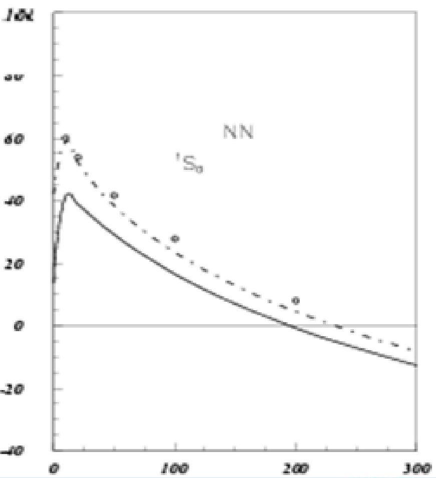
Results of the model

		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

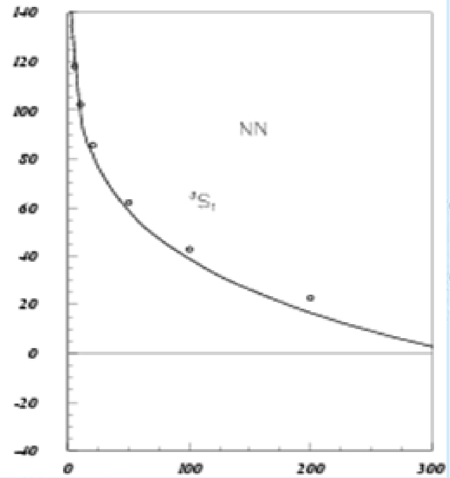
For deuteron

Results of the model

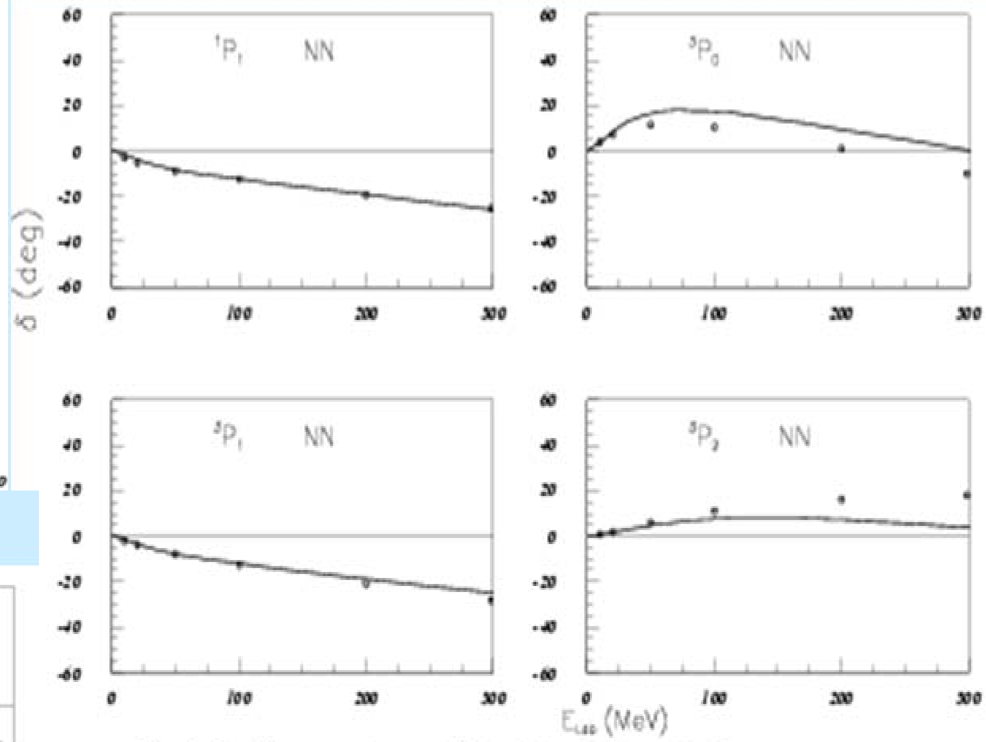
$^{1}S_{0}$



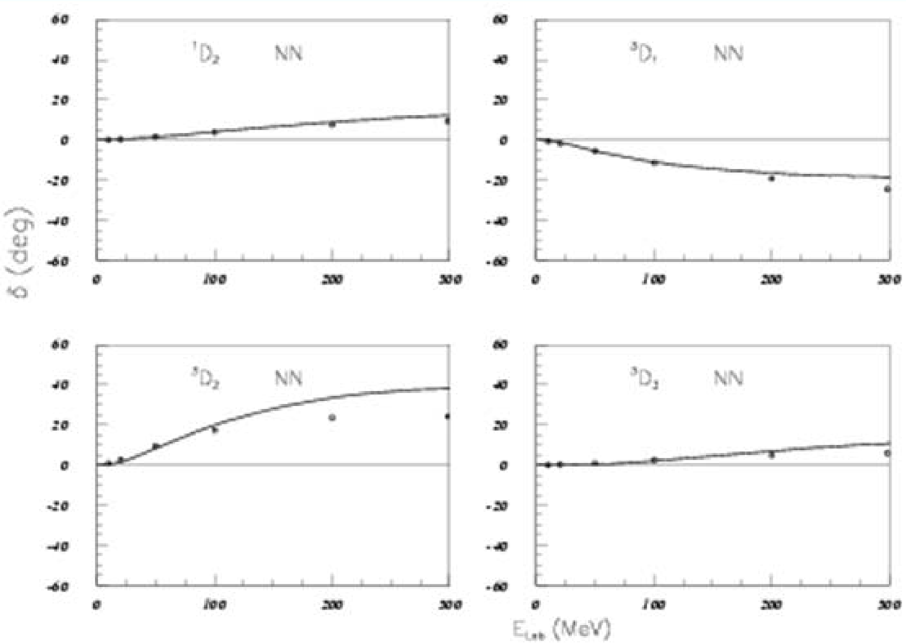
$^{3}S_{1}$



N-N P wave



N-N D wave



Phase-shift (N-N)

Results of the model (3)

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

Phys.Rev.C60(1999)045203

d*(ΔΔ + CC (IS=03))

CC(2/3)

New analysis

1505.05395

Appear on CPC

TABLE II. Binding energy, root-mean-square radius (RMS) of 6 quarks, and fraction of channel wave function for d^* in the chiral SU(3) quark model and extended chiral SU(3) quark model with ratios of tensor coupling to vector coupling f/g=0 and f/g=2/3 for vector meson fields.

	$\Delta\Delta$ $(L=0,2)$			$\Delta\Delta-CC$ $(L=0,2)$		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
Binding energy (MeV)	28.96	62.28	47.90	47.27	83.95	70.25
RMS of 6q (fm)	0.96	0.80	0.84	0.88	0.76	0.78
Fraction of $(\Delta\Delta)_{L=0}$ (%)	97.18	98.01	97.71	33.11	31.22	32.51
Fraction of $(\Delta\Delta)_{L=2}$ (%)	2.82	1.99	2.29	0.62	0.45	0.51
Fraction of $(CC)_{L=0}$ (%)				66.25	68.33	66.98
Fraction of $(CC)_{L=2}$ (%)				0.02	0.00	0.00

Wave function(1)

Pauli principle

$$\Psi_{6q} = (1_{(1)} - 9P_{36_{(2)}})[\phi_\Delta \phi_\Delta \eta_{\Delta\Delta}(\mathbf{r})]_{SIC=30(00)} + (1_{(3)} - 9P_{36_{(4)}})[\phi_C \phi_C \eta_{CC}(\mathbf{r})]_{SIC=30(00)}$$

Two channels
Model space

Resonating group method (RGM)

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

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

Orthogonal states
Anti-symmetrize effect

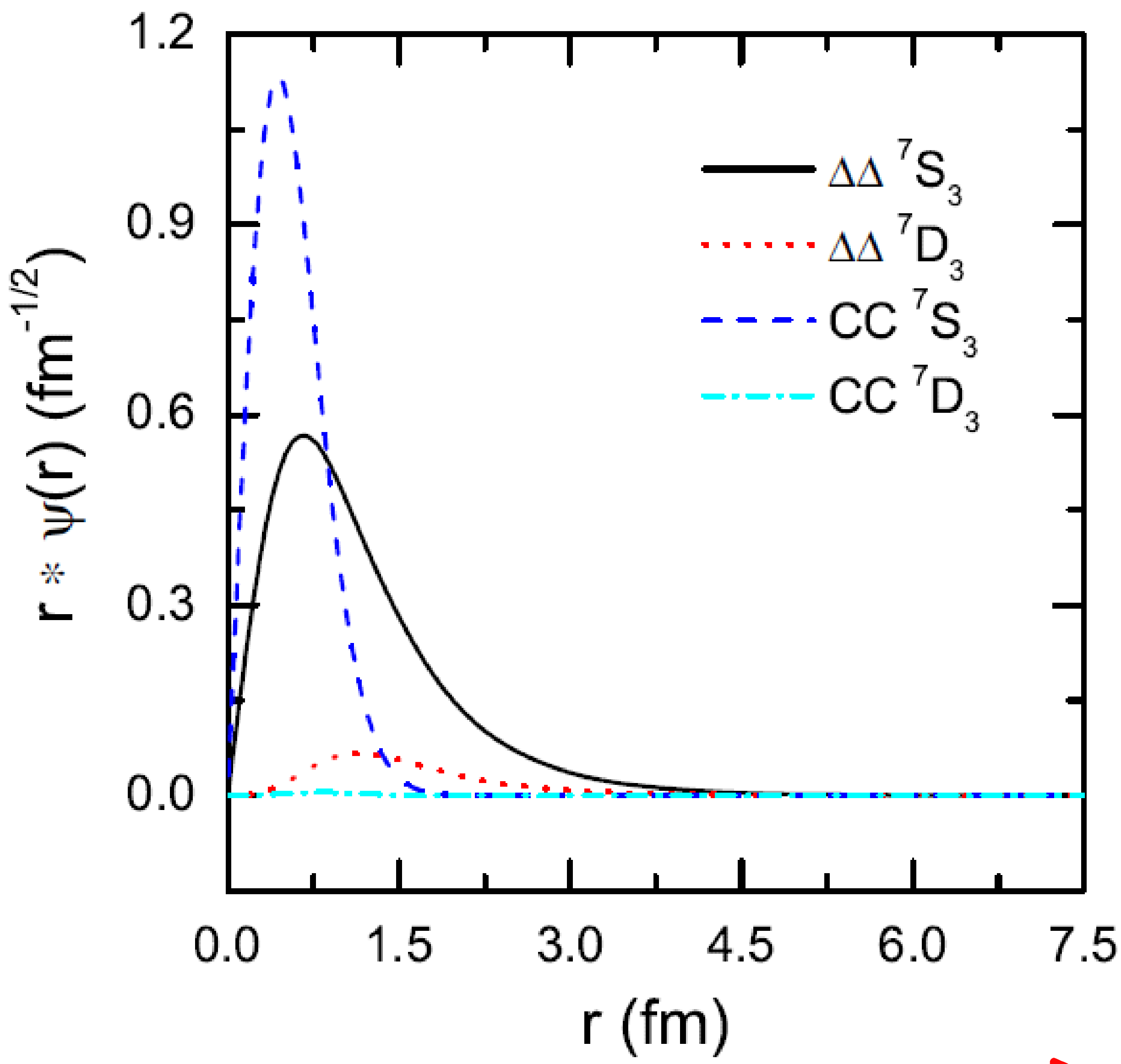
→ Relative Wave functions

Quark's Degrees of freedom are integrated out.
Equivalent to hadronization

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

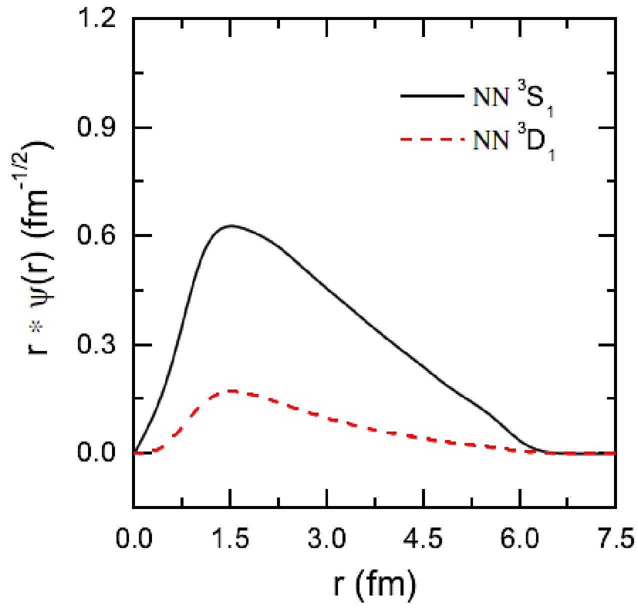
2015/8/6

d* Wave function



D-wave is small, and the system looks compact

d*:rms:(0.76~0.8)fm



(a) Deuteron

Deuteron, rms~2fm

3, Model calculation of

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

a, Quark model for Δ→π+N

Wave functions of Δ and N

$$|N\rangle = \frac{1}{\sqrt{2}}[\chi_\rho \psi_\rho + \chi_\lambda \psi_\lambda]\Phi_N(\vec{\rho},\vec{\lambda}) \qquad |\Delta\rangle = \chi_s \psi_s \Phi_\Delta(\vec{\rho},\vec{\lambda})$$

Interaction of qqπ

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

$$M \to 3 < N\pi \,|\, \mathrm{H}_{qq\pi} \,|\, \Delta >$$

$$\langle S_\alpha || \frac{\sigma_3}{2} || S_\beta \rangle = \frac{\sqrt{3}}{6}\begin{bmatrix} \sqrt{5} & 0 & -2 \\ 0 & 3 & 0 \\ 2\sqrt{2} & 0 & -1 \end{bmatrix},$$

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

Simon Capstick, PRD46,2864

b, application of wave functions to

$$d^* \rightarrow d + \pi^0 + \pi^0$$

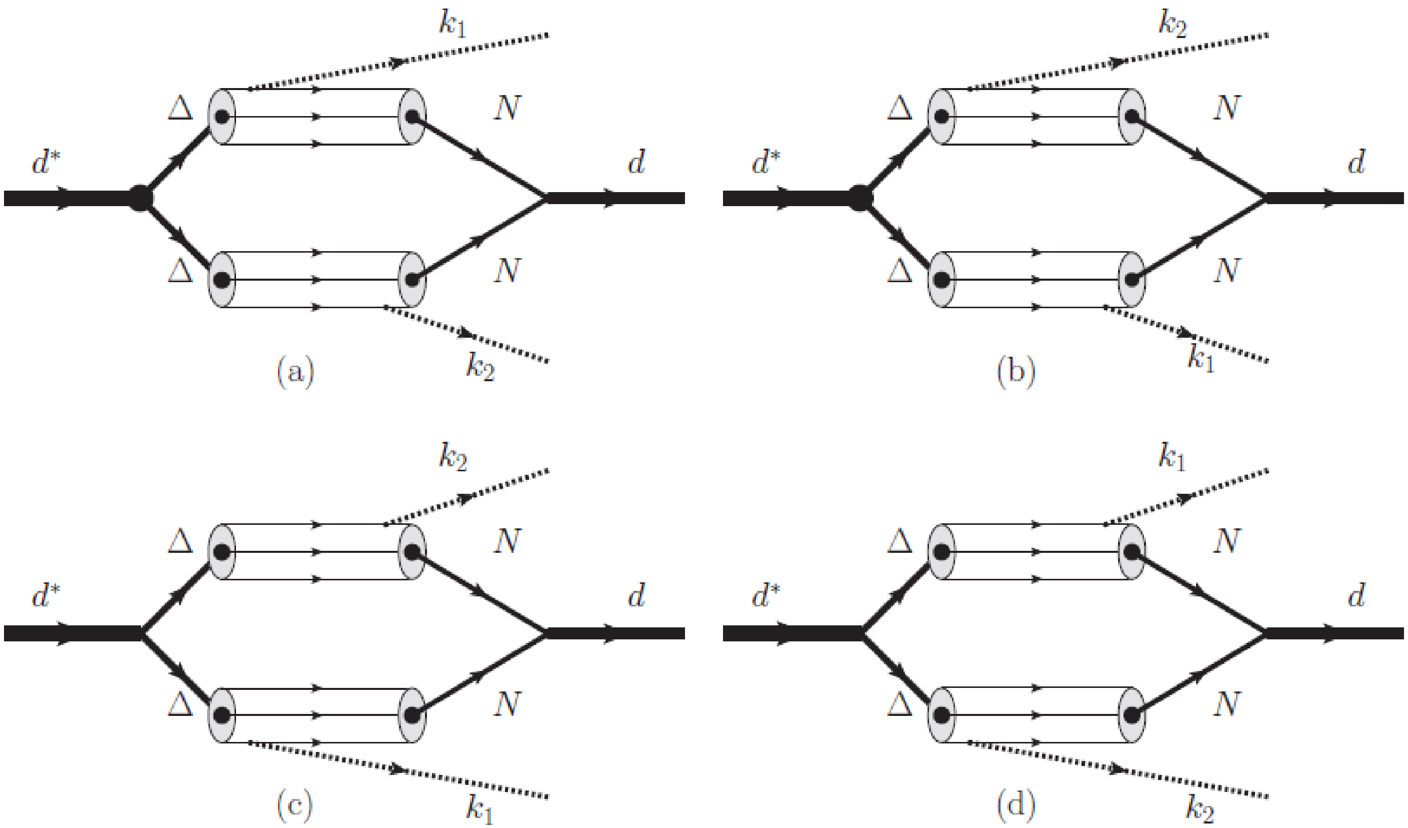


FIG. 1. Four possible emission paths in the decay of the d^* resonance composed of the $\Delta\Delta$ structure only. Two pions with momenta of $\vec{k}_1$ and $\vec{k}_2$ are emitted from one of the three quarks in two Δs, respectively.

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

$$\mathcal{M}_{if}^{\pi^0\pi^0} \sim \int d^3q \Big[\frac{\chi_d^*(\vec{q} - \frac{1}{2}\vec{k}_{12})}{E_\Delta(q) - E_N(q-k_1) - \omega_1} + \frac{\chi_d^*(\vec{q} + \frac{1}{2}\vec{k}_{12})}{E_\Delta(q) - E_N(q-k_2) - \omega_2} + \frac{\chi_d^*(\vec{q} + \frac{1}{2}\vec{k}_{12})}{E_\Delta(-q) - E_N(-q-k_1) - \omega_1} + \frac{\chi_d^*(\vec{q} - \frac{1}{2}\vec{k}_{12})}{E_\Delta(-q) - E_N(-q-k_2) - \omega_2} \Big] \chi_{d^*}(\vec{q})$$

$$\Gamma = \int \frac{1}{2!} d^3k_1 d^3k_2 d^3p_D 2\pi\delta^3(\vec{k}_1 + \vec{k}_2 + \vec{p}_D)\delta(E_{k_1} + E_{k_2} + E_{p_D}^D - M_{d^*}) \mid \overline{\mathcal{M}_{if}} \mid^2$$

Constraint: the experimental data show that the angle between the two outgoing pions is almost zero, namely, the pions are propagating in the same direction

$\Rightarrow$ $\vec{k}_1 \parallel \vec{k}_2 \parallel \hat{z}$

Wave functions (Model space (ΔΔ+CC))

$$\Psi_d = \left[\phi_N(\xi_1,\xi_2)\phi_N(\xi_4,\xi_5)\chi_d(R) + \phi_C^d(\xi_1,\xi_2)\phi_C^d(\xi_4,\xi_5)\chi_{CC}^d(R)\right]\zeta_{(SI)=(10)},$$

$$\Psi_{d^*} = \left[\phi_\Delta(\xi_1,\xi_2)\phi_\Delta(\xi_4,\xi_5)\chi_{\Delta\Delta}(R) + \phi_C^{d^*}(\xi_1,\xi_2)\phi_C^{d^*}(\xi_4,\xi_5)\chi_{CC}^{d^*}(R)\right]\zeta_{(SI)=(30)},$$

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

d* ΔΔ ~ 1/3
CC ~ 2/3

deuteron:CC ~0

Overlap of the two WFs also reduces spatial integral

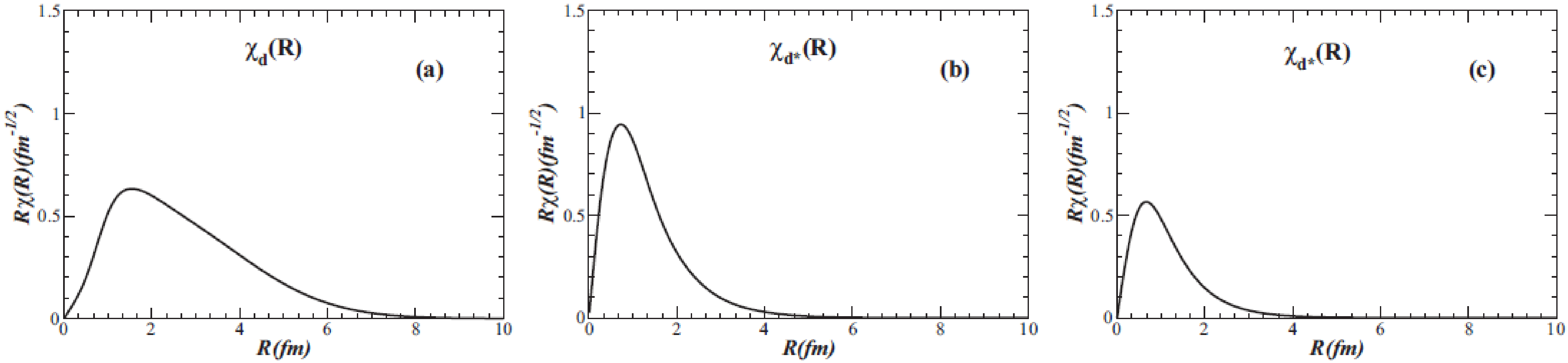


FIG. 2. Relative wave functions in the S wave in the extended chiral SU(3) quark model: (a) for deuteron, (b) for $\chi_{\Delta\Delta}$ in the single $\Delta\Delta$ channel case for $d^*(2380)$, and (c) for $\chi_{\Delta\Delta}$ in the coupled $\Delta\Delta$ and CC channel case for $d^*(2380)$.

Numerical results

M_{d^*}(MeV)	Ours			Expt.	
Mode	Single channel $\Delta\Delta$	Two channels $\Delta\Delta + CC$		[4,20,21,23]	
	2374	2380		2375	
	Γ(MeV)	$\mathcal{B}_r$	Γ(MeV)	$\mathcal{B}_r$	Γ(MeV)
$d^* \to d\pi^0\pi^0$	16.6	13.3%	9.2	14(1)%	10.2
$d^* \to d\pi^+\pi^-$	30.1	24.3%	16.8	23(2)%	16.7
$d^* \to pn\pi^0\pi^0$	14.1	11.3%	7.8	12(2)%	8.7
$d^* \to pn\pi^+\pi^-$	34.6	27.8%	19.2	30(4)%	21.8
$d^* \to pp\pi^0\pi^-$	7.06	5.65%	3.9	6(1)%	4.4
$d^* \to nn\pi^+\pi^0$	7.06	5.65%	3.9	6(1)%	4.4
$d^* \to pn$	8.24	12.0%	8.3	12(3)%	8.7
Total	117.7	99.9%	69.1	103(14)%	74.9

Two decay modes calculated

d*→dππ(neutral)

d*→dππ(charged)

ΔE~70 MeV

The estimated decay widths of the two channel agree well with the data

Unusual narrow width of d(2380) is understood

* Binding energy of d*

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

$< \frac{1}{3}(\Gamma_\Delta + \Gamma_\Delta)$

Discussions(1)

1, Contributions from $\Delta\Delta$ (~1/3) component is considered

2, $(CC)_{00}$ (~2/3): six-quark compact system does not involve in the decay process

3, Isospin breaking, Due to the mass difference of charged and neutral pions.

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

4, Single channel $\Delta\Delta$ widths larger than the data

5, Dynamical effect due to the wave function is obtained (few tens of MeV)

Discussion(2) other modes

M_{d^*}(MeV)	Ours			Expt.	
Mode	Single channel $\Delta\Delta$ 2374	Two channels $\Delta\Delta + CC$ 2380		[4,20,21,23] 2375	
	Γ(MeV)	$\mathcal{B}_r$	Γ(MeV)	$\mathcal{B}_r$	Γ(MeV)
$d^* \to d\pi^0\pi^0$	16.6	13.3%	9.2	14(1)%	10.2
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Total	117.7	99.9%	69.1	103(14)%	74.9

Other modes

are estimated according to the cross section ratios

Table 1: Experimental branching ratios of the d^* resonance into its decay channels based on eqs. (3) and (12) and the peak cross sections given under (i) and (ii).

decay channel	branching ratio	derived from
np	12(3) %	measurement, Ref. [8]
$d\pi^0\pi^0$	14(1) %	measurement, Ref. [3]
$d\pi^+\pi^-$	23(2) %	measurement, Ref. [3]
$np\pi^+\pi^-$	30(4) %	measurement, Ref. [6]
$np\pi^0\pi^0$	12(2) %	measurement, Ref. [5]
$pp\pi^0\pi^-$	6(1) %	measurement, Ref. [4]
$nn\pi^+\pi^0$	6(1) %	isospin symmetry
$(NN\pi)_{I=0}$	0(14) %	estimate, see text

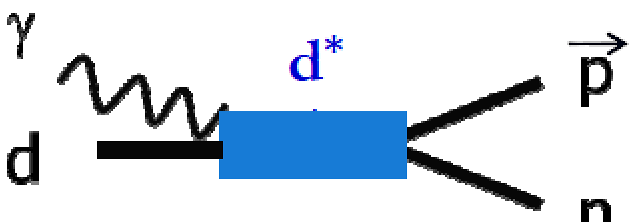
1502.07156

$$d^* \to d\pi^0\pi^0, \ \sigma \sim 0.27mb$$

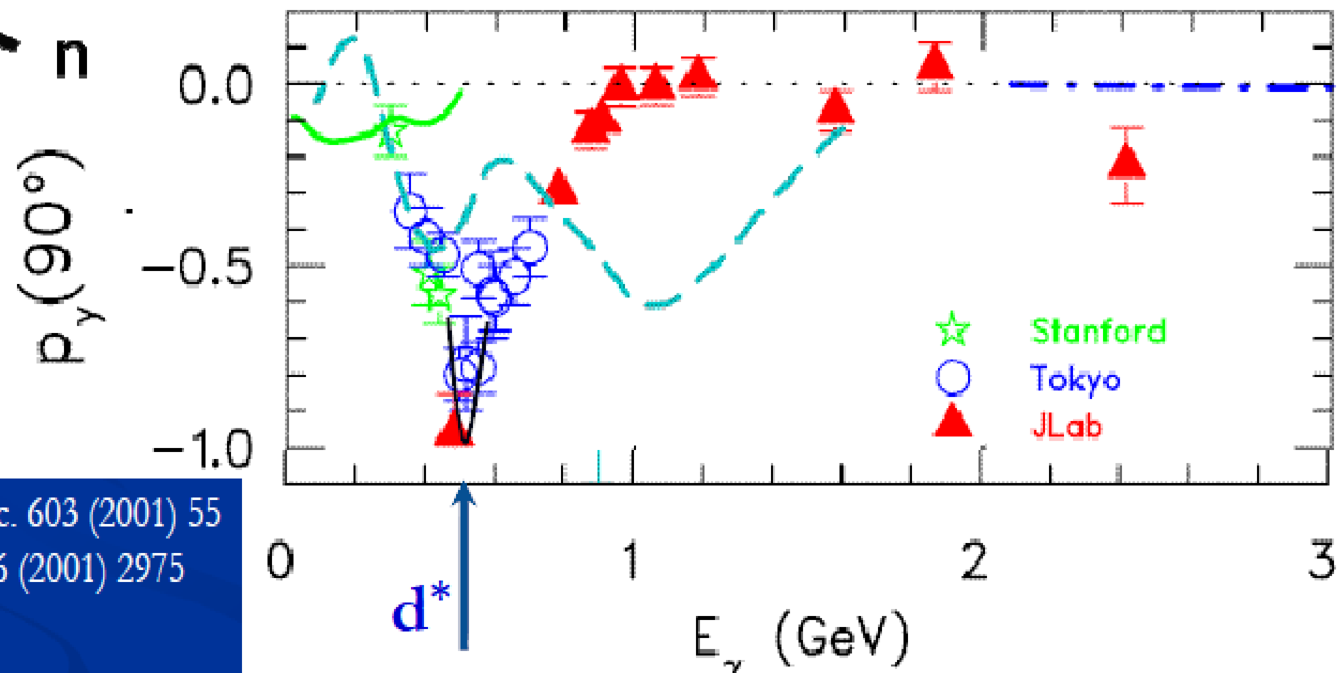
$$d^* \to np\pi^0\pi^0, \sigma \sim 0.27mb$$

$$d^* \to pp\pi^0\pi^-, \sigma \sim 0.10mb$$

4.1, Outlook



$\gamma d \to \vec{p} n$



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K. Wijesooriya et al., Phys. Rev. Lett. 86 (2001) 2975

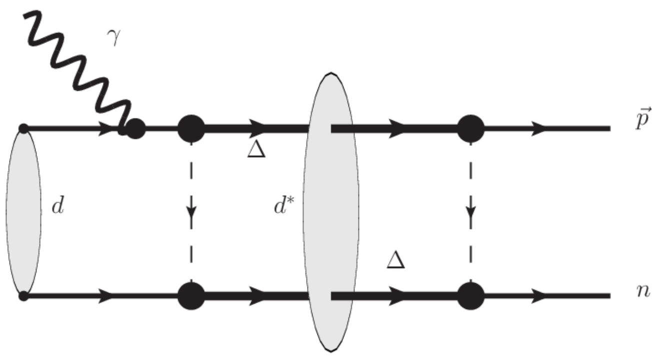
T. Kamae, T. Fujita Phys. Rev. Lett. 38 (1977) 471

H. Ikeda et al., Phys. Rev. Lett. 42 (1979) 1321

Possible in
Jefferson Lab and Mainz

Courtesy of
H. Clement

NPA451, 751



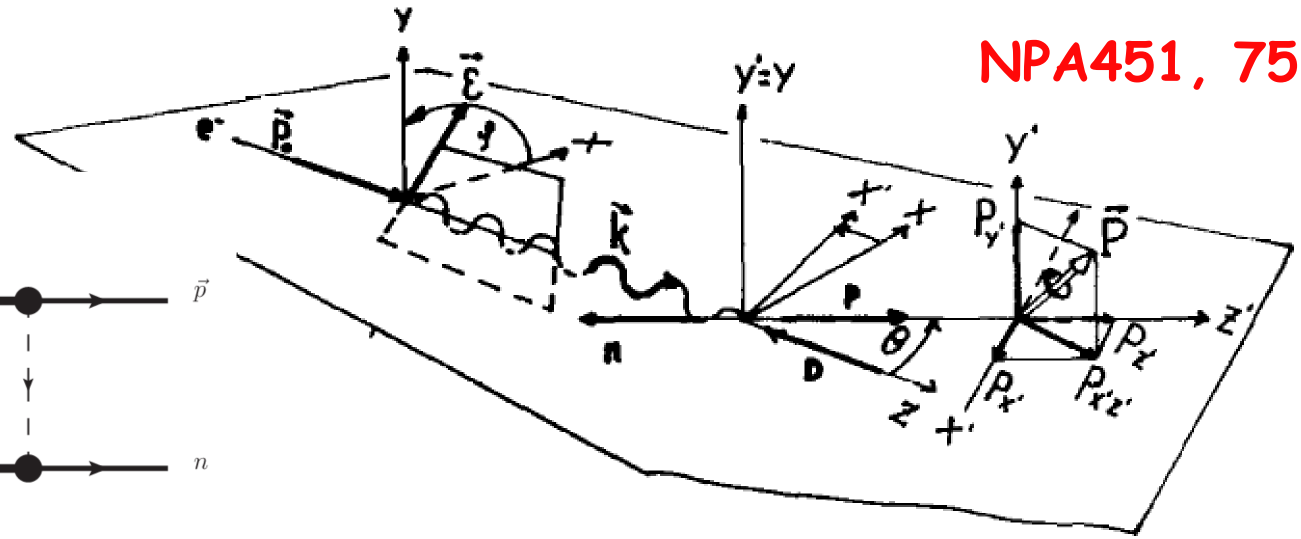


Fig. 1. Coordinate system for the double-polarization experiment in $\gamma d \to pn$. $\boldsymbol{P}_0$: initial electron momentum; $\boldsymbol{\varepsilon}$: photon linear polarization vector; $\boldsymbol{k}$: photon momentum; $\boldsymbol{p}$: proton polarization.

$$P_y = \frac{(\mathrm{d}\sigma/\mathrm{d}\Omega)^+ - (\mathrm{d}\sigma/\mathrm{d}\Omega)^-}{(\mathrm{d}\sigma/\mathrm{d}\Omega)^+ + (\mathrm{d}\sigma/\mathrm{d}\Omega)^-}$$

is the recoil-proton polarization with unpolarized photon and deuteron: $(\mathrm{d}\sigma/\mathrm{d}\Omega)^{+(-)}$ is the differential cross section for the reaction, where the proton spin is directed along (against) the vector $\boldsymbol{k} \times \boldsymbol{p}$;

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right)_0 = \frac{\alpha}{192\pi E^2}\frac{p}{\omega}f(\theta),$$

$$F_{i\pm} = \langle \lambda_p, \lambda_n | T | \lambda_\gamma, \lambda_d \rangle$$

$$F_{1\pm} = \langle \pm\tfrac{1}{2}, \pm\tfrac{1}{2} | T | 1, 1 \rangle, \qquad F_{2\pm} = \langle \pm\tfrac{1}{2}, \pm\tfrac{1}{2} | T | 1, 0 \rangle, \qquad f(\theta) = \sum_{i=1}^{6} [|F_{i+}|^2 + |F_i-|^2] \equiv \sum_{i=1}^{6}\sum_{\pm} |F_{i\pm}|^2,$$

$$F_{3\pm} = \langle \pm\tfrac{1}{2}, \pm\tfrac{1}{2} | T | 1, -1 \rangle, \qquad F_{4\pm} = \langle \pm\tfrac{1}{2}, \mp\tfrac{1}{2} | T | 1, 1 \rangle,$$

$$F_{5\pm} = \langle \pm\tfrac{1}{2}, \mp\tfrac{1}{2} | T | 1, 0 \rangle, \qquad F_{6\pm} = \langle \pm\tfrac{1}{2}, \mp\tfrac{1}{2} | T | 1, -1 \rangle, \quad P_y = 2\,\mathrm{Im}\sum_{i=1}^{3}\sum_{\pm} \pm F^*_{i\pm} F_{(i+3)\mp}/f(\theta),$$

4.2, Summary(1)

- 1, Interpretation of d*(2380) in our chiral
- quark-model

3, Novel structure of CC component is explicitly shown

- 2, Decay widths of d*$\to d+2\pi$ are successfully
- estimated (Dynamical effect)
- * unusual narrow width is obtained
- * the approach can simultaneously give

the binding energy +widths of the system

4.2, Summary (2)

- 4, Future applications ($\gamma d \rightarrow \vec{p} n$,
- polarizations)

- 5, Other observations of the resonances
- at Jefferson, Mainz, and Belle.

- Thanks for your attention!