Nuclear force is a QCD duplication of QED molecular force

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Dedicate to 88's birthday of A. Arima
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Outline

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II. Similarity of nuclear and molecular force

III. NN interaction-a QCD duplication of QED interaction between atoms

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I. Introduction

- NN interaction has been studied since the proposal of proton-neutron model of nuclei.
- H. Yukawa proposed the meson exchange model of NN interaction and succeeded in one pion exchange. However the multi-pion exchange met serious difficulties.
- The effective one boson exchange model, such as Bonn, Nijmegen meson exchange models, successfully describe the NN interaction.

- Chiral perturbation, with strong QCD basis, successfully describe the low energy NN interaction.
- The phenomenological model, such as AV18, also describes the NN interaction well.
- The chiral quark model, such as the Salamanca model describes the NN interaction as well as other models, in addition it describes the hadron internal structure.
- Lattice calculation also approaches the realistic NN interaction.

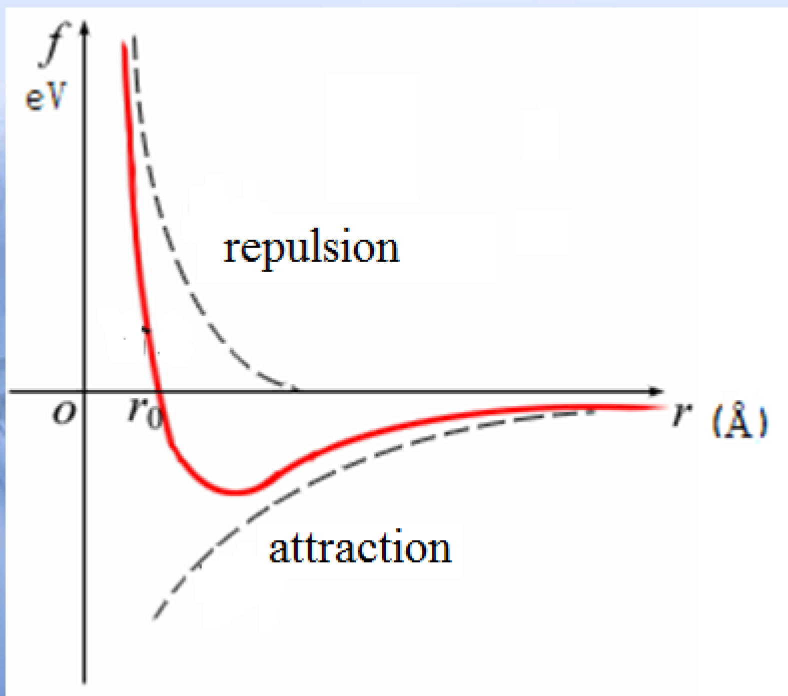
However all of these models had not answered the question:

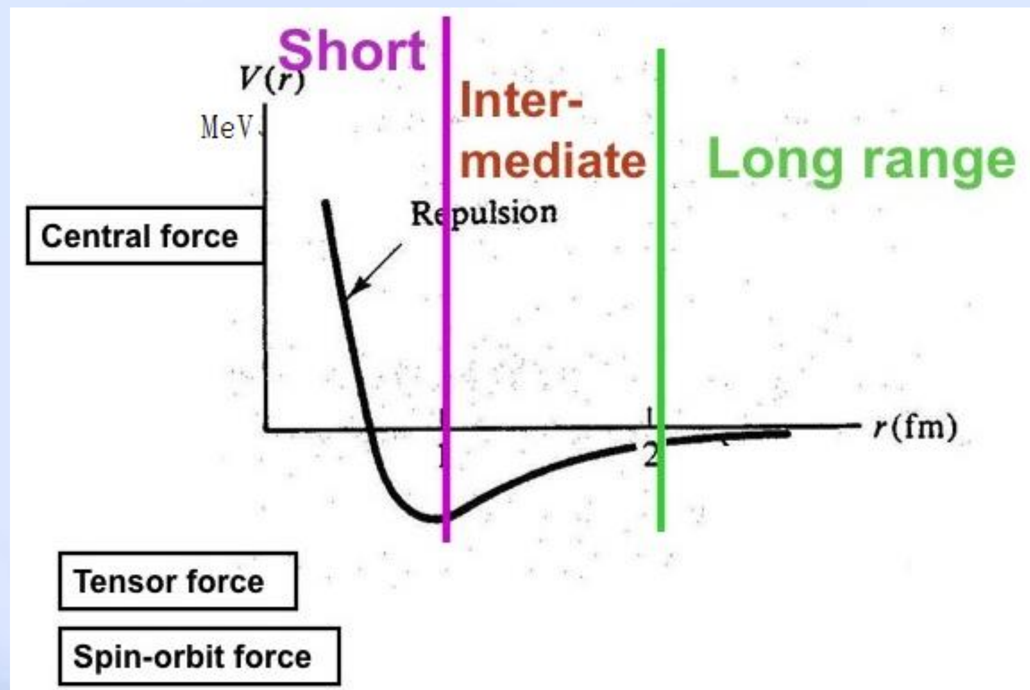
Why is the nuclear force similar to the molecular force？

II. Similarity
of nuclear force and molecular force

A. Bohr and B. R. Mottelson, Nuclear structure, 1975

spin singlet	spin triplet isospin singlet
interaction between H atoms	interaction between nucleons





Under the point nucleon model it is impossible to understand this similarity; The development of quark model paved the way to understand it.

Residual interaction between

two atoms	two nucleons
1. QED interaction between charged electrons and protons	1. QCD interaction between colored quarks
2. charge neutral atom screening QED interaction between atoms	2. color neutral nucleon screening QCD interaction between nucleons
3. electron delocalization between atoms distorting the electric charge distribution inducing the residual interaction-molecular force	3. quark delocalization between nucleons distorting the color distribution inducing the residual interaction-nuclear force.

Criticism from Anderson and statement of US CPEP

(contemporary physics education project)

- Criticism from P.W. Anderson:

  Meson exchange model ignores nucleon internal structure, nuclear force can not be solely due to meson exchange.

  Phys. Today, 53(2), 11 (2000) 14, http://dx.doi.org/10.1063/1.882955

- CPEP statement(2003):

  The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. .

III. NN interaction-a QCD duplication of QED interaction between atoms

- Quark model used to understand the NN interaction started by the end of 1970’s. In the early stage only repulsive core was obtained. This led the Tokyo group to introduce the meson exchange between quarks.

- We have developed a alternative quark model based on the Heitler-London hydrogen molecule covalent bond approach but with variational extension.

PRL 69(1992)2901,arXiv:nucl-th 921002

Instead assuming quark be confined within individual nucleon we allow quark delocalizing from one nucleon to the other as nucleon closing each other.

- Two center orbital wave function with **delocalization**:

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

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

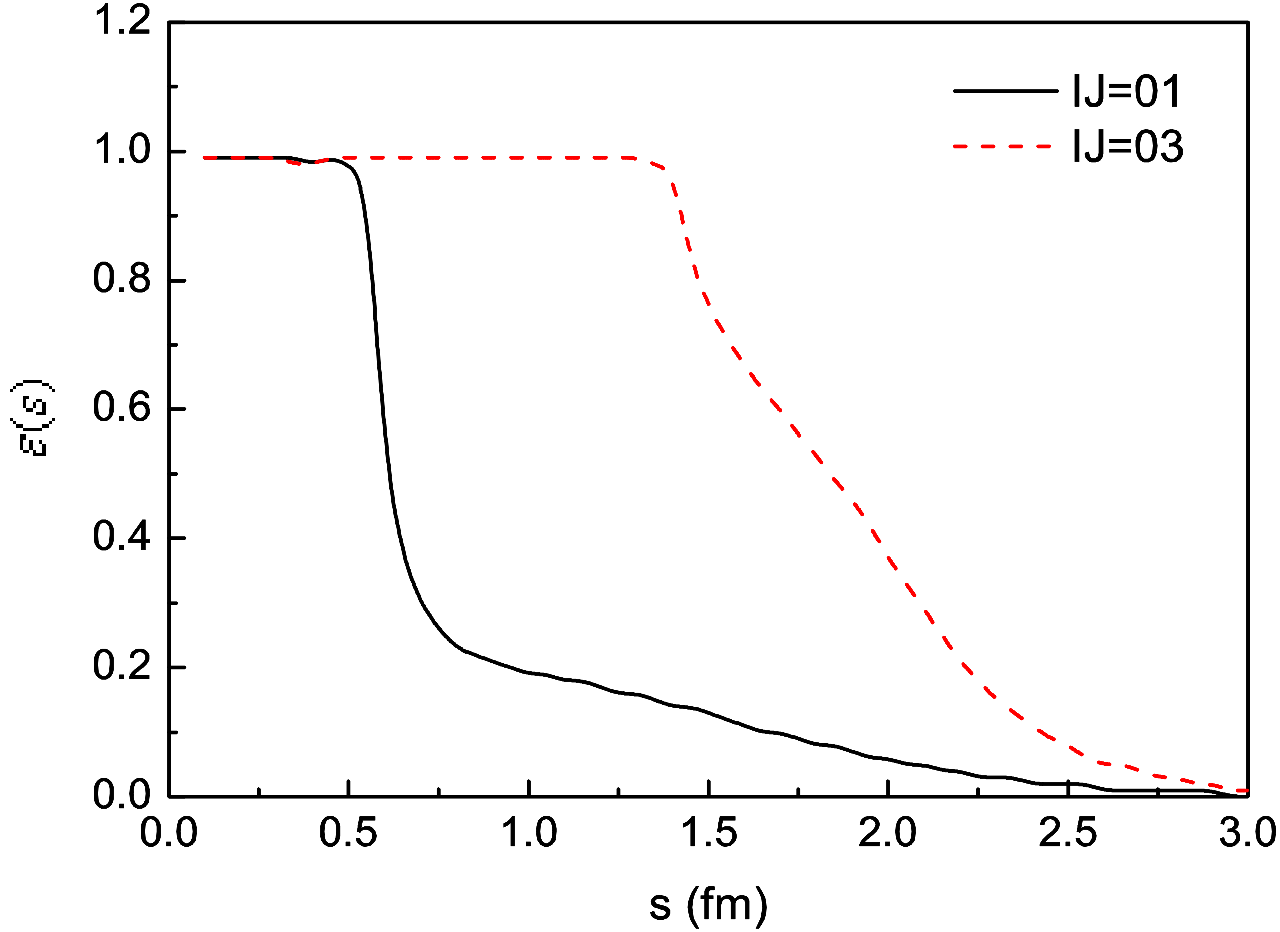
The delocalization parameter **ε(s)** is determined by **system dynamics** via variational principle.

Single Gaussion quark orbital wf is used to simplify the numerical calculation.

The realistic one should be a **multi-Gaussion** expansion. This simplification worsens the long rang behavior of the model NN interaction.

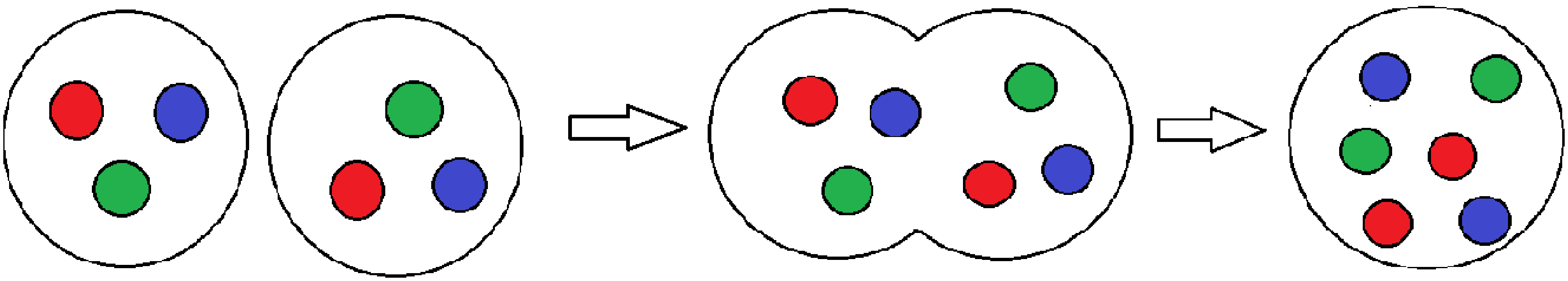
- The advantage of this model :

the delocalization parameter is determined through its own dynamics, so multiquark system **chooses its most favorable configuration via variation** at every separation s. **Two nucleons deform gradually as they close together and finally merge into a compact 6-quark cluster**.



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

Two nucleons gradually deformed from two well separated ones merged into six quark cluster



A nonrelativistic Hamiltonian is used to describe the dynamics of this model:

1. Color screening confinement is used to mock up the $q\bar{q}$ excitation and hidden color channel coupling coupling effects.

PRC84(2011)064001,arXirv:1109.5607[nucl-th]

2. Including a pion exchange is aimed to use single Gaussian quark orbital wf instead of the multi-Gaussian expansion to simplify the calculation.

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

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

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

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

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

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

Resonating group two-nucleon cluster wf and **generating coordinate** expansion is used to do both bound and scattering calculation.

TABLE I. Parameters of three-quark models discussed in this paper.

	ChQM	QDCSM1	QDCSM2	QDCCM
$m_{u,d}$ (MeV)	313	313	313	313
b (fm)	0.518	0.518	0.60	0.518
a_c (MeV fm^{-2})	46.938	56.755	18.5	56.755
V_0 (fm^2)	−1.297	−0.5279	−1.3598	−0.5279
μ (fm^{-2})		0.45	1.00	
α_s	0.485	0.485	0.996	0.485
m_π (MeV)	138	138	138	138
α_{ch}	0.027	0.027	0.027	0.027
m_σ (MeV)	675			
Λ (fm^{-1})	4.2	4.2	4.2	4.2

The properties of deuteron.

	ChQM	QDCSM1	QDCSM2
B (MeV)	2.0	1.94	2.01
$\sqrt{r^2}$ (fm)	1.96	1.93	1.94
P_D (%)	4.86	5.25	5.25

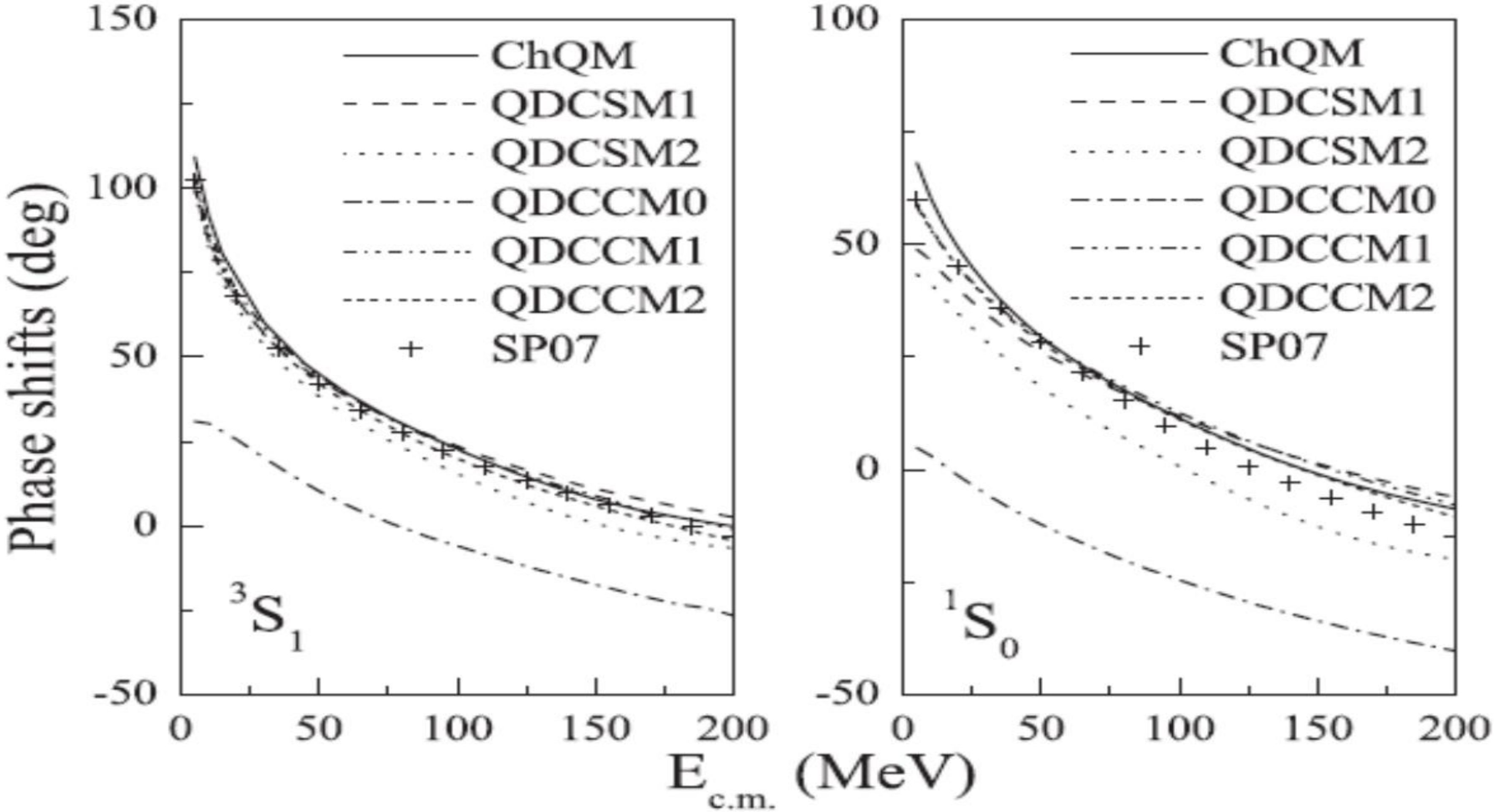


FIG. 1. The phase shifts of NN S-wave scattering.

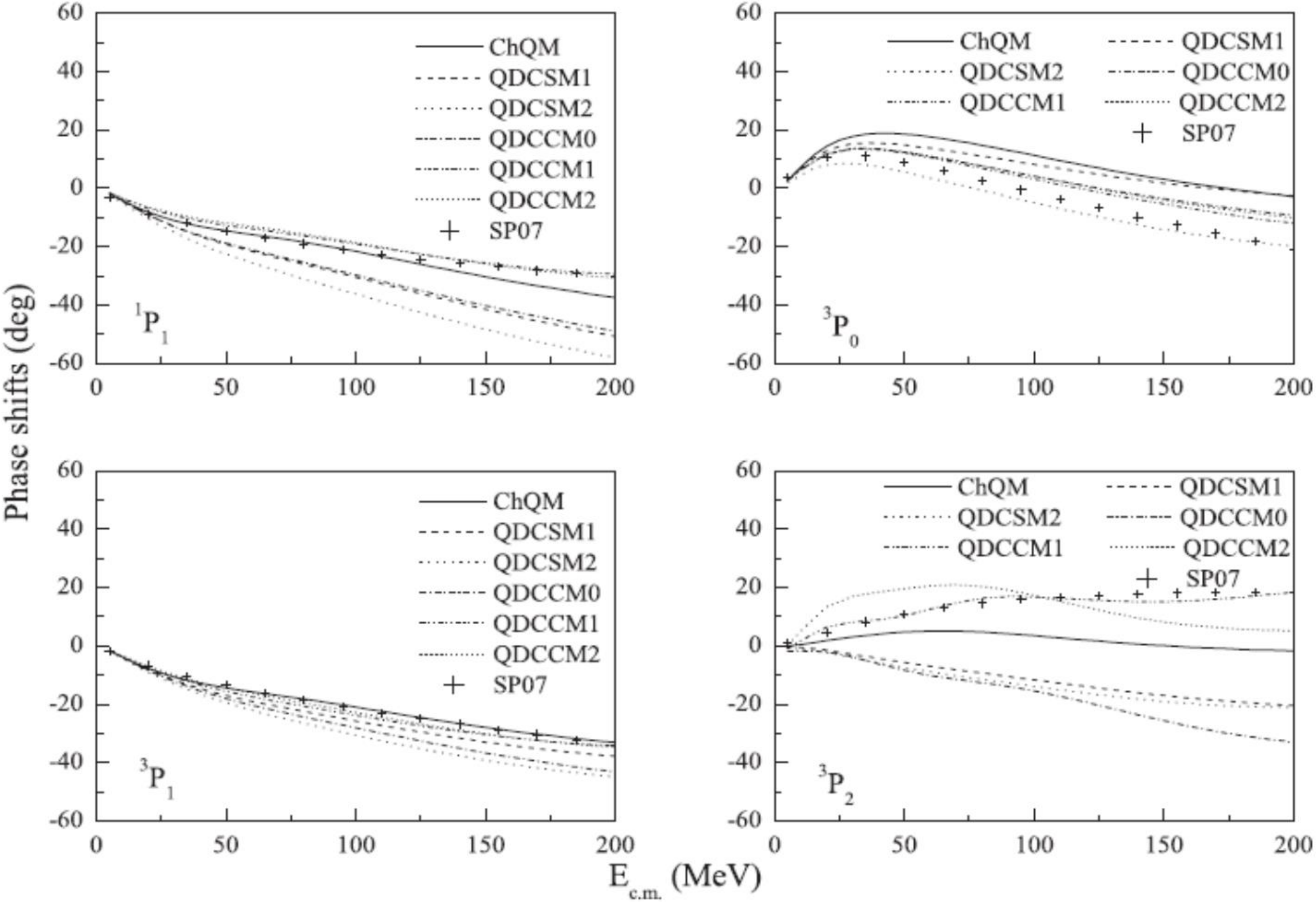


FIG. 2. The phase shifts of NN P wave scattering.

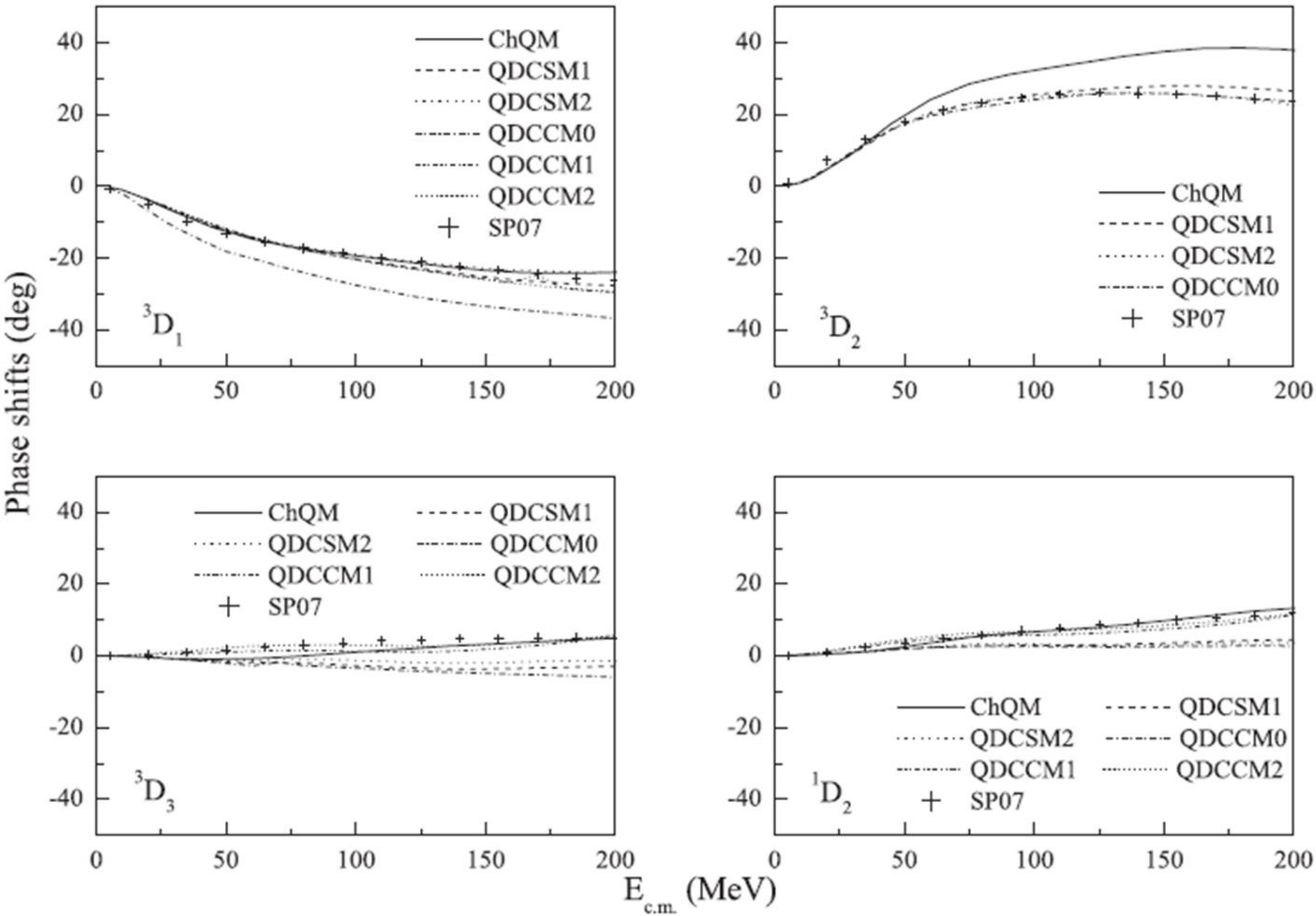


FIG. 4. The phase shifts of NN D-wave scattering.

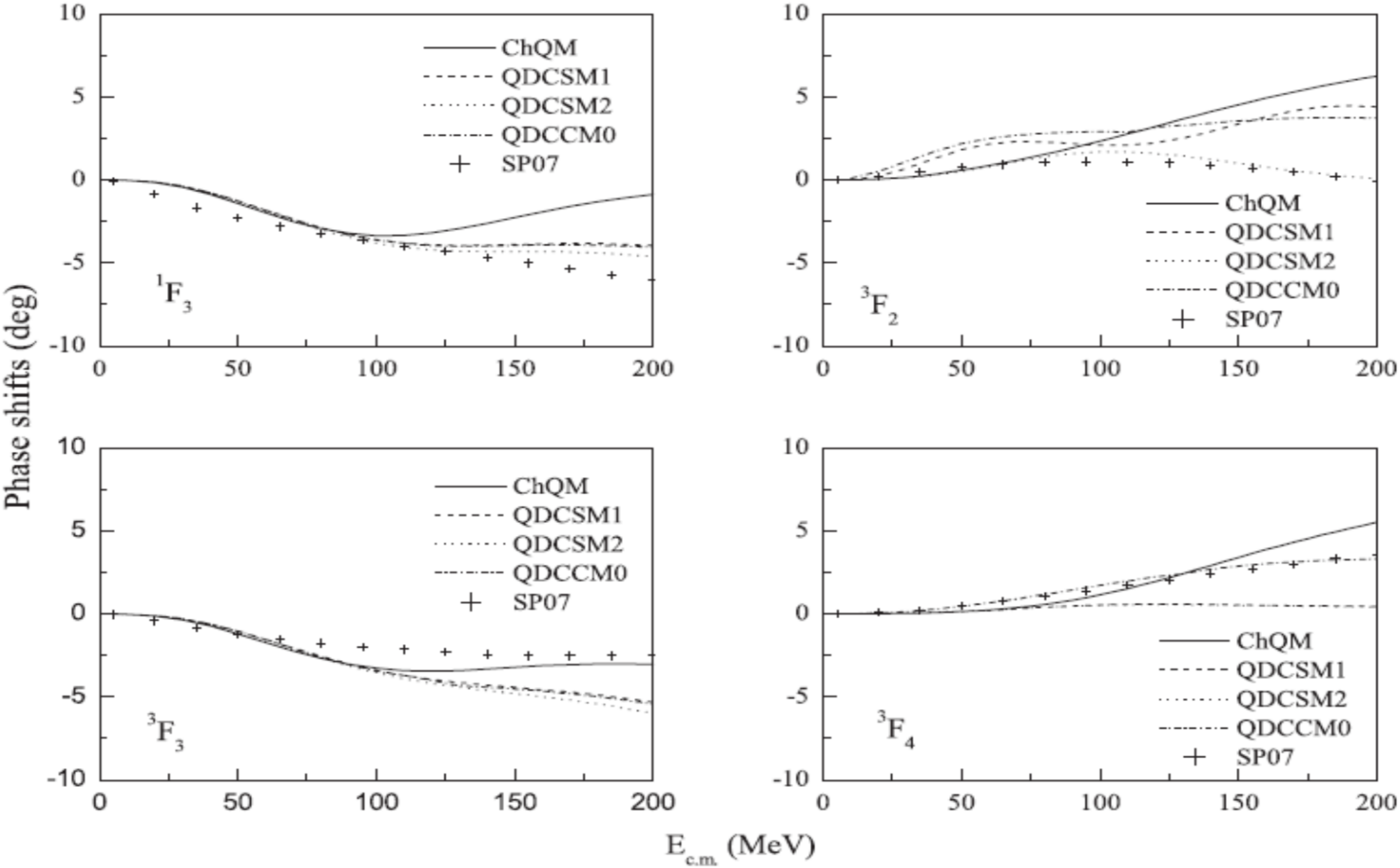


FIG. 5. The phase shifts of NN F-wave scattering.

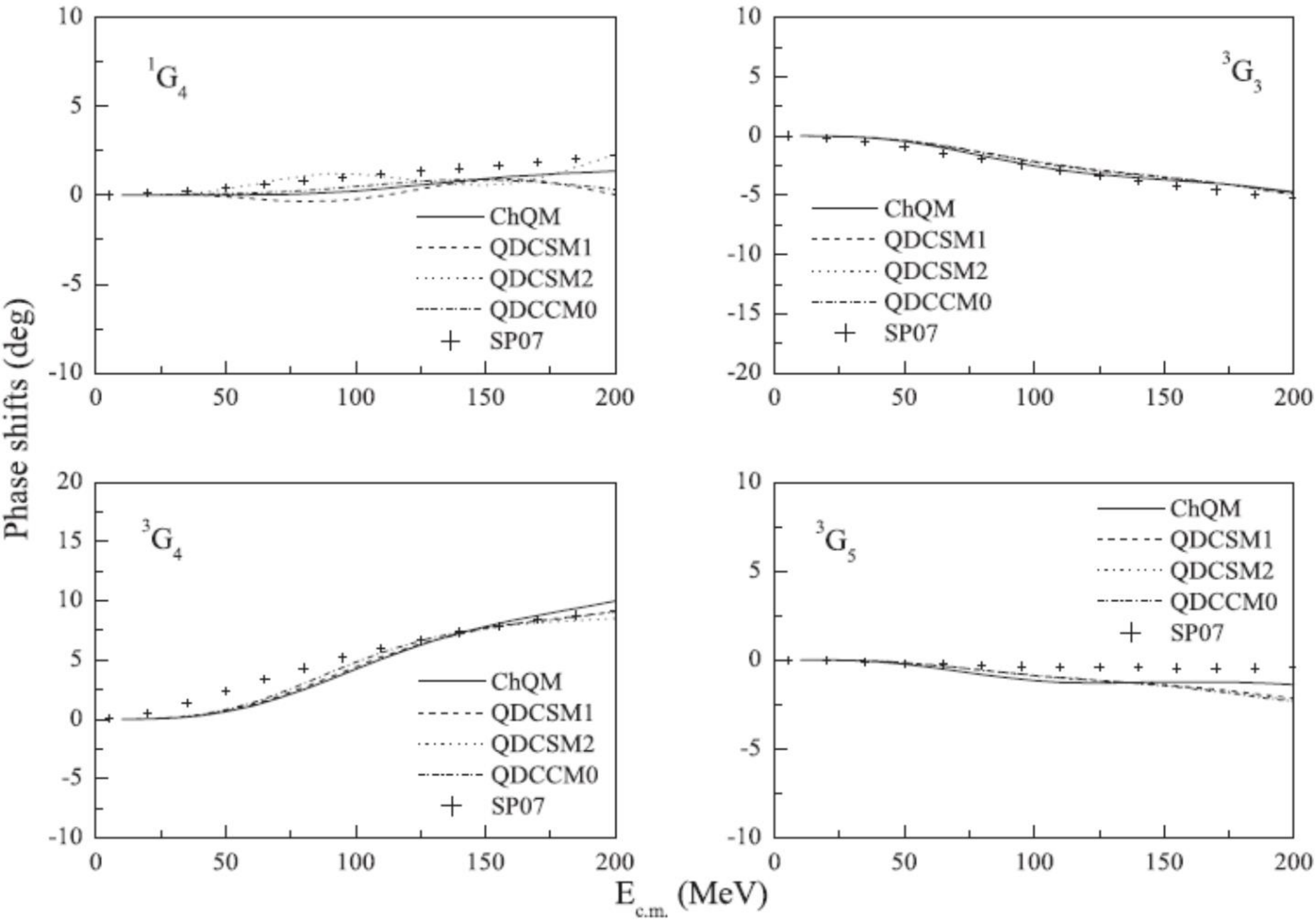


FIG. 6. The phase shifts of NN G-wave scattering.

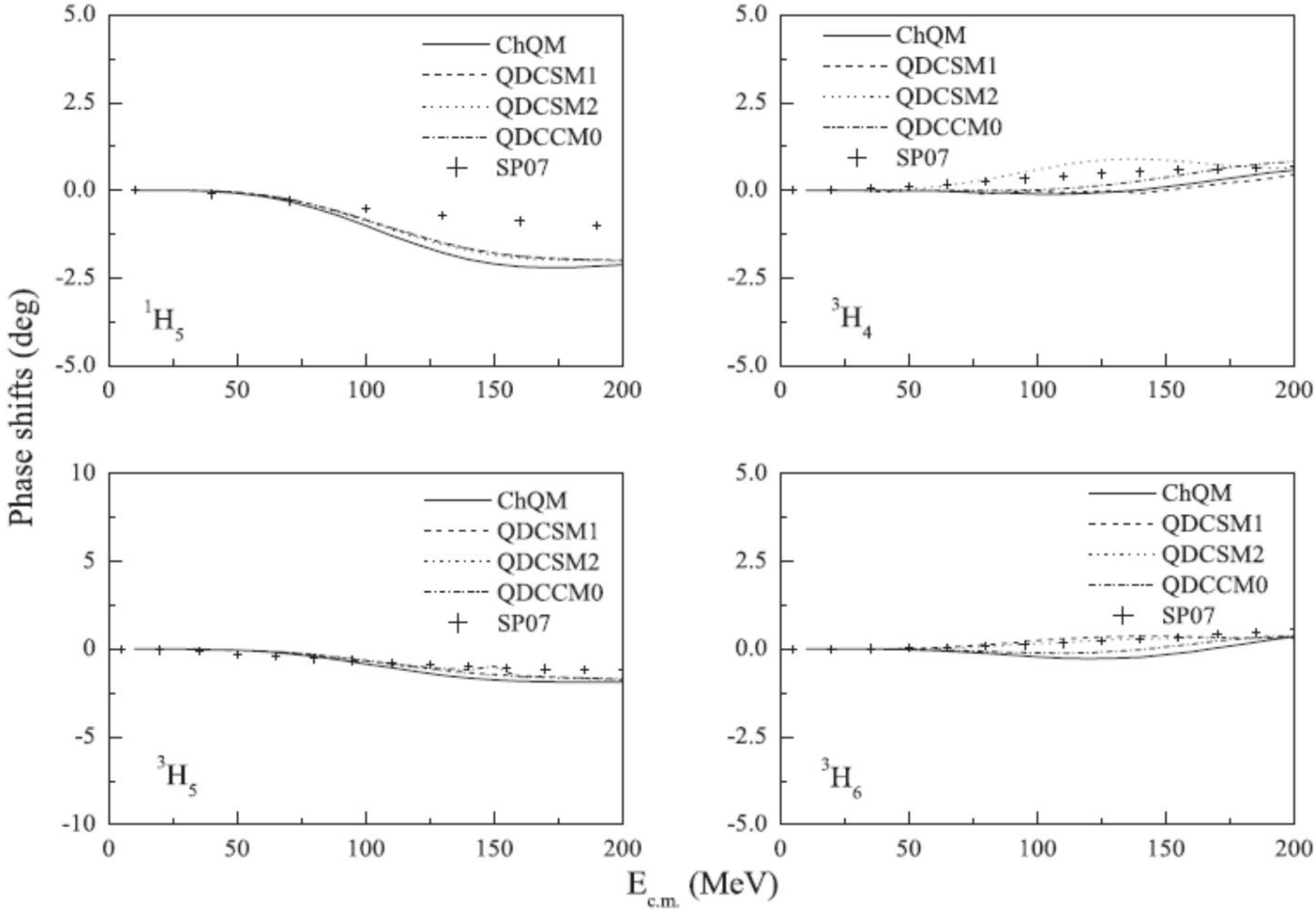


FIG. 7. The phase shifts of NN H-wave scattering.

IV. Dscussions

- This model using 9, in comparing with about 30 parameters of one boson exchange and chiral perturbation, describing the NN interaction as well as other models. Not perfect!
- 8 parameters are determined from the octet and decuplet baryon properties, one additional parameter is fixed by the deuteron properties. In this sense this model **predicts** the NN interaction, **unified** the description of baryon internal structure and interaction. With one additional parameter, the s-quark mass, this model describes SU(3) baryon internal structure and their interactions well.

- Up to now this model is the unique one explained the similarity between nuclear and molecular force.
- This model finds the NN repulsive core is due to the qq color magnetic interaction and the octet flavor structure, neither the Pauli exclusion nor the hidden color components as suggested by S. Brodsky and others. Repulsive core is universal for octet-octet baryon interactions but disappears for octet-decuplet and decuplet-decuplet channels.

arXiv:1711.01445[hep-ph]

Difference of the color magnetic interaction between two baryons and six-quark states

$$\langle CMI\rangle_N = -3C\langle\lambda_2\cdot\lambda_3\rangle_A\left[\langle\sigma_2\cdot\sigma_3\rangle_A+\langle\sigma_2\cdot\sigma_3\rangle_S\right]/2 = -8C,$$

$$\langle CMI\rangle_\Delta = -3C\langle\lambda_1\cdot\lambda_2\rangle_A\langle\sigma_1\cdot\sigma_2\rangle_S = 8C,$$

$$\begin{aligned}\langle CMI\rangle_d &= -15C\left\{\langle\lambda_5\cdot\lambda_6\rangle_A\left[\frac{5}{30}\langle\sigma_5\cdot\sigma_6\rangle_A+\frac{13}{30}\langle\sigma_5\cdot\sigma_6\rangle_S\right]\langle\lambda_5\cdot\lambda_6\rangle_S\left[\frac{5}{30}\langle\sigma_5\cdot\sigma_6\rangle_A+\frac{7}{30}\langle\sigma_5\cdot\sigma_6\rangle_S\right]\right\}\\ &= -\frac{8}{3}C,\end{aligned}$$

$$\langle CMI\rangle_d-2\langle CMI\rangle_N = \frac{40}{3}C,$$

$$\langle CMI\rangle_d-2\langle CMI\rangle_\Delta = -\frac{56}{3}C,$$

- The NN intermediate range attraction is due to the quark delocalization, similar to the electron delocalization for the hydrogen molecule covalent bond, the color van der Waals force plays the minor role.
- This model predicts there are shallow bound octet-octet dibaryons (hadron molecule), deep bound decuplet-decuplet dibaryons (compact six quark state) and intermediate bound octet-decuplet dibaryons.

Three kinds of dibaryons

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

- Octet-octet dibaryons:

  repulsive core, weak attraction, small binding energy

  typical example: well reproduced the deuteron as a baryon molecule.

- Decuplet-decuplet dibaryons:

  no repulsive core, strong attraction, large binding energy

  typical example: predicted IJ=03 d* as a deep bound inevitable dibaryon PRC39 (1989)1889;discovered by WASA@COSY collab. in 2009-2014.

- Octet-decuplet dibaryons:

  in between above two cases: typical example: NΩ

  predicted in PRL 59(1987)627; supported by HALQCD's Nucl.Phys. A928 (2014)89. arXiv:1403.7284; STAR collaboration found evidence, arXiv:**1808.02511**

The discovery of d*: WASA-at-COSY measurements

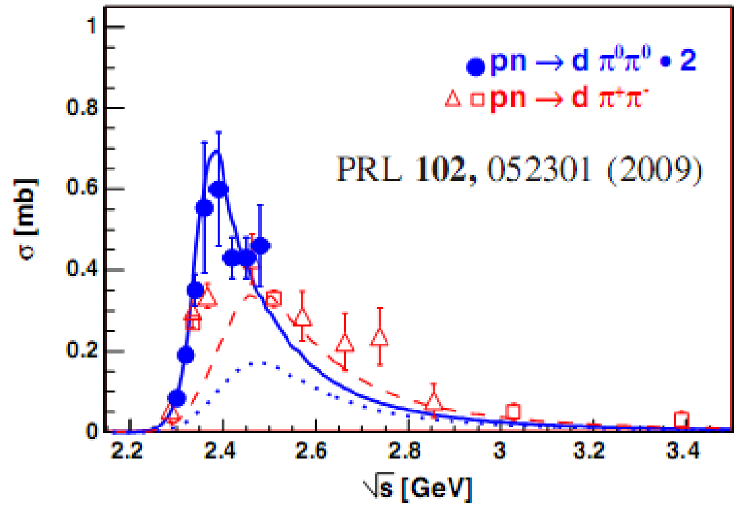
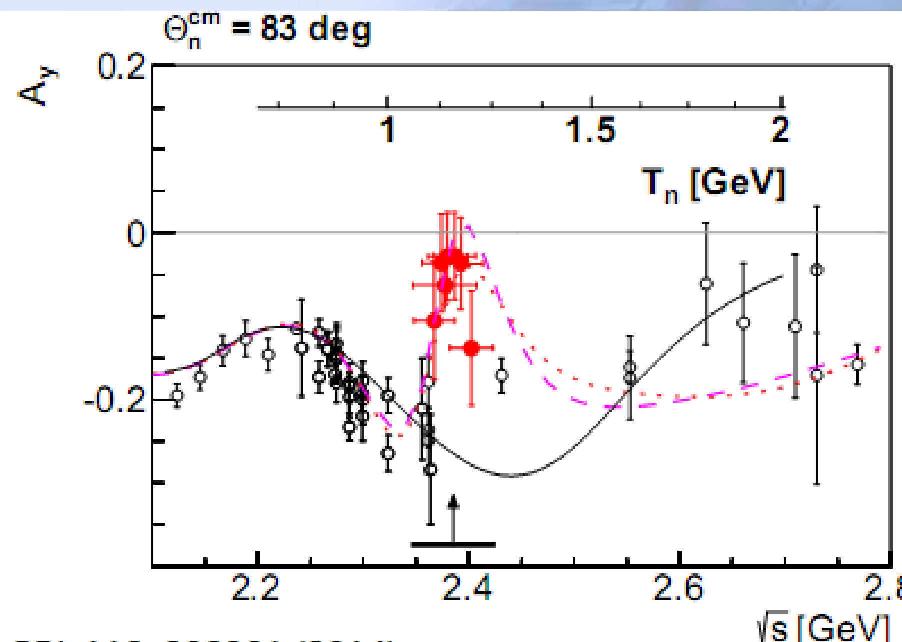


FIG. 4 (color online). Energy dependence of the total cross section for the $pn \to d\pi^+\pi^-$ reaction from threshold ($\sqrt{s}$ = 2.15 GeV) up to $\sqrt{s}$ = 3.5 GeV. Experimental data are from Refs. [8] (open squares) and [4] (open triangles). The results of this work for the $\pi^0\pi^0$ channel—scaled by the isospin factor of 2—are given by the full circles. Dashed and dotted lines represent the cross sections for $\pi^+\pi^-$ and $\pi^0\pi^0$ channels, respectively, as expected from the isovector $\pi^+\pi^0$ data by isospin relations (see text). The solid curve includes an s-channel resonance in the $\Delta\Delta$ system adjusted to describe the ABC effect in the $\pi^0\pi^0$ channel.



PRL 112, 202301 (2014)

FIG. 4: (Color online) Energy dependence of the np analyzing power at $\Theta_n^{cm} = 83°$. The solid symbols denote the results from this work, the open symbols those from previous work [7–9, 21–25]. For the meaning of the curves see Fig. 1. Vertical arrow and horizontal bar indicate pole and width of the resonance.

- The predicting power of this model is limited by the uncertainty of model parameters. Even though we have vast amount of NN interaction data, which had made the NN interaction being the very difficult problem in physics, it is still can not fix the only 9 model parameters and the dibaryon properties is very sensitive to these model parameters.

V. Conclusion

- Based on all of these evidences we try to propose that the nuclear force is a duplication of QED molecular force.

- We tentatively propose further that the Gell-Mann quark model and its extension, the quark cluster model of NN interaction with quark delocalization, should have their non-perturbative QCD background. The non-perturbatice QCD –DSE approach might have given limited support.

Thanks!!!

d* in NN and ΔΔ channel coupling scattering

PRC 79 (2009) 024001; arXiv:0806.0458[nucl-th].

The delicate deuteron properties and the vast NN scattering data are still not able to fix the model parameters and cause the uncertainty of d* mass.

	ChQM2 (ChQM1)	ChQM2a	QDCSM0	QDCSM1	QDCSM3
b	0.518	0.60	0.48	0.518	0.60
a_c	46.938 (67.0)	12.39	85.60	56.75	18.55
V_0	−1.297	0.255	−1.299	−1.3598	−0.5279
μ			0.30	0.45	1.00
α_s	0.485	0.9955	0.3016	0.485	0.9955
α_{ch}	0.027 (0.0269)	0.027	0.027	0.027	0.027
a_t	4.52	20.8	34.9	5.94	6.03
r_t	1.56	2.24	2.27	1.75	1.67
ε_d	3.35	0.11	0.04	1.75	1.64
a_s	−170	−2.48	−2.32	−6.90	−5.41
r_s	2.17	5.42	4.48	2.63	3.56

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
$\Gamma_{\rm inel}$	136
B_{NN}	0.09

QDCSM1:	
M_R	2357
Γ_{NN}	14
$\Gamma_{\rm inel}$	96
B_{NN}	0.13

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

binding reduces the width to about 100MeV

[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].

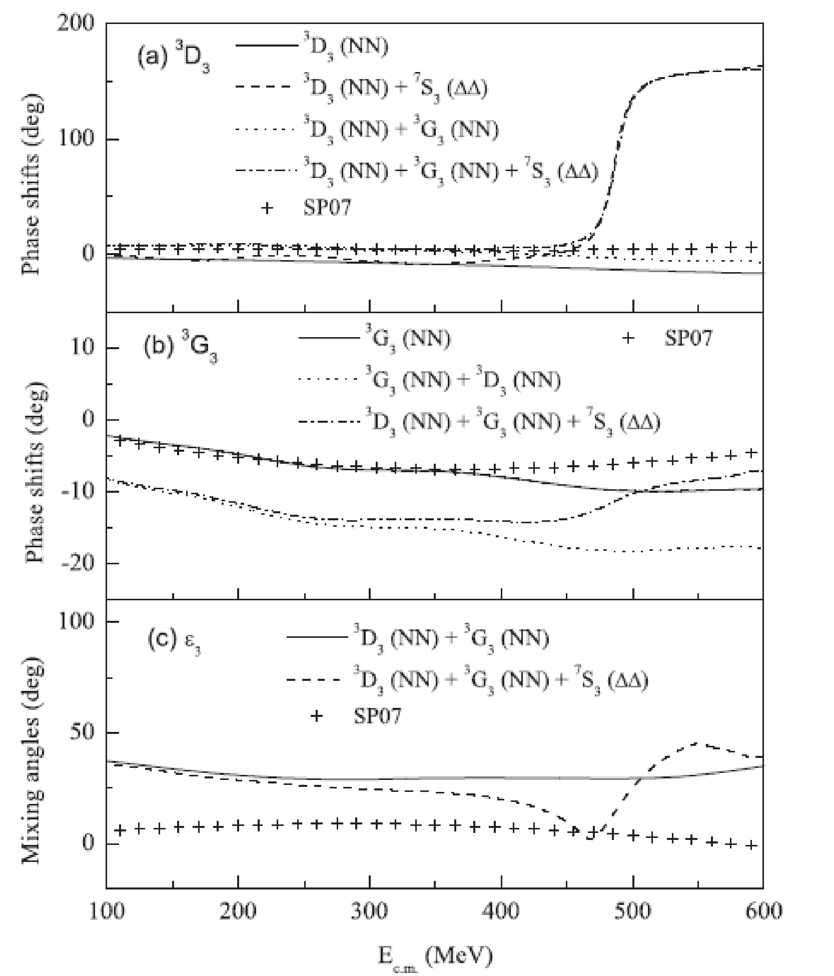


FIG. 1. $^3D_3^{NN}$ and $^3G_3^{NN}$ phase shifts including their mixing angles ε_3 in QDCSM.

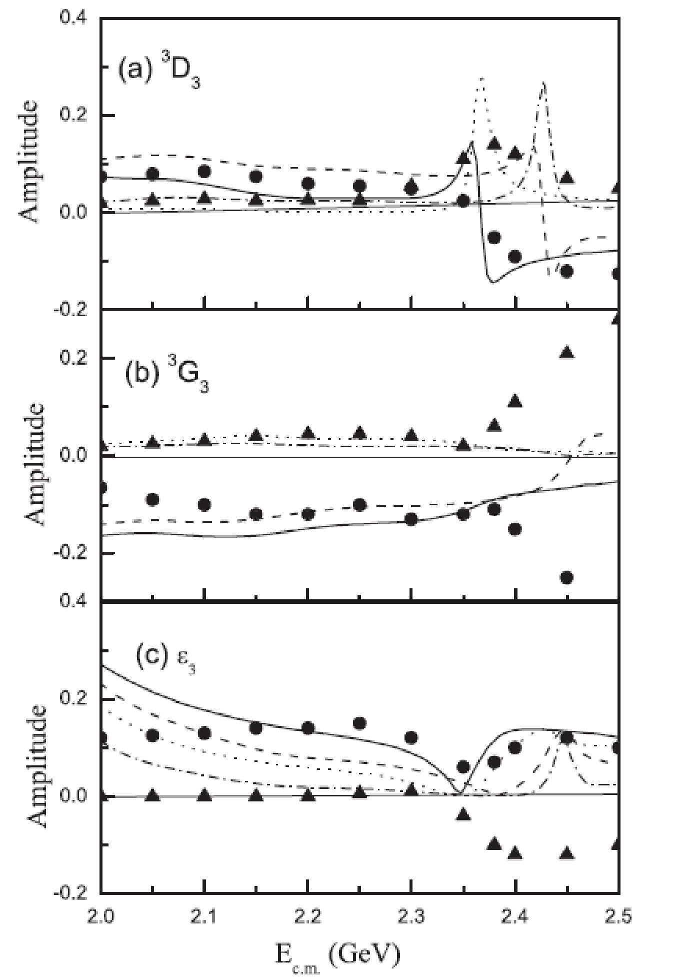


FIG. 3. $^3D_3^{NN}$ and $^3G_3^{NN}$ amplitudes including their mixing amplitude ε_3 in two quark models. Solid (dotted) curves give the real (imaginary) part of partial-wave amplitudes in QDCSM, whereas the dashed (dash-dotted) curves represent the real (imaginary) part of