The quark model study of the dibaryon d*

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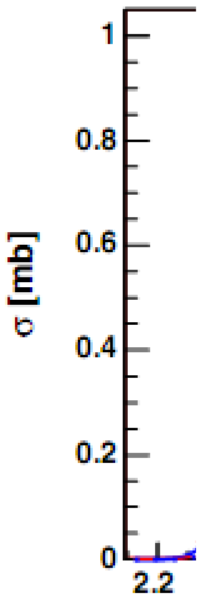


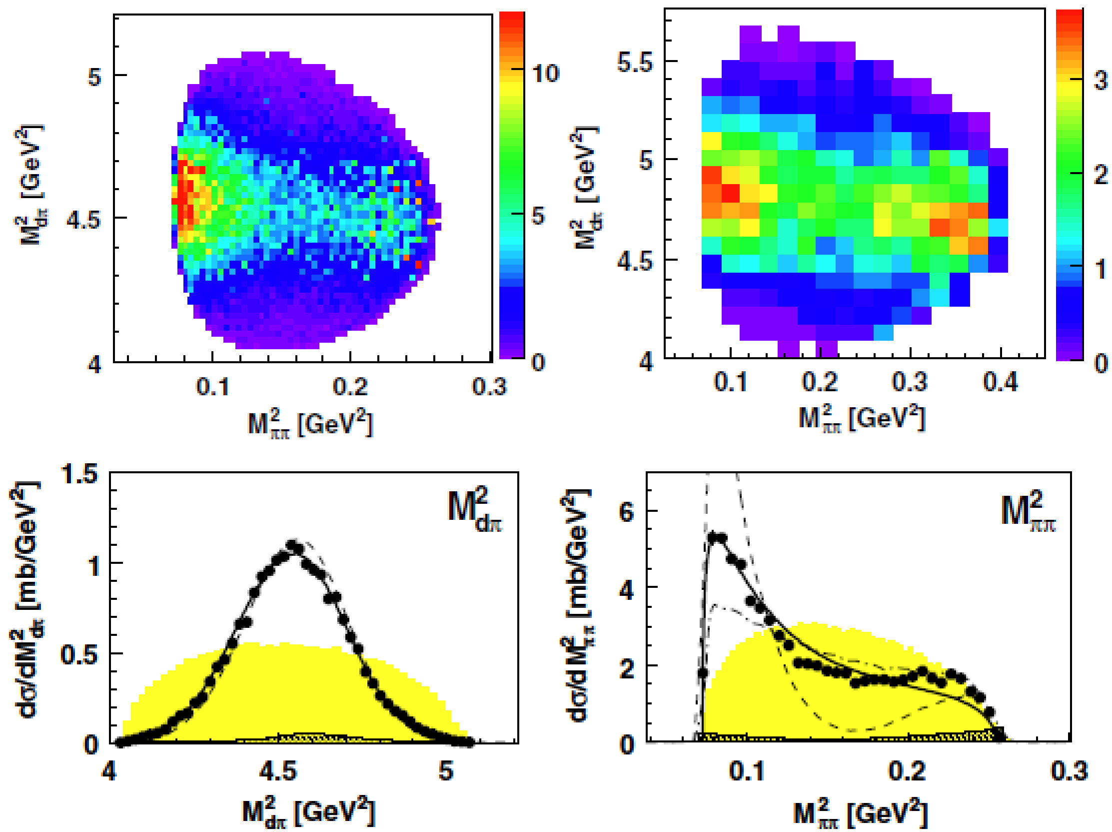
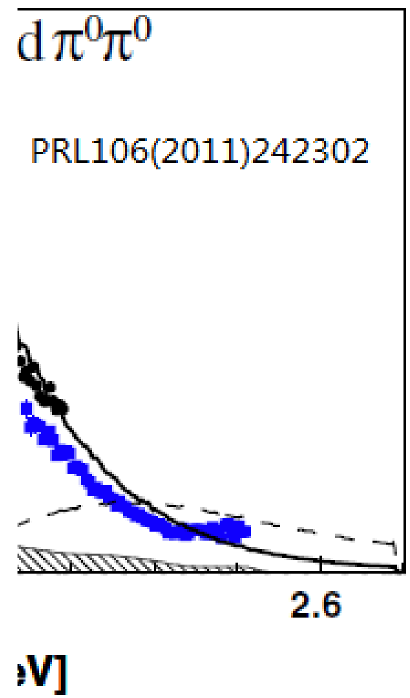


FIG. 4 (color online). Top: Dalitz plots of $M^2_{d\pi^0}$ versus $M^2_{\pi^0\pi^0}$ at $\sqrt{s} = 2.38$ GeV (peak cross section) (left) and at $\sqrt{s} = 2.5$ GeV (right). Bottom: Dalitz plot projections $M^2_{d\pi^0}$ (left) and $M^2_{\pi^0\pi^0}$ (right) axes at $\sqrt{s} = 2.38$ GeV. The curves denote calculations for a s-channel resonance decaying into $\Delta\Delta$ with $J^P = 3^+$ with (solid) and without (dash-dotted) form factor as well as for $J^P = 1^+$ (dashed). Hatched and shaded areas represent systematic uncertainties and phase-space distributions, respectively.



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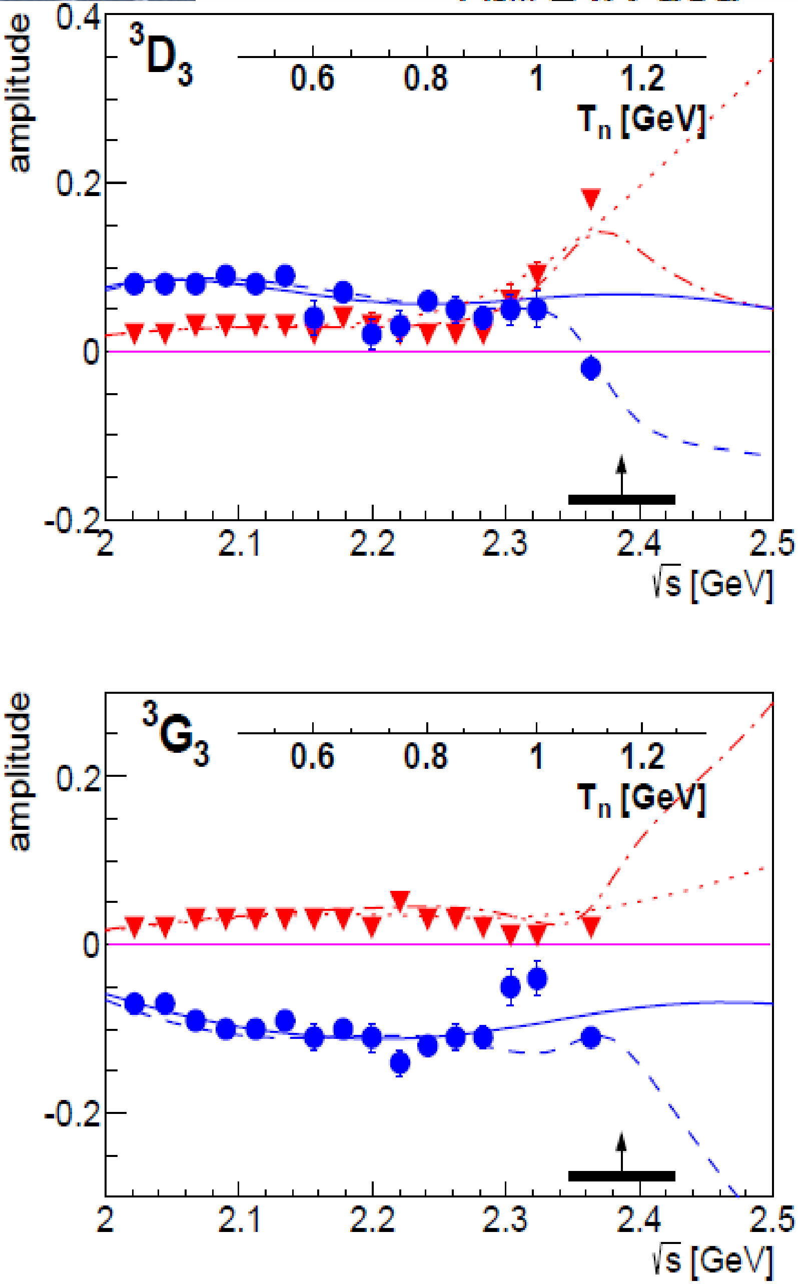


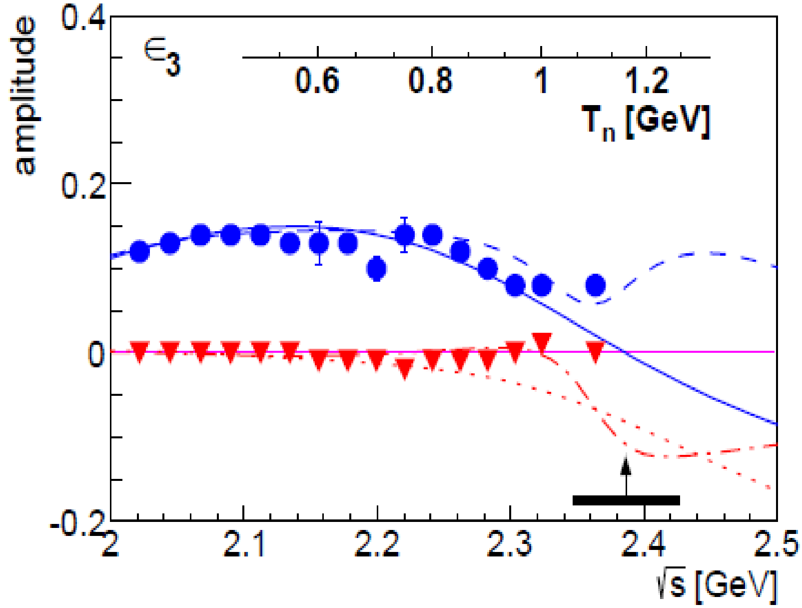


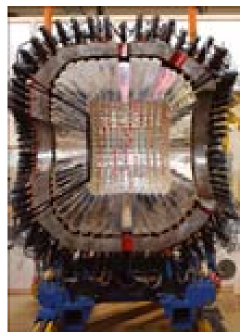
FIG. 3: (Color online) Changes to the (dimensionless) $^3D_3$ (top) and $^3G_3$ (middle) partial waves including their mixing amplitude ϵ_3 (bottom). Solid (dotted) curves give the real (imaginary) part of the partial-wave amplitudes from SP07, whereas the dashed (dash-dotted) curves represent the new (weighted) solution. Results from previous single energy fits [16] are shown by solid circles (real part) and inverted triangles (imaginary part). Vertical arrow and horizontal bar indicate pole and width of the resonance.

CERN Courier 2011

- http://cerncourier.com/cws/article/cern/46855

Aug 26, 2011

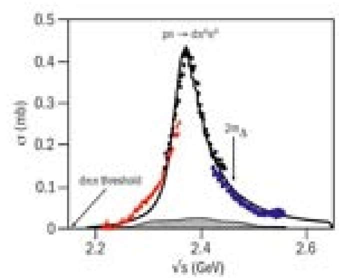
COSY finds evidence for an exotic particle...



WASA detector

Experiments at the Jülich Cooler Synchrotron, COSY, have found evidence for a new complex state in the two-baryon system, with mass 2.37 GeV and width 70 MeV. The structure, containing six valence quarks, could constitute either an exotic compact particle or a hadronic molecule. The result could cast light on the long-standing question of whether there are eigenstates in the two-baryon system other than the deuteron ground-state. This has awaited an answer since Robert Jaffe first envisaged the possible existence of non-trivial six-quark configurations in QCD in 1977.

The new structure has been observed in high-precision measurements carried out by the WASA-at-COSY collaboration, using the Wide-Angle Shower Apparatus (WASA). The data exhibit a narrow isoscalar resonance-like structure in neutron-proton collisions for events where a deuteron is produced together with a pair of neutral pions. From the differential distributions, the spin-parity of the new system is deduced to be $J^P = 3^+$ and its main decay mode is via formation of a $\Delta\Delta$ system below the nominal threshold of $2m_\Delta$. The collaboration will further test the resonance hypothesis in elastic proton-neutron collisions with a polarized beam; the $J^P = 3^+$ partial waves should be dominated by the new structure, while its contribution to the elastic cross-section should be small.



Measurement of energy dependence

The resonance structure also turns out to be intimately connected to the so-called ABC effect, in which the two pions produced in a nuclear fusion process are emitted preferentially in parallel. This 50-year-old puzzle, which is named after the initial letters of the surnames of its first observers A Abashian, N E Booth and K M Crowe, could now find its explanation in the way that such a resonance decays.

Further reading

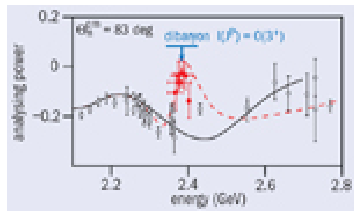
P Adlarson et al. 2011 **Phys. Rev. Lett. 106** *242302.*

CERN Courier 2014

- http://cerncourier.com/cws/article/cern/57836

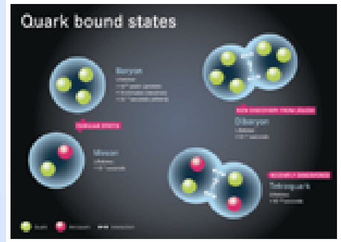
Jul 23, 2014

COSY confirms existence of six-quark states



Energy dependence

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.



Quark configurations

The new resonance was observed in high-precision measurements carried out by the WASA-at-COSY collaboration. The first signals of the new state had been seen before in neutron-proton collisions, where a deuteron is produced together with a pair of neutral pions (CERN Courier September 2011 p8). Now this state has also been observed in polarized neutron-proton scattering and extracted using the partial-wave analysis technique - the generally accepted ultimate method to reveal a resonance. In the SAID partial-wave analysis, the inclusion of the new data produces a pole in the $^3D_3$ partial wave at (2380±10 - i 40±5) MeV.

The mass of the new state is amazingly close to that predicted originally by Dyson, based on SU(6) symmetry breaking. Moreover, recent state-of-the-art Faddeev calculations by Avraham Gal and Humberto Garcilazo reproduce the features of this new state very well. The quantum numbers favour this state as a dibaryon resonance - the "inevitable" non-strange dibaryon predicted by Terry Goldman and colleagues in 1989.

Further reading

P Adlarson et al. 2014 Phys. Rev. Lett. **112** *202301.*

Theoretical side

- 1964, Dyson & Xuong, $M(D_{03})$=2350 MeV (PRL13, 815)

  no interesting
- 1977, Jaffe, H particle (PRL 38, 195)

  over 30 years searching: none
- 1989, T. Goldman,…,Fan Wang, (PRC 39, 1889)

  "inevitable nonstrange dibaryon" d*
- 1995, Fan Wang, JL Ping, et al, (PRC 51, 3411)

  u,d,s world systematic searching
- …
- 2009, JL Ping et al, (PRC 79, 024001)

  d* as np scattering resonance
- 2013, Bashkanov et al., (PLB 727, 438)

  hidden-color → narrow width
- 2014, F. Huang et al, arXiv:1408.0458, hidden-color → narrow width

Quark model: prediction power

- Gell-Mann-Zweig quark model:
  classification system -- *Eightfold Way*
  SU(3) flavor symmetry → Ω
  1962: Theo. 1680 MeV (Gell-Mann-Okubo formula)
  1964: Exp. 1686±12 MeV

- Dyson & Xuong: Dibaryon

$$M = A + B[T(T+1) + J(J+1) - 2]$$

  1964: Theo. D_{03} 2350 MeV
  2014: Exp. d* 2380 MeV

- The success of quark model

Dynamical symmetry in strong interaction system

- Dynamical symmetry:

H: Hamiltonian of a system

$$H = F(C, C_1, C_2, ...) = F(C, C(s))$$

$C, C_1, C_2, \ldots\ldots$: Casimir operators or class operators of group chain $G \supset G_1 \supset G_2 \supset ......$

properties:

$$[H, G] \neq 0, \quad [H, C] = 0, [H, C(s)] = 0$$

Eigen energy of the system:

$$E = F(\nu, m_1, m_2, ...) = F(\nu, m)$$

eigenvalues of operators $C, C_1, C_2, \ldots\ldots$

Group chain of quark system

Light hadron ground states:

orbital: $U^x(1)$ (baryon) or $SU^x(2)$ (dibaryon)

color: $SU^c(3)$

flavor: $SU^f(3)$

spin: $SU^\sigma(2)$

Group chain:

$$SU(18) \supset SU^c(3) \otimes (SU^{f\sigma}(6) \supset (SU^f(3) \supset SU^I(2) \otimes U^Y(1)) \otimes SU^\sigma(2))$$

$$[1^n] \qquad [c] \qquad [\mu] \qquad [f] \qquad I \qquad Y \qquad J$$

Dynamical symmetry applied to light quark systems

- Color: singlet, [c] fixed

$$H = F(C_{SU^{f\sigma}(6)}, C_{SU^{f}(3)}, C_{SU^{I}(2)}, C_{U^{Y}(1)}, C_{SU^{\sigma}(2)})$$

$$M = M_0 + A\,C_{SU^{f}(3)} + B\,C_{SU^{\sigma}(2)} + C\,C_{U^{Y}(1)} + D\,C_{SU^{I}(2)}$$

- Gursey-Radicati mass formula (PRL13(1964)173)

$$M = M_0 + A\,C_{SU^{f}(3)} + B\,J(J+1) + C\,Y + D\left[I(I+1) - Y^2/4\right]$$

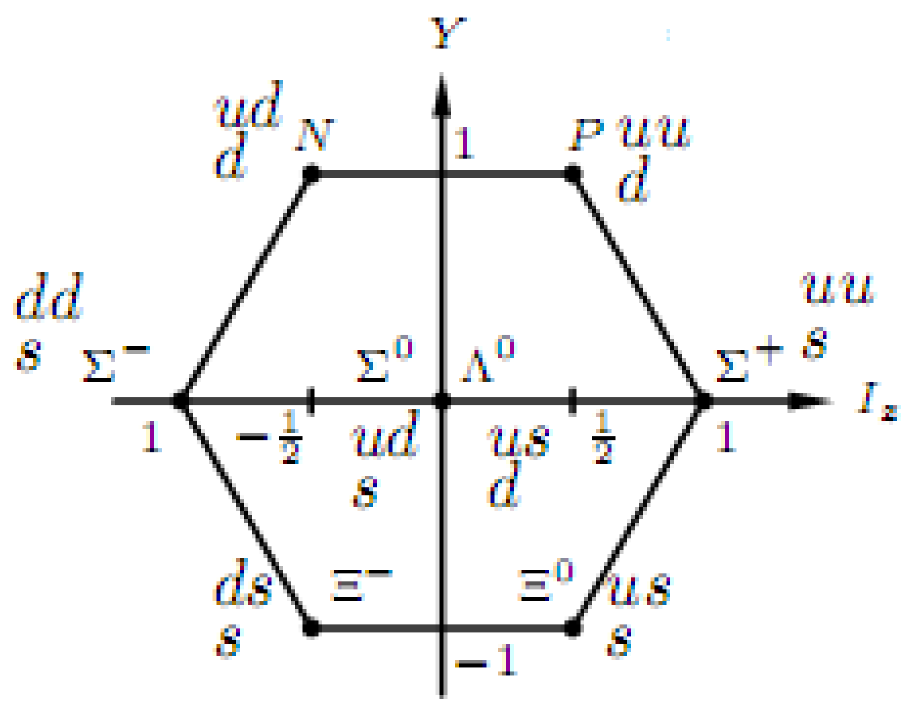
- Parameters ⟸ the masses of baryons

A=9.2962 B=48.238 C=-196.34 D=35.080

(unit: MeV)

Baryon: M_0=1021.9 MeV

Dibaryon: M_0=2093 MeV


Y
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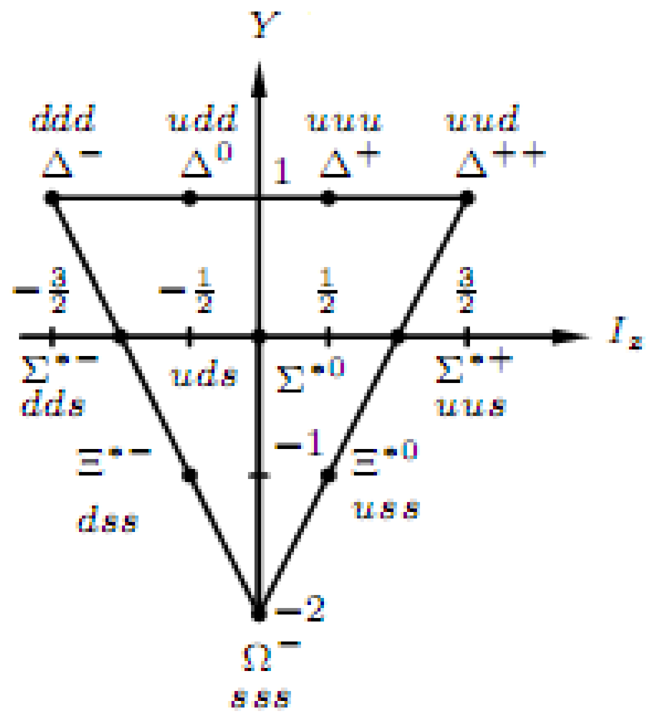
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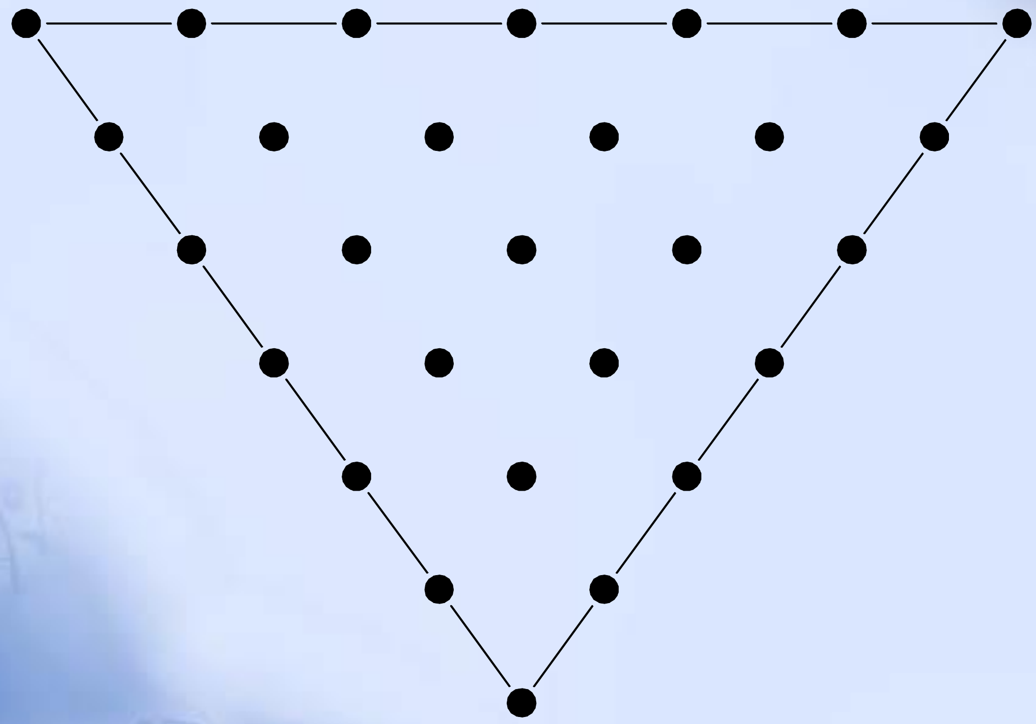
Ξ*−
dss
Ξ*0
uss
Ω−
sss

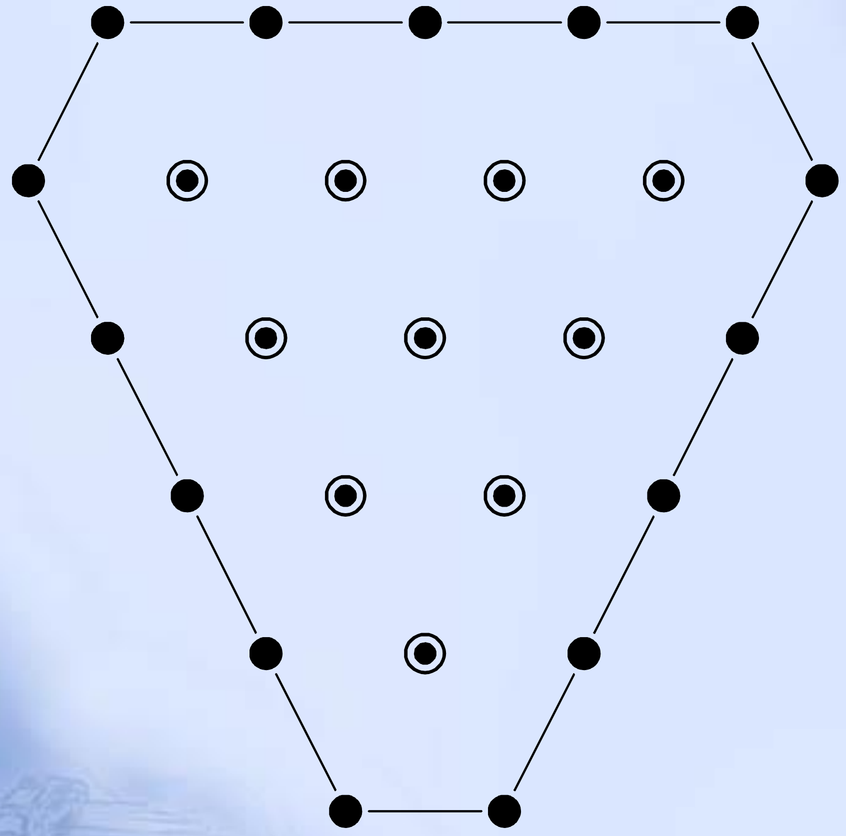
Baryons:

	N	Λ	Σ	Ξ	Δ	Σ*	Ξ*	Ω
Y	1	0	0	-1	1	0	-1	-2
I	½	0	1	½	3/2	1	½	0
J	½	½	½	½	3/2	3/2	3/2	3/2
[f]	[21]	[21]	[21]	[21]	[3]	[3]	[3]	[3]
theo	935	1114	1184	1328	1241	1384	1528	1672
err	2.6	1.9	2.6	1.6	4.8	3.8	2.7	1.7
exp	939	1116	1193	1318	1232	1383	1533	1672

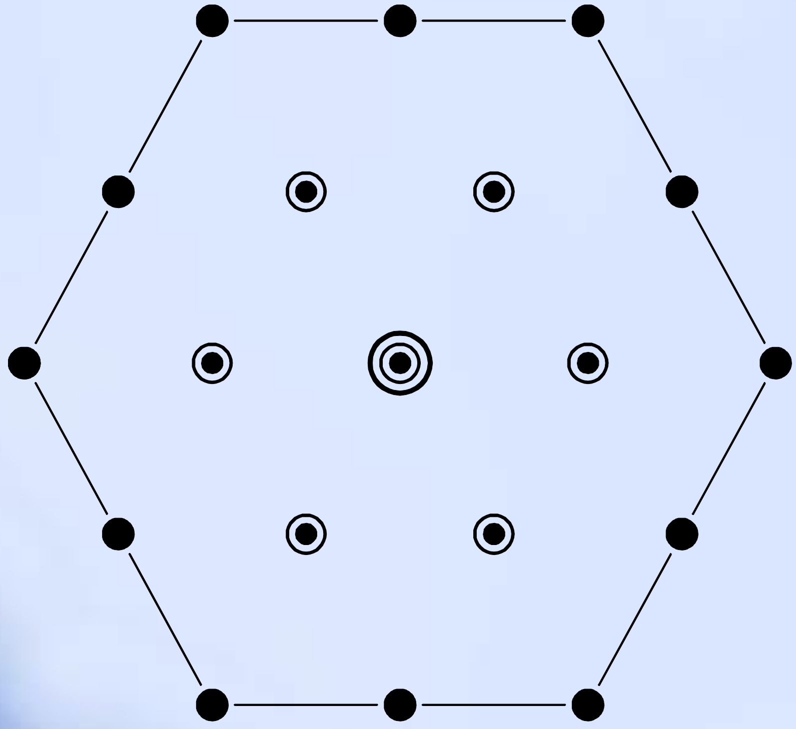
- $[f]=[6]$ dim=28



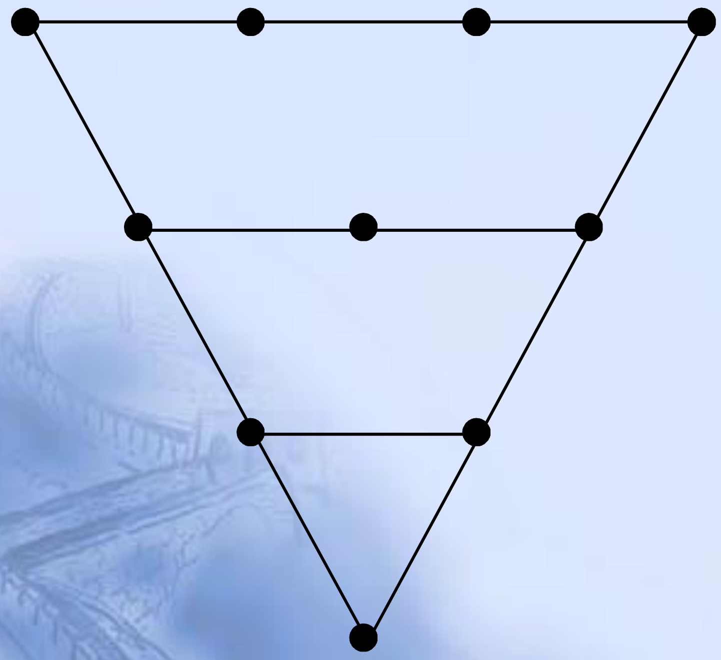
- [f]=[51]   dim=35

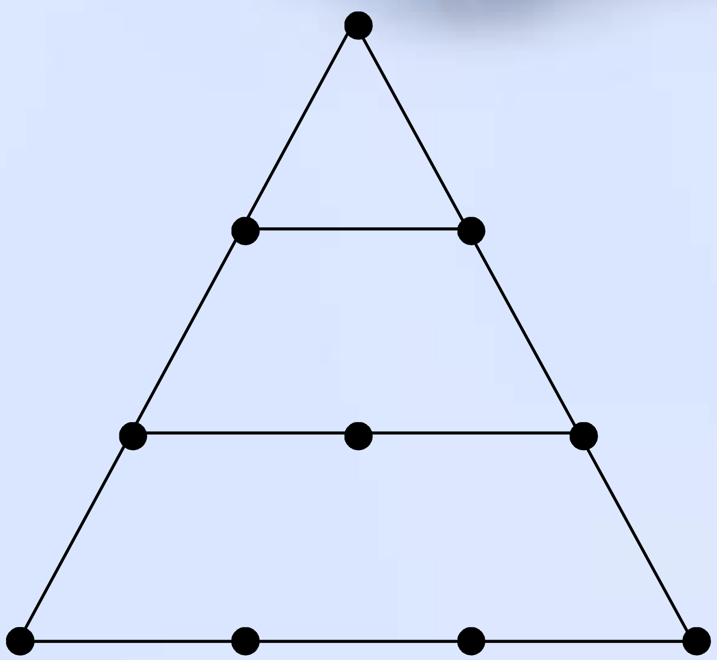


- [f]=[42]   dim=27

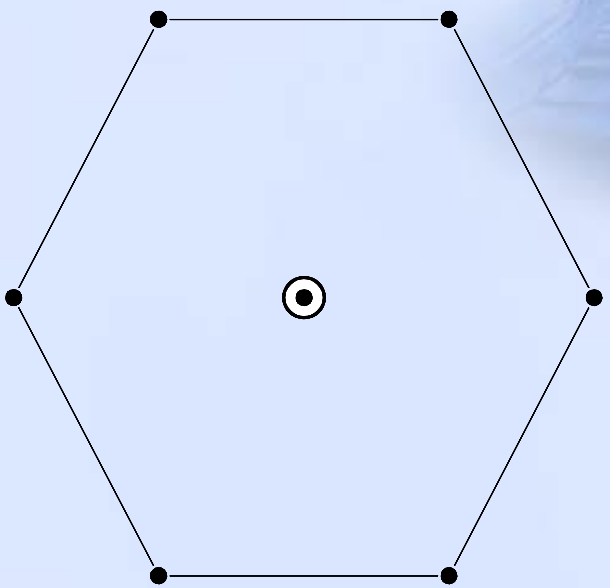


- [f]=[411]   dim=10   [f]=[33]   dim=10

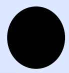




- [f]=[321]   dim=8



- [f]=[222]   dim=1



Dibaryons:

	D_{01}	D_{10}	D_{03}	D_{30}	D_{12}	NΩ	ΩΩ	H
Y	2	2	2	2	2	-1	-4	0
I	0	1	0	3	1	½	0	0
J	1	0	3	0	2	2	0	0
[f]	[33]	[42]	[33]	[6]	[42]	[321]	[6]	[222]
theo	1873	1884	2355	2420	2173	2652	3072	2093
err	5.6	6.6	6.6	13	7.2	4.0	4.7	2.9
exp	1876	1878?	2380	?	2148?	?	?	?

- D_{01}: deuteron (n-p bound state)
- D_{10}: di-neutron (zero-energy resonance)
- D_{03}: d*
- D_{30}: dibaryon candidate with larger decay width
- D_{12}: 1980's-1990's NN $^1D_2$ phase shift

  → 2048-i59 MeV resonance.
- For the strange dibaryon:

  H(-200), mass is too low

  $N\Omega$(-3½ 2): around threshold. HAL LQCD calculation arXiv:1403.7284[hep-lat]

  Ω Ω (-600): di-omega.

Glashow-Isgur naïve quark model

- Dynamical calculations of baryon masses and hadron interactions with quark models.

- GI model:

  Color confinement + One-gluon-exchange

  describes baryon properties quite well

- Extended to multi-quark systems?

  fails to obtain

  the intermediate-range attraction of NN interaction

Quark model for multi-quark system

The criterions:

1. Describing the vast strong interaction experimental data from deuteron bound state to NN, YN scattering data.

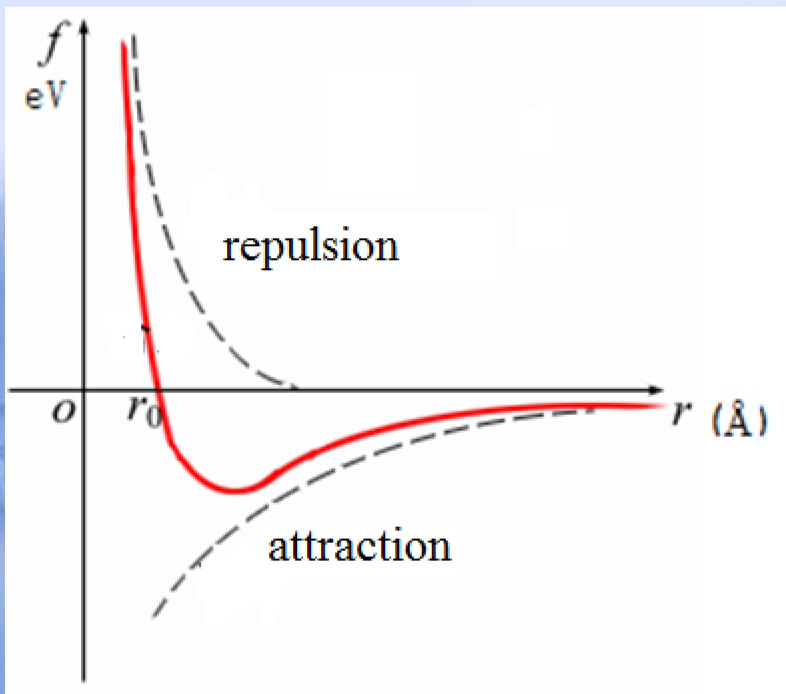
2. Explaining the similarity of nuclear force and molecular force.

3. Predicting something new and if it confirmed by measurements.

Similarity between nuclear force and molecular force

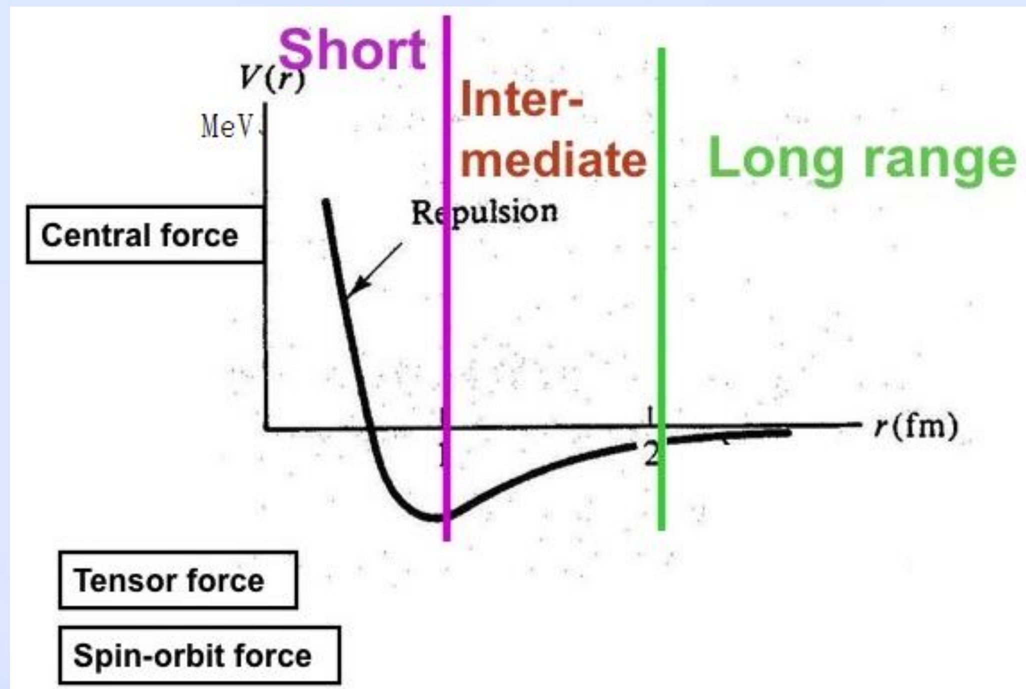
spin singlet

interaction between atoms



spin triplet isospin singlet

interaction in deuteron



Improving quark models for multi-quark systems

- Two approaches:

- Chiral quark model:

  Color confinement + OGE + OBE

  describes hadron-hadron interactions well
- Quark delocalization color screening model (QDCSM)

  describes hadron-hadron interactions well, too

  F. Wang et al. PRL 69(1992)2901(arXiv:nucl-th/921002).

  G.H. Wu et al. PRC 53(1996)1161; NPA 673(2000)279.

Problems of chiral quark model

- fail to explain the similarity between molecular force and nuclear force

  Phenomenological one boson exchange and chiral perturbation have the same problem.

- Phenomenological σ meson exchange effect is different from the correlated two-pion exchange: too weak attraction

  N.Kaiser, et al., Nucl. Phys. **A637**, 395 (1998);
  E.Oset, et al., Prog. Theor. Phys. **103**, 351 (2000);
  M.Kaskulov et al., Phys. Rev. C **70**, 014002 (2004).

QDCSM (PRL69(1992)2901)

- Two ingredients (based on quark cluster model):
  quark delocalization (color and orbital destortion)
  color screening (an effective description of hidden color channel coupling.)

- describing deuteron, NN scattering, N-Hyperon scattering, flavor octet and decuplet BB interactions *well*
  PRL 69(1992)2901; PRC 53(1996)1161; NPA 673(2000)279…….

- Quark delocalization:

$$\psi_l = (\varphi_l + \varepsilon\varphi_r)/N, \;\; \psi_r = (\varphi_r + \varepsilon\varphi_l)/N$$

$$\varphi_l = \left(\frac{1}{2\pi b^2}\right)^{3/4} e^{-\frac{(\mathbf{r}+\mathbf{s}/2)^2}{2b^2}}, \qquad \varphi_r = \left(\frac{1}{2\pi b^2}\right)^{3/4} e^{-\frac{(\mathbf{r}-\mathbf{s}/2)^2}{2b^2}}$$

variational parameter ε(s) 🡐 dynamics of system

- The main advantage of QDCSM :

  the delocalization parameter is determined through its own dynamics, so multiquark system chooses its most favorable configuration by its own dynamics.

QDCSM

- Color screening：

  qq interaction: inside baryon

  outside baryon different

$$H=\sum_{i=1}^{6}\left(m_i+\frac{p_i^2}{2m_i}\right)-T_c+\sum_{i<j}[V^G(r_{ij})+V^\pi(r_{ij})+V^C(r_{ij})],$$

$$V^G(r_{ij})=\frac{1}{4}\alpha_s\boldsymbol{\lambda}_i\cdot\boldsymbol{\lambda}_j\left[\frac{1}{r_{ij}}-\frac{\pi}{m_q^2}\left(1+\frac{2}{3}\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\right)\delta(r_{ij})-\frac{3}{4m_q^2r_{ij}^3}S_{ij}\right]+V_{ij}^{G,LS},$$

$$V_{ij}^{G,LS}=-\frac{\alpha_s}{4}\boldsymbol{\lambda}_i\cdot\boldsymbol{\lambda}_j\frac{1}{8m_q^2}\frac{3}{r_{ij}^3}[\mathbf{r}_{ij}\times(\mathbf{p}_i-\mathbf{p}_j)]\cdot(\boldsymbol{\sigma}_i+\boldsymbol{\sigma}_j),$$

$$V^\pi(r_{ij})=\frac{1}{3}\alpha_{ch}\frac{\Lambda^2}{\Lambda^2-m_\pi^2}m_\pi\left\{\left[Y(m_\pi r_{ij})-\frac{\Lambda^3}{m_\pi^3}Y(\Lambda r_{ij})\right]\boldsymbol{\sigma}_i.\boldsymbol{\sigma}_j+\left[H(m_\pi r_{ij})-\frac{\Lambda^3}{m_\pi^3}H(\Lambda r_{ij})\right]S_{ij}\right\}\boldsymbol{\tau}_i\cdot\boldsymbol{\tau}_j,$$

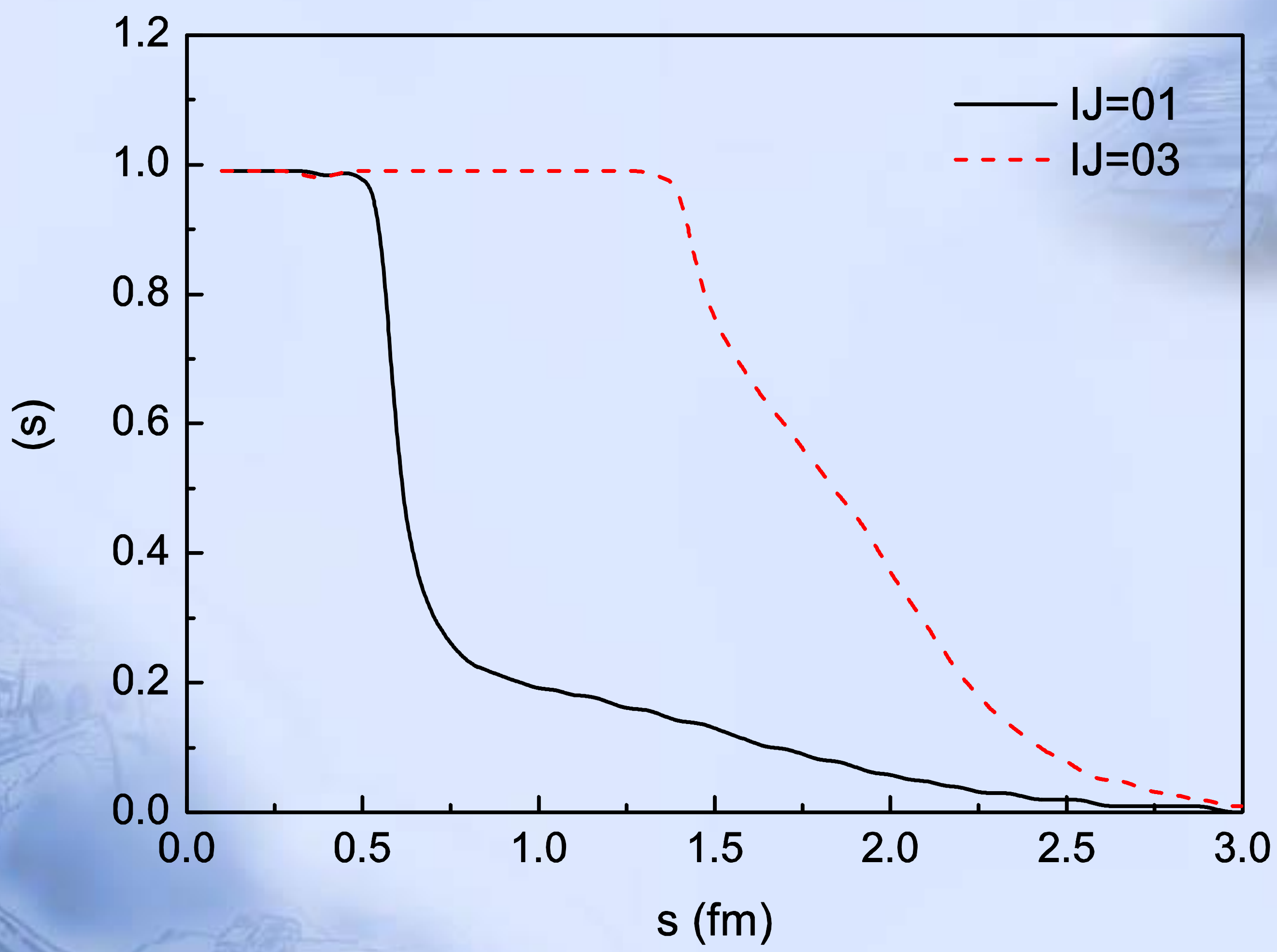
$$V_{ij}^{\mathrm{CON}}(r_{ij})=-a_c\boldsymbol{\lambda}_i\cdot\boldsymbol{\lambda}_j[f_{ij}(r_{ij})+V_0]+V_{ij}^{C,LS},$$

$$f_{ij}(r_{ij})=\begin{cases} r_{ij}^2 & \text{i,j in the same baryon orbit}\\ \frac{1}{\mu}(1-e^{-\mu r_{ij}^2}). & \text{otherwise}\end{cases}$$

the color structure is taken into consideration

three gluons exchange ➔0 (inside baryon)

= 0 (outside baryons)


1.2
1.0
0.8
0.6
0.4
0.2
0.0
(s)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
s (fm)
lJ=01
lJ=03

RGM+GCM

- RGM wavefunction

$$|\Psi_{6q}\rangle = \mathcal{A}\sum_{L}\left[[\Phi_{B_1}\Psi_{B_2}]^{[\sigma]IS} \otimes \chi_L(\vec{R})\right]^J,$$

$$\int H(\vec{R},\vec{R}')\chi(\vec{R}')\,\mathrm{d}\vec{R}' = E\int N(\vec{R},\vec{R}')\chi(\vec{R}')\,\mathrm{d}\vec{R}',$$

$$\chi(\vec{R}) = \frac{1}{\sqrt{4\pi}}\sum_{L}\left(\frac{3}{2\pi b^2}\right)^{3/4}\sum_{i} C_{i,L}\int \mathrm{e}^{-\frac{3}{4}(\vec{R}-\vec{S}_i)^2/b^2} Y^L(\hat{\vec{S}}_i)\,\mathrm{d}\Omega_{S_i}.$$

$$\sum_{j,L} C_{j,L} H_{i,j}^{L,L'} = E\sum_{j} C_{j,L'} N_{i,j}^{L'}$$

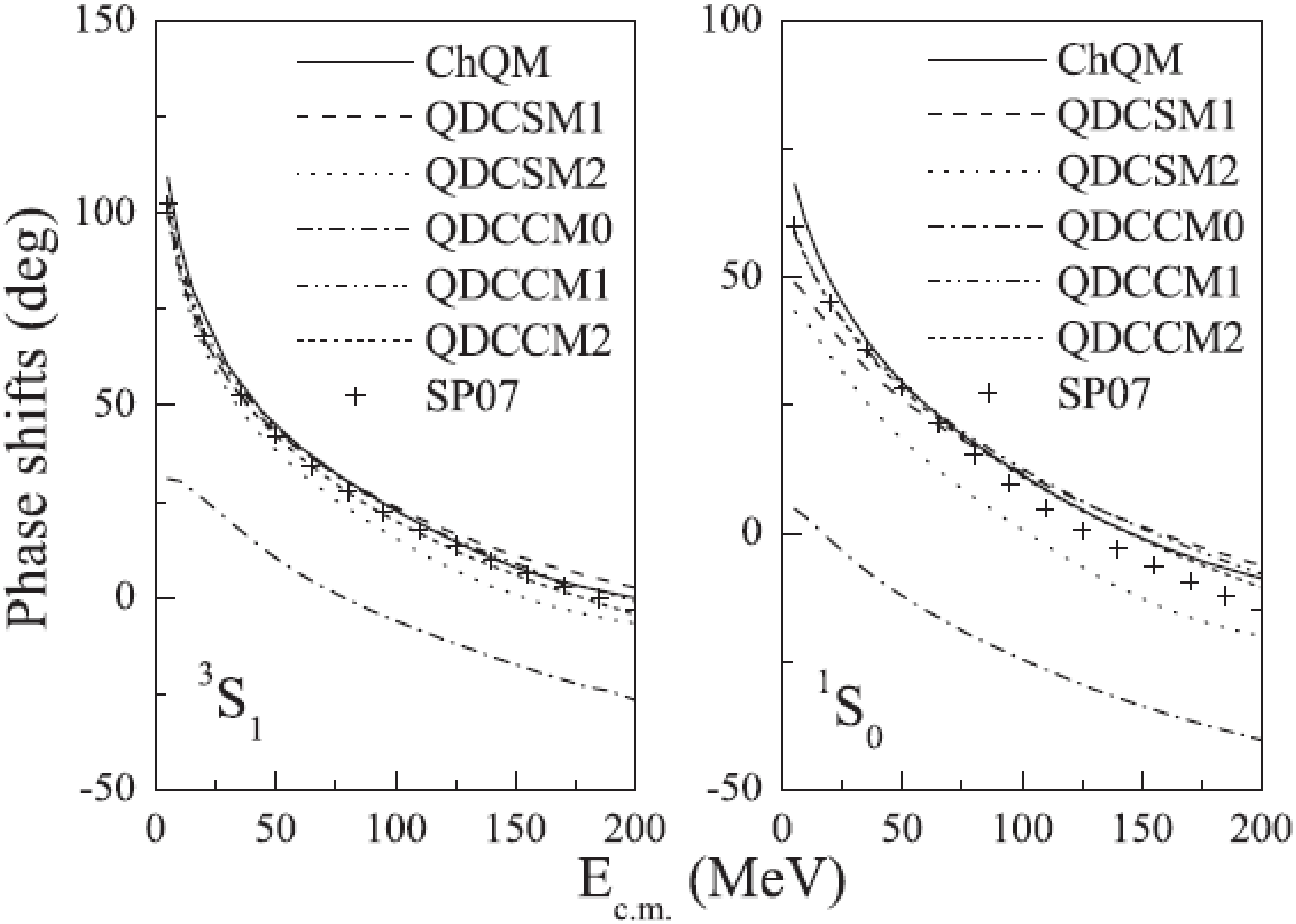


FIG. 1. The phase shifts of *N N* *S*-wave scattering.

deuteron

TABLE II. The properties of the deuteron.

	Salamanca model	QDCSM		
		set 1	set 2	set 3
B (MeV)	2.0	1.94	2.01	2.01
$\sqrt{r^2}$ (fm)	1.96	1.93	1.92	1.94
$P_D(\%)$	4.86	5.25	5.25	5.25

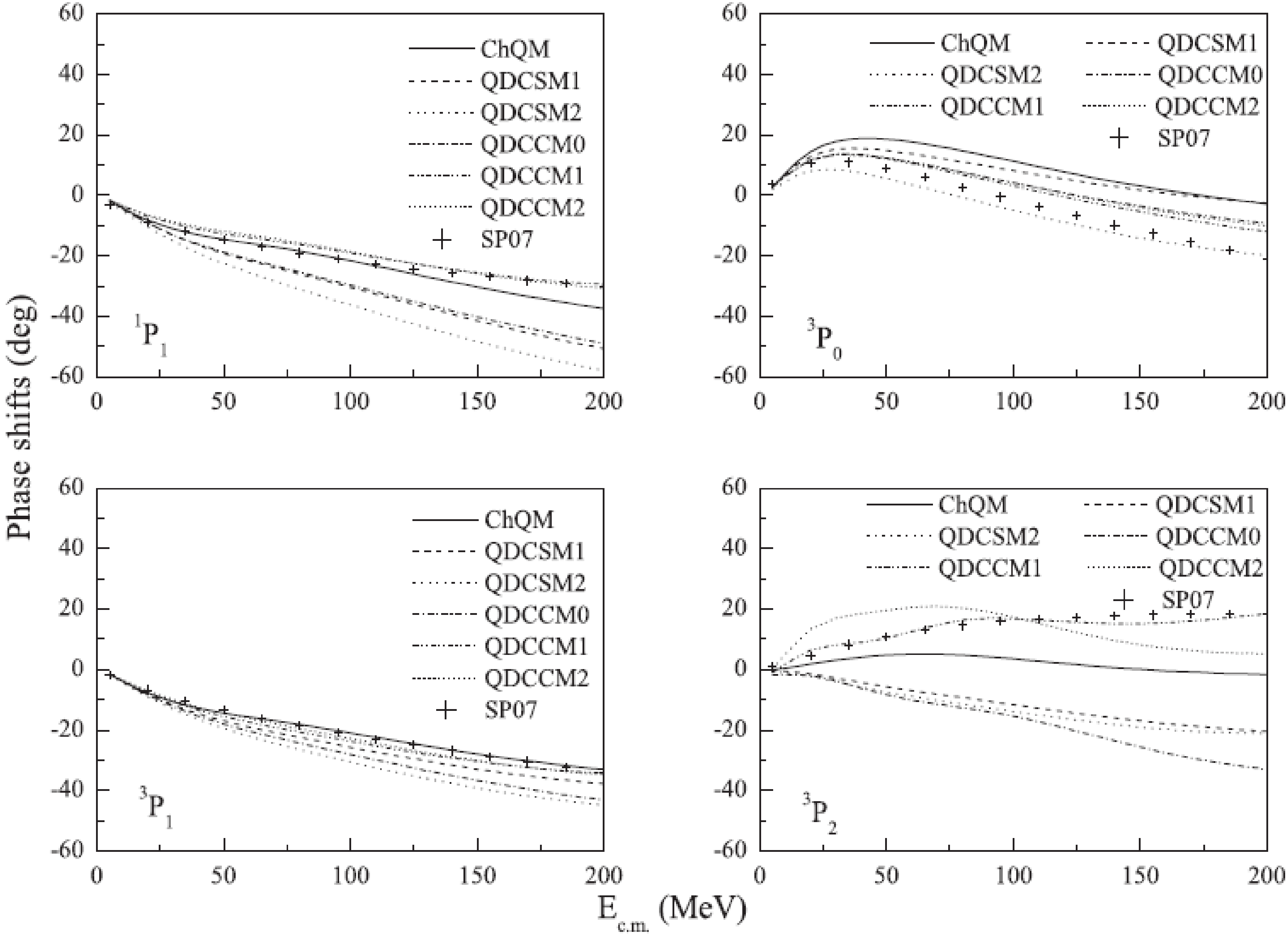


FIG. 2. The phase shifts of *N N P* wave scattering.

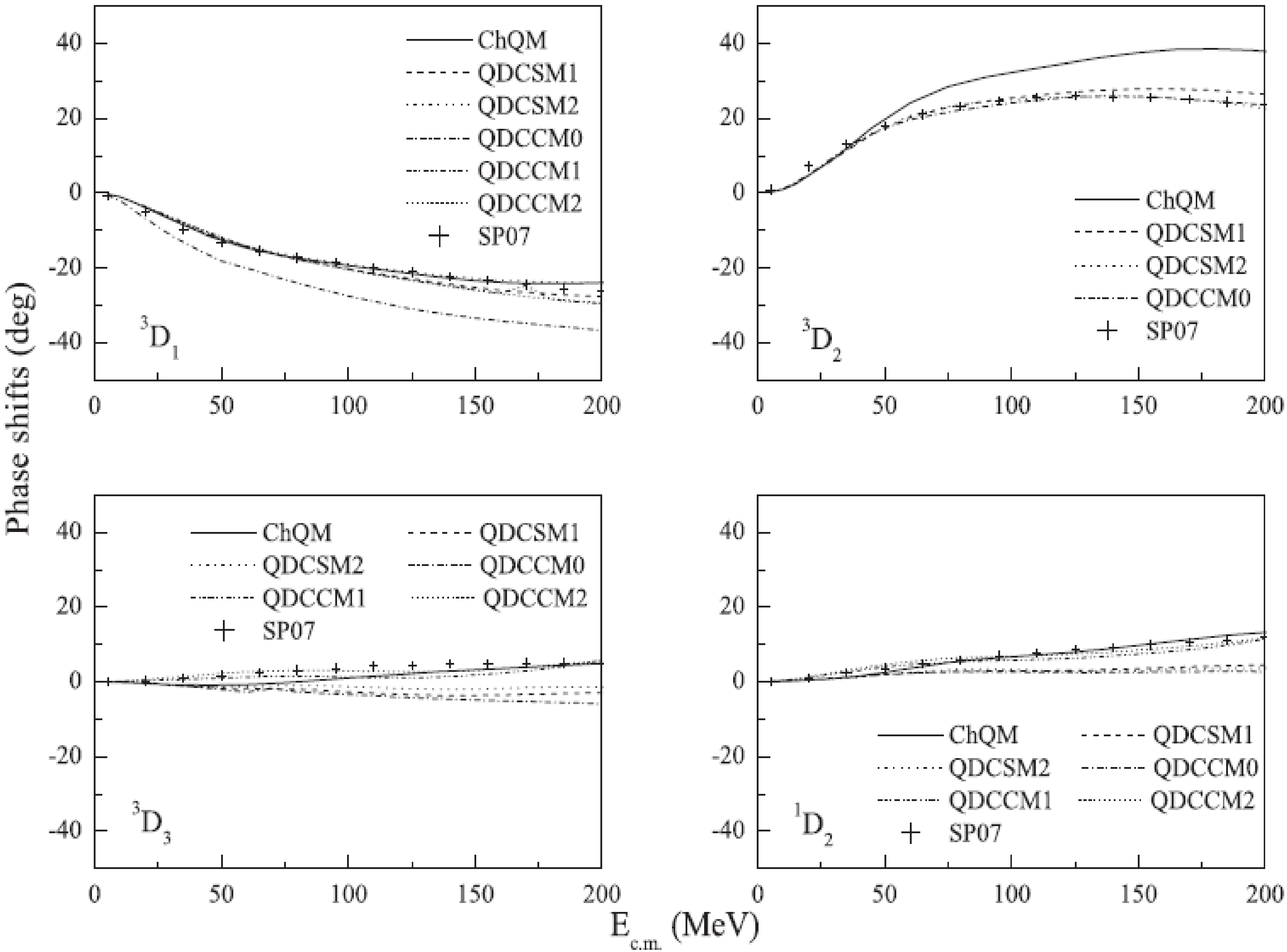


FIG. 4. The phase shifts of NN D-wave scattering.

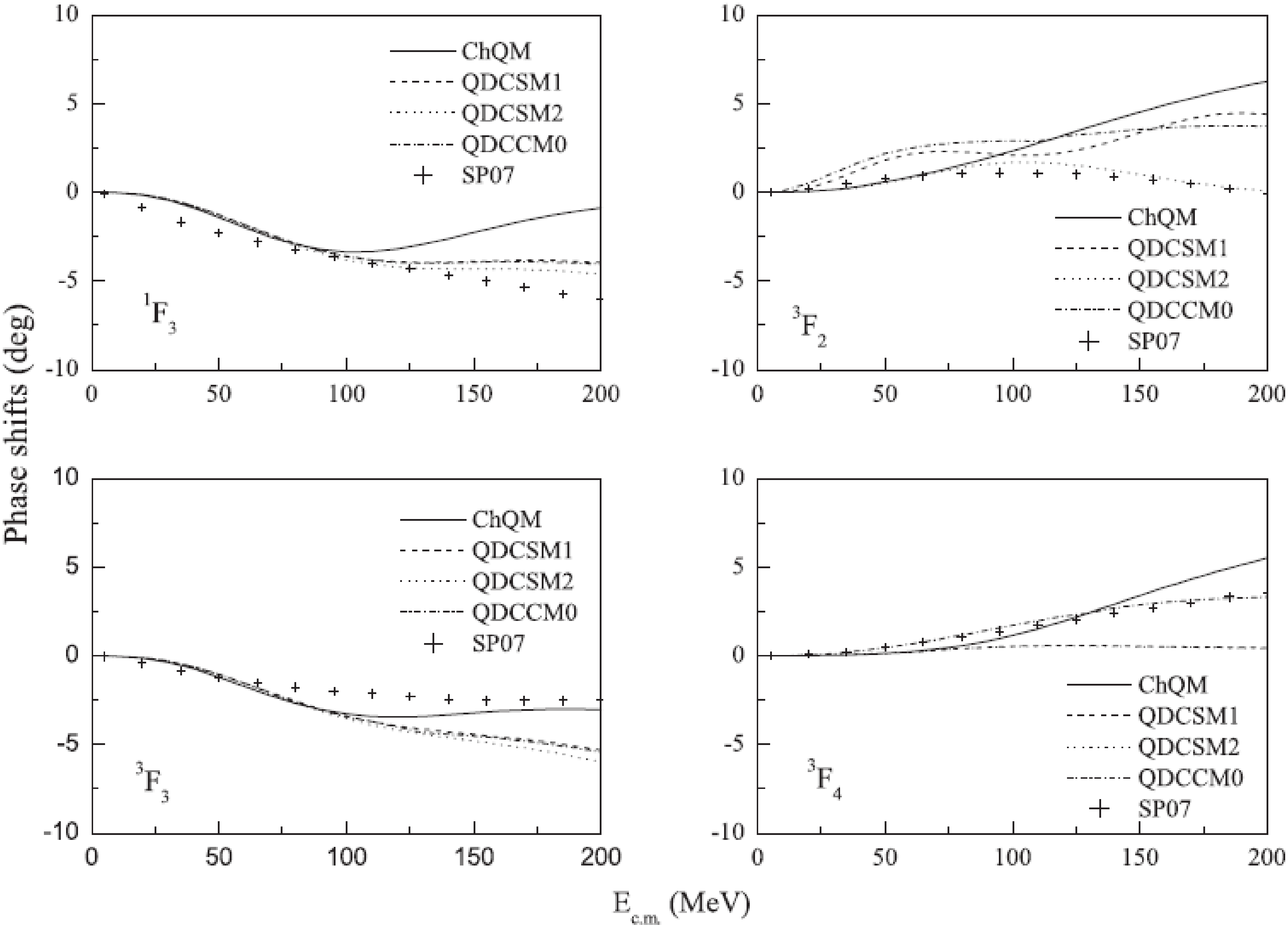


FIG. 5. The phase shifts of NN F-wave scattering.

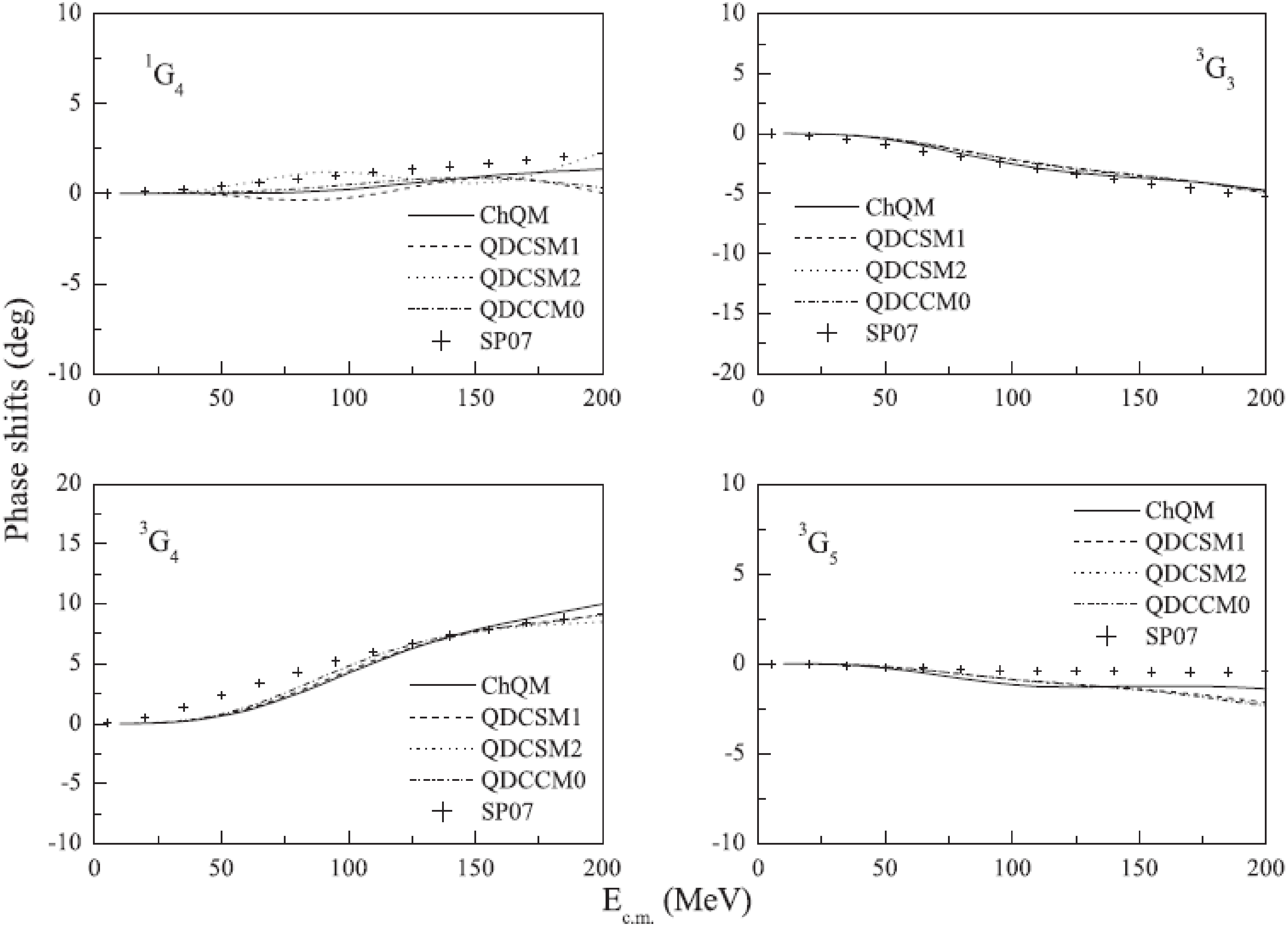


FIG. 6. The phase shifts of NN G-wave scattering.

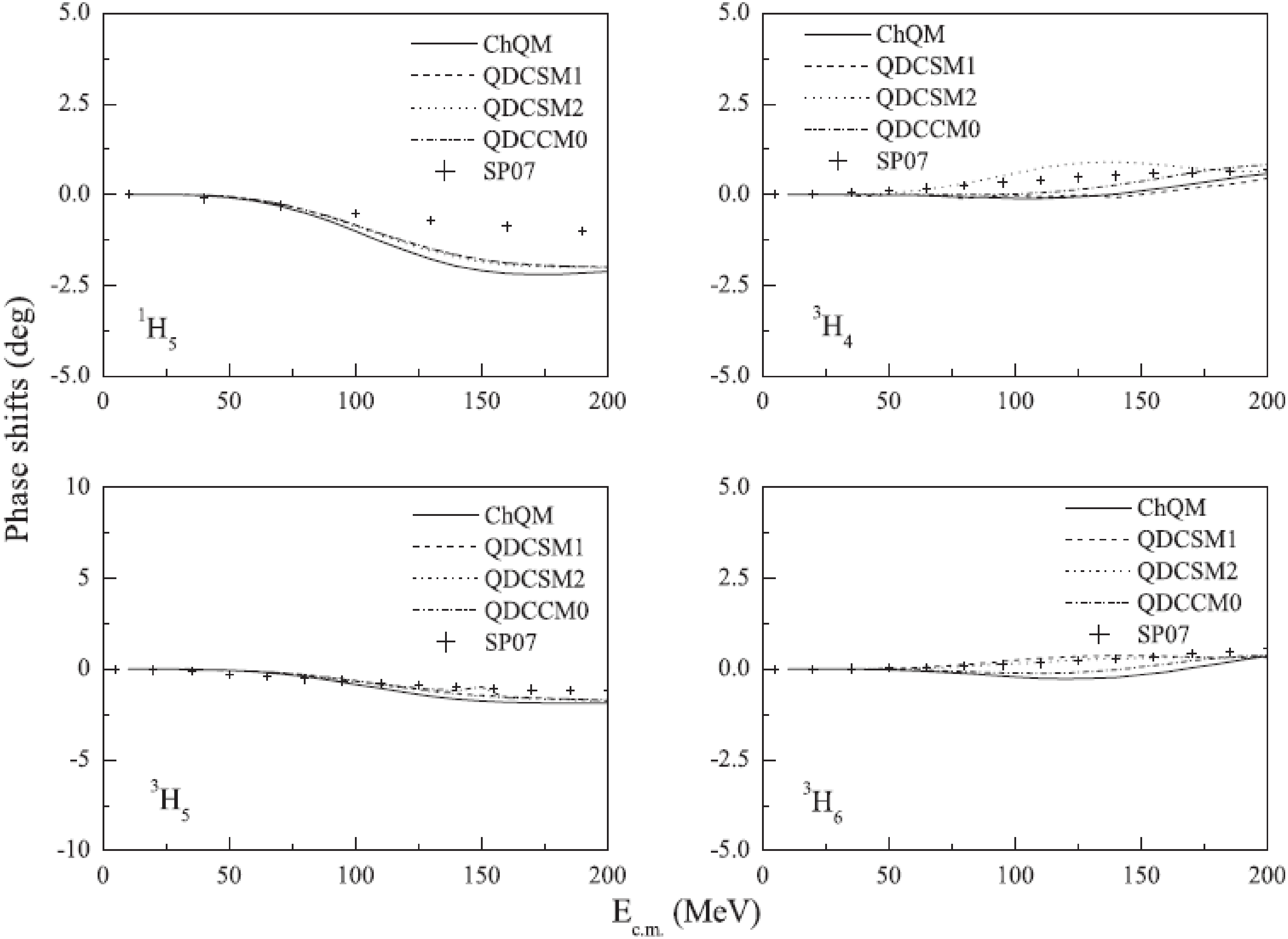


FIG. 7. The phase shifts of NN H-wave scattering.

- the similarity: molecular and nuclear force

Atoms: electric neutral,
electric charge and orbital distortion → molecular force
(electron percolation)

Nucleons: color neutral,
color charge and orbital distortion → nuclear force
(quark delocalization)

d* in quark models

- “inevitable” dibaryon

  T. Goldman, K. Maltman, F. Wang et al.,

  in Brookhaven 1988:Glueballs, hybrids and exotic hadrons, p. 413;

  PRC39 (1989)1889.

1. Kinetic energies: quark delocalization reduces the quark kinetic energy of dibaryon systems.
2. Color-Magnetic Interaction $-(\frac{3}{4})\sum_{i<j}\sigma_i\cdot\sigma_j\lambda_i^a\lambda_j^a$. gives rise effective attraction between flavor decuplet baryons.

the existence of $IJ^P=03^+$ dibaryon is inevitable

$IJ^P=03^+$ dibaryon: a spin excitation of d, named d*

Two kinds of dibaryons

in Intersections between particle and nuclear physics (1994) p.538.

- Octet-octet dibaryons:

  low spin (J<=1) and small binding energy

  typical example: deuteron

- Decuplet-decuplet dibaryons:

  high spin (J>=2) and large binding energy

coupling with octet-octet channels and shown as resonances

  typical example: d*

- Octet-decuplet dibaryons:

  typical example: $N\Delta, N\Omega$

Robust of d* in quark models

- In PRC 51 (1995) 3411 we did a general survey of the dibaryon candidates in the u,d,s three-flavor like quark world and found the d*(IJP=03+) has the largest binding energy.

  The binding energy is large enough to allow the quark model to have as large an uncertainty as 200 MeV, the d* is still survive.

  This confirms our 1989 predictions.

  A relativistic quark model calculation confirmed the non-relativistic quark model result.

  Mod. Phys. Lett. A13(1998)59;arXiv:nucl-th/9803002.

d* mass and width in NN- ΔΔ channel coupling scattering

N_{ch}	ChQM2		ChQM2a		QDCSM0		QDCSM1		QDCSM3	
	M	Γ	M	Γ	M	Γ	M	Γ	M	Γ
1c	2425	–	2430	–	2413	–	2365	–	2276	–
2cc	2428	17	2433	10	2416	20	2368	20	2278	19
4cc	2413	14	2424	9	2400	14	2357	14	2273	17
10cc	2393	14			–	–	–	–	–	–
10cc′	2353	17			–	–	–	–	–	–
10cc″	2351	21			–	–	–	–	–	–

Total decay width of d*

	ChQM2:
M_R	2393
Γ_{NN}	14
Γ_{inel}	136
B_{NN}	0.09

	QDCSM1:
M_R	2357
Γ_{NN}	14
Γ_{inel}	96
B_{NN}	0.13

Only phase space reduction:

(structure of d* is not considered)

$$\Gamma_{b\Delta}(M_{b\Delta}) \approx \Gamma_{f\Delta}\frac{k_b^{2\ell}\rho(M_{b\Delta})}{k_f^{2\ell}\rho(M_{f\Delta})},$$

[33] B. Julia-Diaz, T.-S. H. Lee, A. Matsuyama, and T. Sato, Phys. Rev. C **76**, 065201 (2007).

NN 3D3-3G3 partial-waves in NN- ΔΔ channel coupling scattering

PRC 90(2014)064003;arXiv:1404.0947[nucl-th].

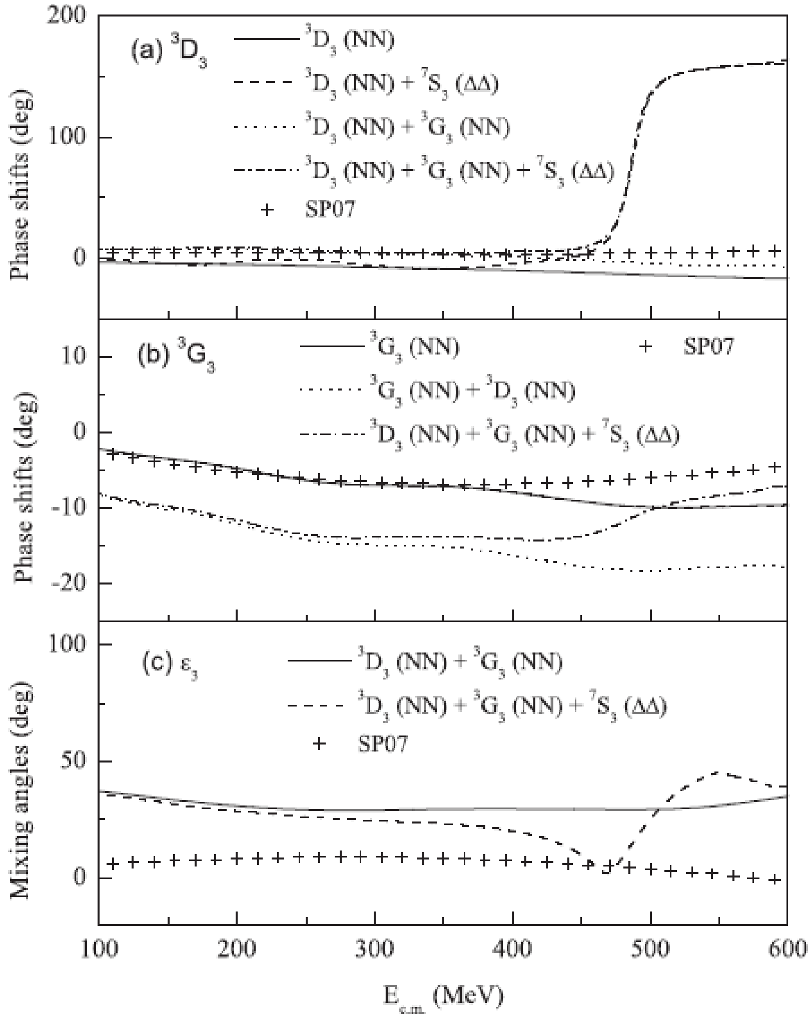
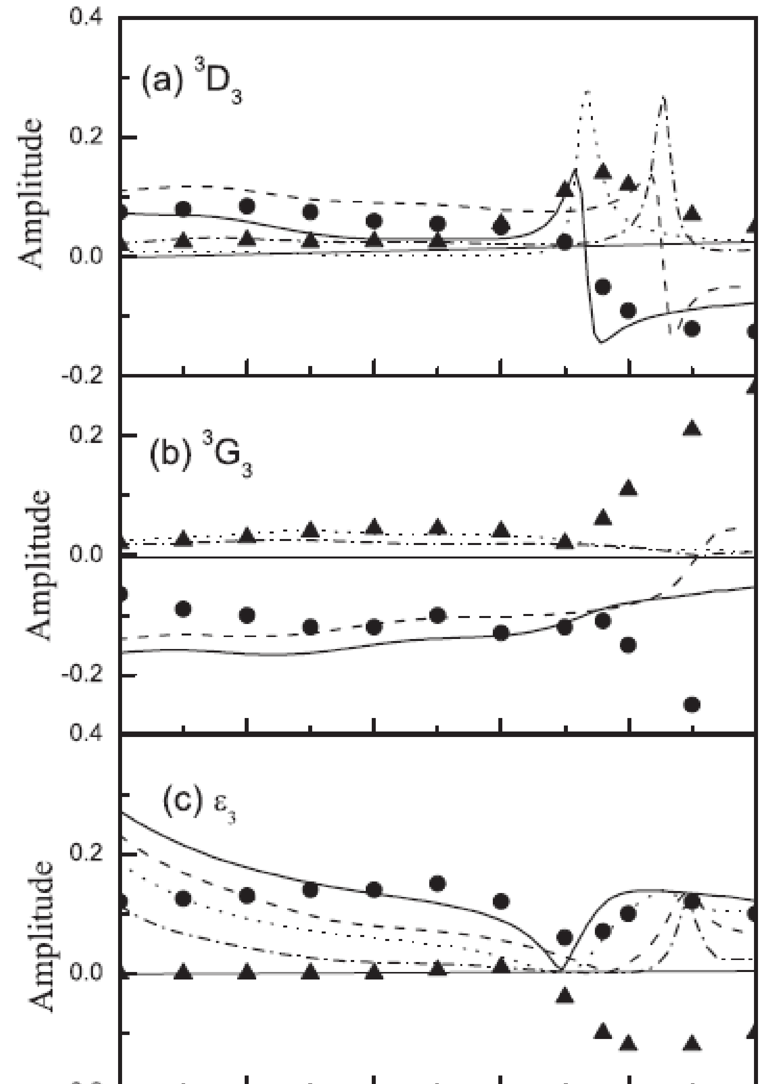


FIG. 1. $^3D_3^{NN}$ and $^3G_3^{NN}$ phase shifts including their mixing angles in QDCSM



Narrow width of d*

Bashkanov-Brodsky-Clement: PLB 727(2013)438

According to M. Harvey [66] there are only two possible quark structures for an $I(J^P) = 0(3^+)$ resonance in the two-baryon system:

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

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

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.

- A. Gal et al., PRL 111 (2013) 172301

  M=2363$\pm$20 MeV   Γ=65$\pm$17 MeV

- Huang-Zhang-Shen-Wang: arXiv: 1408.0458

  CC channel: 66%--68% → 70 MeV

- A. Gal et al., Nucl. Phys. A928 (2014) 73

  M=2363$\pm$20 MeV   Γ=33$\pm$20 MeV

What is the hidden-color channels?

M. Harvey: NPA352(1981)301: SU(2)

J.Q. Chen: NPA393(1983)122

F.Wang, J.L.Ping, T. Goldman: PRC51(1995)1648: SU(3)

Physical basis:

$$\Psi_{\alpha k}(B_1 B_2) = \mathcal{A}[\psi(B_1)\psi(B_2)] \overset{[\sigma]}{W} \overset{I}{M_I} \overset{J}{M_J}$$
$$= \mathcal{A}\left[\left|[\sigma_1][\mu_1]\overset{[\nu_1]}{[f_1]}Y_1 I_1 J_1\right\rangle \left|[\sigma_2][\mu_2]\overset{[\nu_2]}{[f_2]}Y_2 I_2 J_2\right\rangle\right] \overset{[\sigma]}{W} \overset{I}{M_I} \overset{J}{M_J} ;$$

Symmetry basis:

$$\Phi_{\alpha K}(q^6) = \left|[\sigma]W[\mu]\beta\overset{[\nu]l^3 r^3}{[f]}YIJM_I M_J\right\rangle .$$

Tranformation between physics basis and symmetry basis:

$$\mathcal{A}\left[\left|[\sigma_1][\mu_1]\overset{[\nu_1]l^3}{[f_1]}Y_1 I_1 J_1\right\rangle\left|[\sigma_2][\mu_2]\overset{[\nu_2]r^3}{[f_2]}Y_2 I_2 J_2\right\rangle\right]\overset{[\sigma]}{W}\overset{I}{M_I}\overset{J}{M_J}$$

$$= \sum_{\tilde{\nu}\mu\beta f\gamma} C^{[\tilde{\nu}][\sigma][\mu]}_{[\tilde{\nu}_1][\sigma_1][\mu_1][\tilde{\nu}_2][\sigma_2][\mu_2]} C^{[\mu]\beta[f]\gamma J}_{[\mu_1][f_1]J_1,[\mu_2][f_2]J_2} C^{[f]\gamma Y I}_{[f_1]Y_1 I_1 [f_2] Y_2 I_2} \left| [\sigma]W[\mu]\beta\overset{[\nu]l^3 r^3}{[f]}YIJM_I M_J \right\rangle .$$

For IJP=03+:

	[6][33][33]	[42][33][33]
$\Delta\Delta$	$\sqrt{1/5}$	$\sqrt{4/5}$
CC	$\sqrt{4/5}$	$-\sqrt{1/5}$

[ν][μ][f]

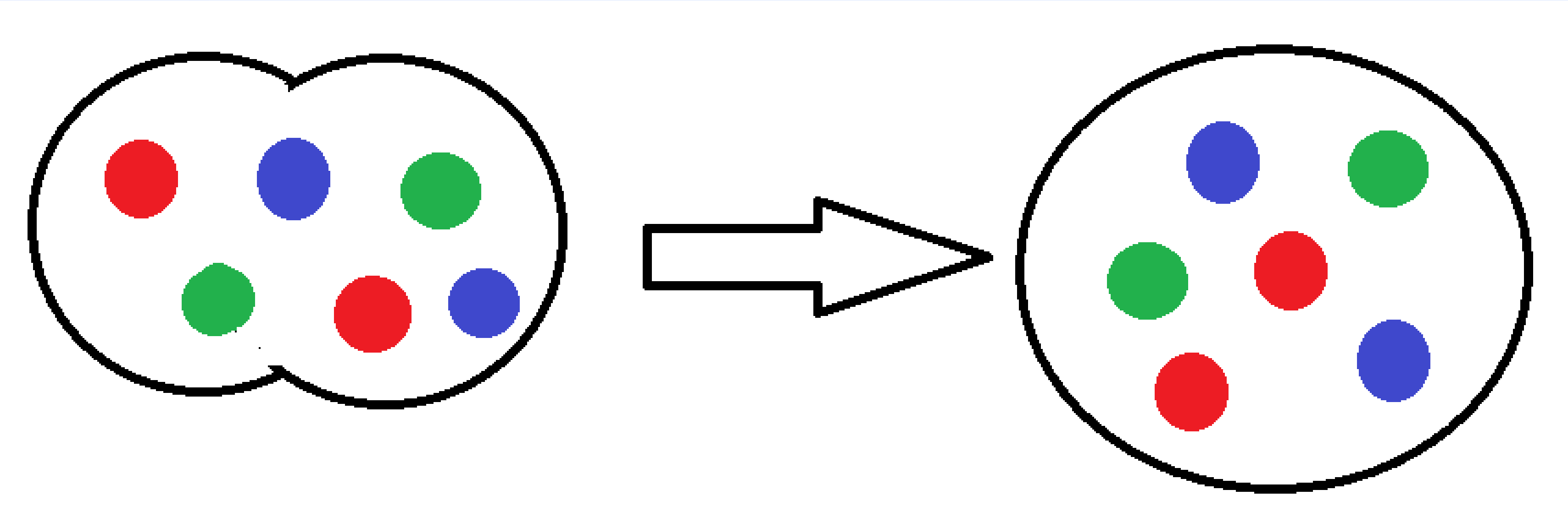
rbital

flavor-spin

flavor

d*: a compact object

taking limit: six quarks in one bag



6 quarks are in the same orbit: [ν]=[6], [42] disappears

Symmetry basis: only [6][33][33] exists

------> number of physical basis: 1

ΔΔ and CC are the same !

antisymmetrization

$< \Delta\Delta \mid CC > = 1$

+S/2, -S/2: the reference centers of baryons

S→0, [6] exists, [42] disappears

$< \Delta\Delta \,|\, CC > = 1$

Continuity → $< \Delta\Delta \,|\, CC >$ approx. 1, when S is small.

S (fm)	$< \Delta\Delta \,|\, CC >$	S (fm)	$< \Delta\Delta \,|\, CC >$
3	0	0.3	0.997
2	7×10^{-3}	0.2	0.999
1	0.7	0.1	0.99996
0.5	0.98	0.001	~ 1
0.4	0.99		

Schmidt orthogonalization

- $$|CC'\rangle = |CC\rangle - \frac{\langle \Delta\Delta | CC \rangle}{\langle \Delta\Delta | \Delta\Delta \rangle} |\Delta\Delta\rangle$$

S (fm)	E1	$\Delta\Delta$(%)	CC' (%)	E2	$\Delta\Delta$(%)	CC'(%)
3	2580	100	0	7770	0	100
2	2571	100	0	4870	0	100
1	2436	98	2	3093	2	98
0.5	2635	98	2	3270	2	98
0.3	2706	95	5	3341	5	95
0.2	2731	94	6	3366	6	94
0.1	2746	93	7	3381	7	93

Outer-product of the permutation group

- For color SU(3), the dimension of irreps [222] =1
- For S(6), the dimension of irreps [222] =5
- Constructing the bases of 6-quark system

from two three-quark clusters

↓

Outer-product of S(6) or CGC of SU(3)

- 5 bases of [222] ← [111]x[111] (color singlet)

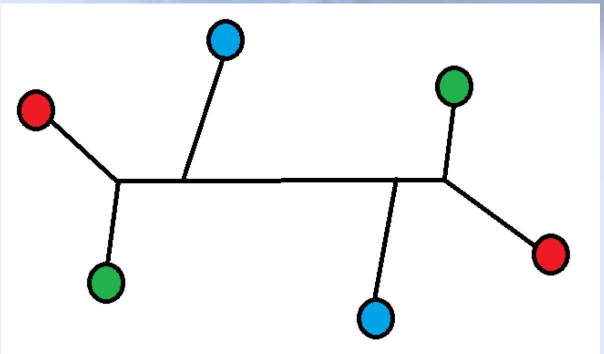
or [21]x[21] (color octet)

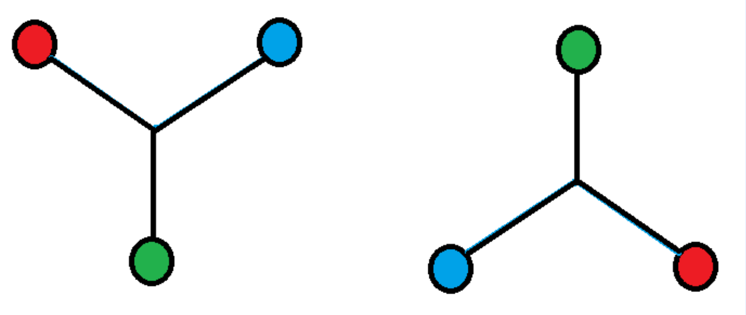
- Hidden-color channel is not necessary for quark-only system!

Hidden color configuration

- String-like structure:

hidden-color





color singlet

work on progress…

Summary

- Based on the dynamical symmetry, the quark model can describe the masses of baryon and dibaryon well. It has the predictive power.
- The improved quark models describe hadron-hadron interactions well
- d* is a compact object in quark model. Its compact six-quark structure is responsible for the narrow width.
- To explain the narrow width of d* by using hidden-color channel is questionable.
- Once the total width of d* is reproduced, the branching ratios of different channels can be reproduced by isospin symmetry and the phase space (Bashkanov et al., arXiv: 1502.07156).
- There are more dibaryons to be discovered.

Thanks!!!

ABC Effects

The ABC effect—first observed by Abashian, Booth, and Crowe [1] in the double-pionic fusion of deuterons and protons to ^{3}He—stands for an unexpected enhancement at low masses in the invariant $\pi\pi$ mass spectrum $M_{\pi\pi}$. Follow-up experiments [2–11] revealed this effect to

[1] N. E. Booth, A. Abashian, and K. M. Crowe, Phys. Rev. Lett. **7**, 35 (1961); **5**, 258 (1960); Phys. Rev. **132**, 2296 (1963).