クォーク模型による
ハイペロンを含んだ3バリオン系の研究

鈴鹿高専　仲本朝基
新潟大理、理研仁科セ　鈴木宣之

１．Introduction
２．クォーク・パウリ効果
３．ノルム核に比例する3体バリオン相関
４．Summary & Future

1. Introduction

3 baryon systemにおける三体力

- Few-body system physics
- Nuclear matter physics
- Neutron star physics
- ……

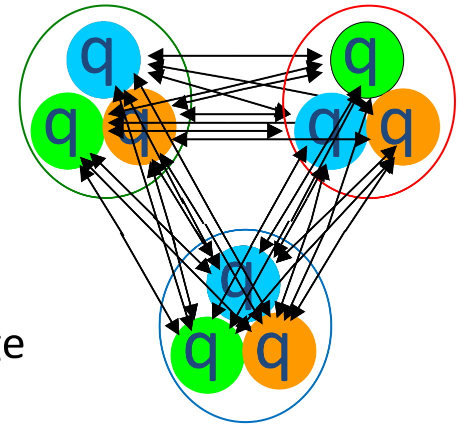
存在するのは確かだが、
その起源は依然として不明確

三体力に対する理論側のアプローチ

- 2π交換ポテンシャル（藤田・宮沢）
- 現象論的模型
- カイラル摂動理論
- 格子QCD計算（HAL-QCD）
- ……

クォーク模型によるアプローチ

９クォーク3バリオン系（３クラスター９体系）
⇒　複合粒子における構成子効果の発露



- Kinematical：　quark-Pauli effect
- Dynamical：　quark-quark interaction　through quark-exchange

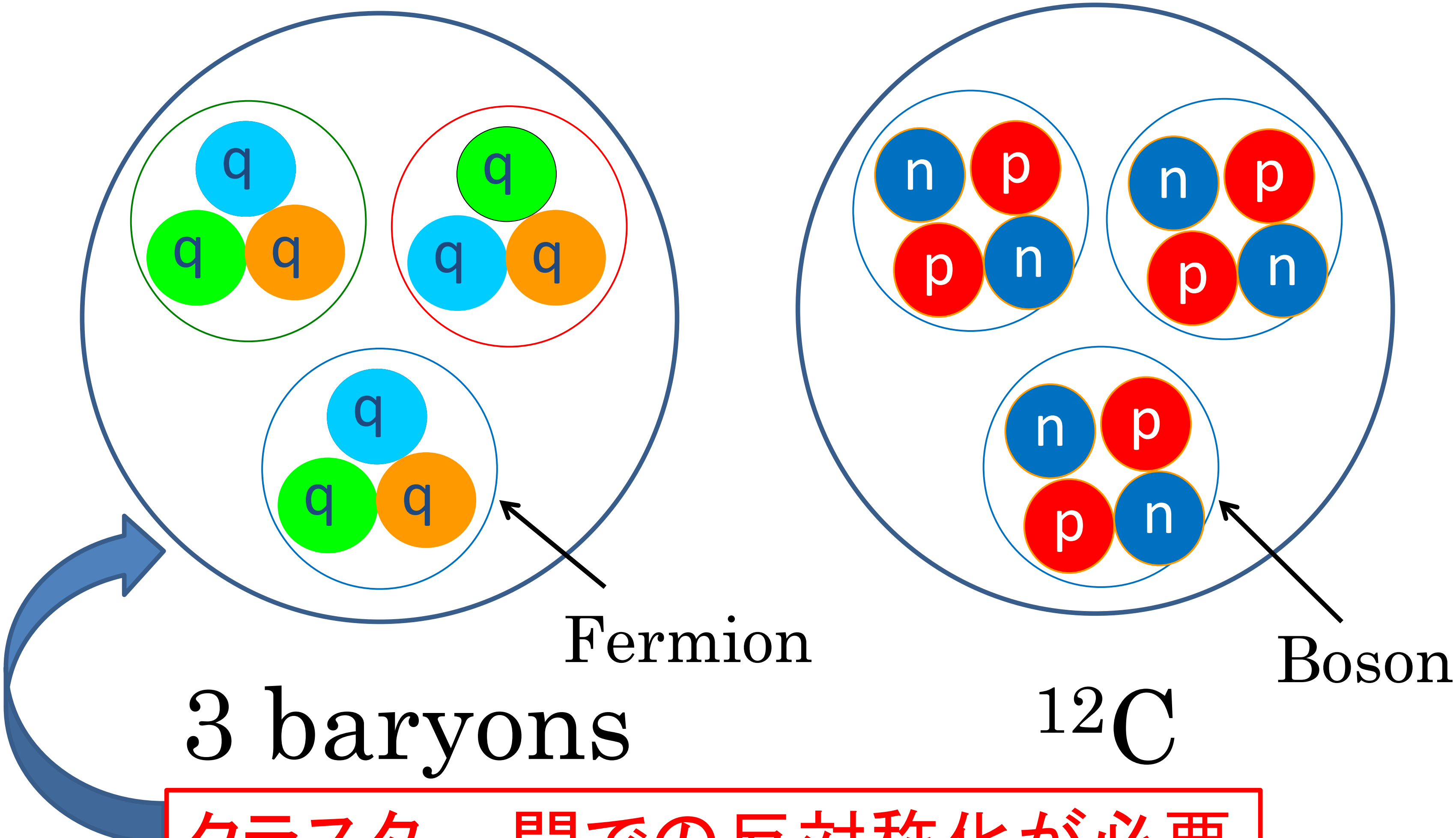
クォーク模型の利点

- 1-baryonからFew-baryonsまで、統一した枠組みで系統的に調べられる
- Pauli effect，各種interactionなど、その効果を別々に評価できる

研究目的

- クォーク模型をプローブとして、三核子系のみならず、三体バリオン力の理解を試みる

原子核とのアナロジー

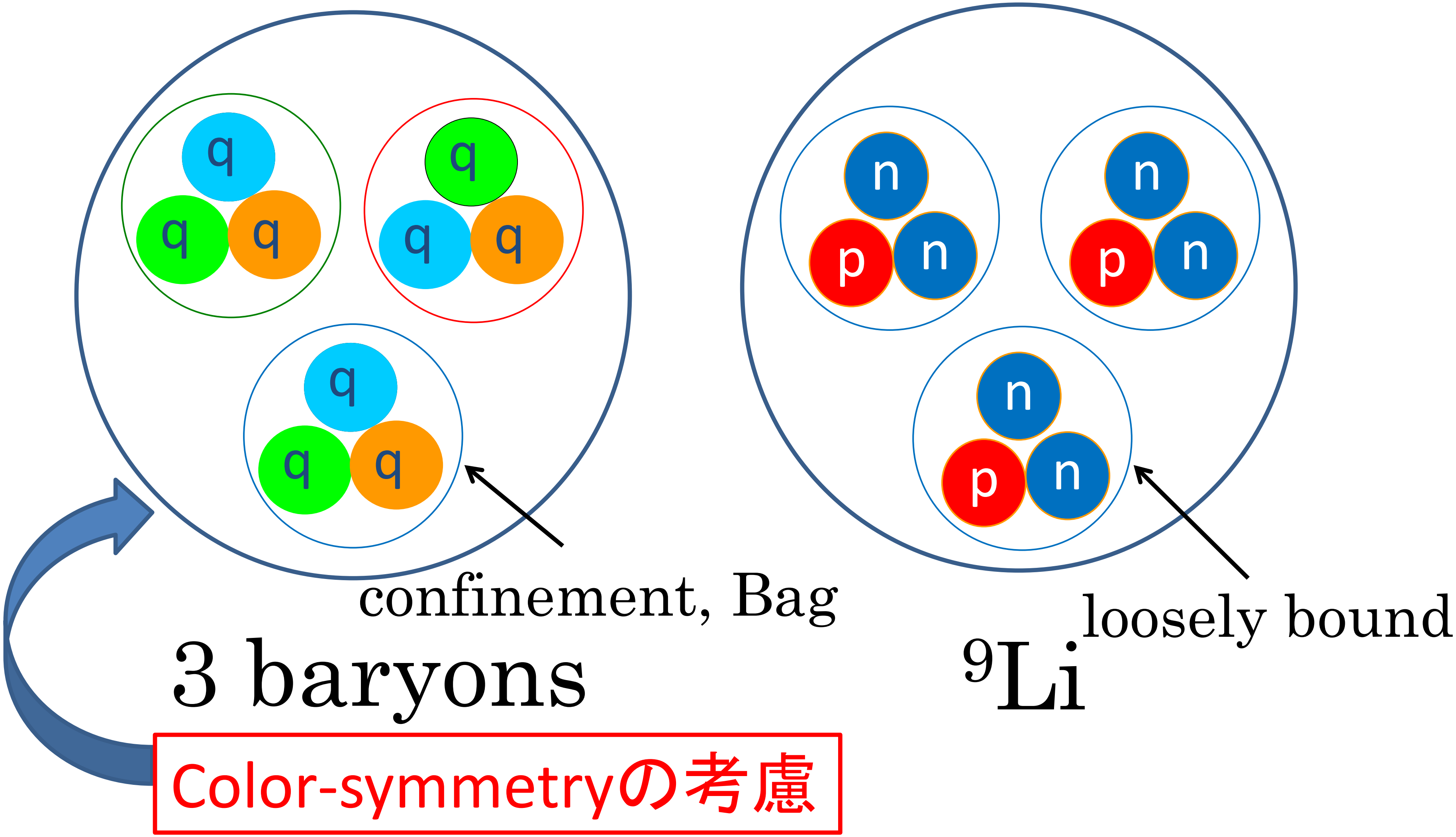


3 baryons

^{12}C

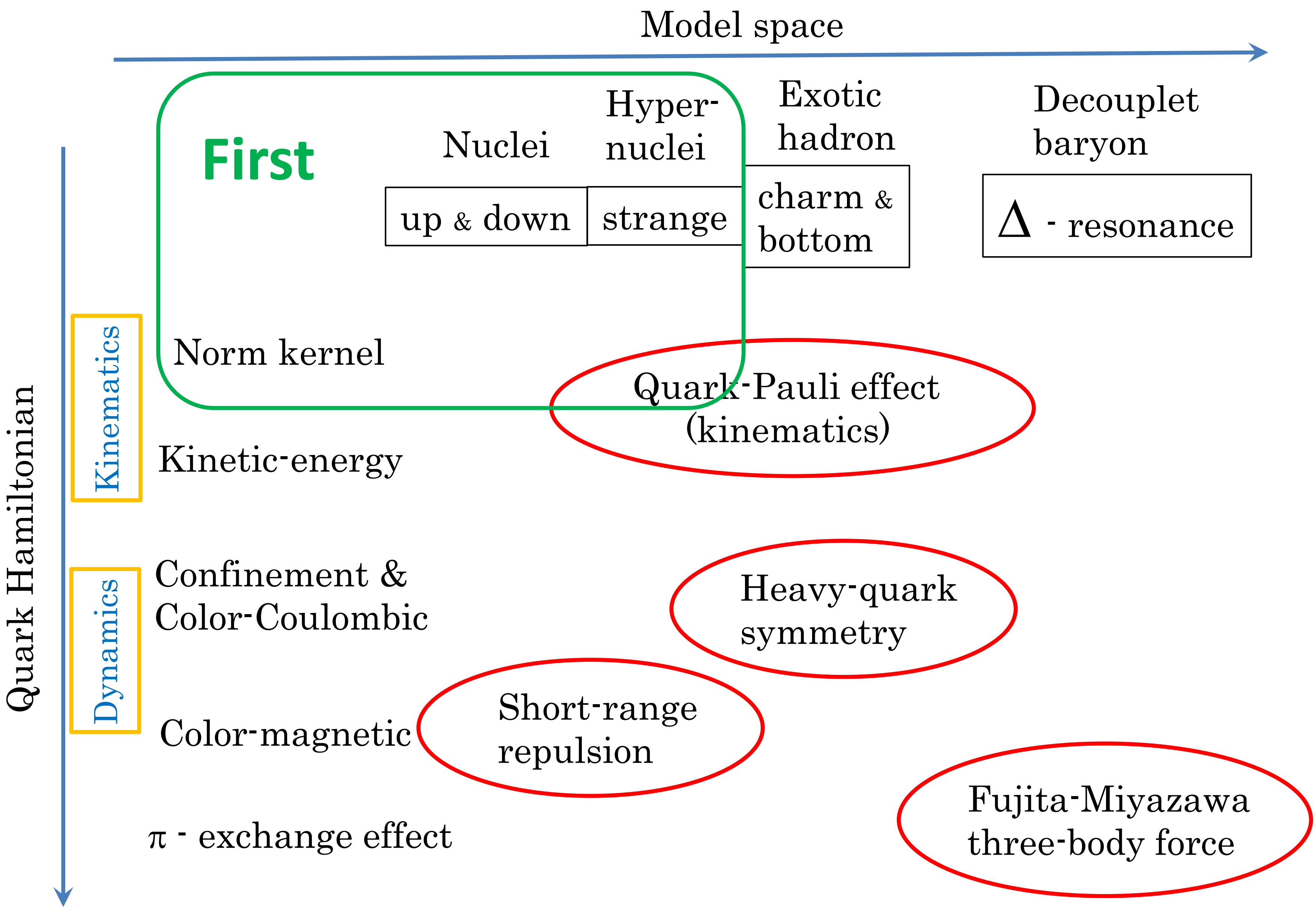
クラスター間での反対称化が必要

~~原子核とのアナロジー~~


q q q
q q q
q q q
n p n
n p n
n p n
confinement, Bag
3 baryons
loosely bound
^{9}Li
Color-symmetryの考慮

先行研究

- Toki, Suzuki, Hecht : PRC26 (1982) 736
  NNN系のノルム核を調べて^{3}He densityに対するPauli効果の検証
- Suzuki, Hecht : PRC29 (1984) 1586
  NNN系におけるFermi-Breit interaction(OGEP)核の評価
- Maltman : NPA439 (1985) 648
  NNN及びNNNN系におけるFB int.のcharge form-factorへの寄与
- Takeuchi, Shimizu : PLB179 (1986) 197
  ΛNN及びΛNNN系のノルム核と運動エネルギー項の評価


Model space
Quark Hamiltonian
First
Nuclei
Hyper-
nuclei
Exotic
hadron
Decouplet
baryon
up & down
strange
charm &
bottom
Δ - resonance
Kinematics
Dynamics
Norm kernel
Kinetic-energy
Quark-Pauli effect
(kinematics)
Confinement &
Color-Coulombic
Heavy-quark
symmetry
Color-magnetic
Short-range
repulsion
π - exchange effect
Fujita-Miyazawa
three-body force

2. クォーク・パウリ効果

2-baryon wave function において

$$\Psi_{B_1 B_2}(1;2) = \frac{1}{\sqrt{2}}\left[\Phi_{B_1}(1)\Phi_{B_2}(2) - \Phi_{B_1}(2)\Phi_{B_2}(1)\right]$$

$$\langle \Psi_{B_1 B_2}(1;2) | \Psi_{B_1 B_2}(1;2) \rangle = 1$$

⇩ クォークの立場から波動関数を表すと・・・

$$\Psi_{(3q)_1 (3q)_2}(123;456) = \mathcal{A}\left\{\frac{1}{\sqrt{2}}\left[\Phi_{(3q)_1}(123)\Phi_{(3q)_2}(456) - \Phi_{(3q)_1}(456)\Phi_{(3q)_2}(123)\right]\right\}$$

クォーク反対称化演算子 ↗ ($\mathcal{A}$)

$$\langle \Psi_{(3q)_1 (3q)_2}(123;456) | \Psi_{(3q)_1 (3q)_2}(123;456) \rangle = \mu$$

μ < 1 : パウリ斥力

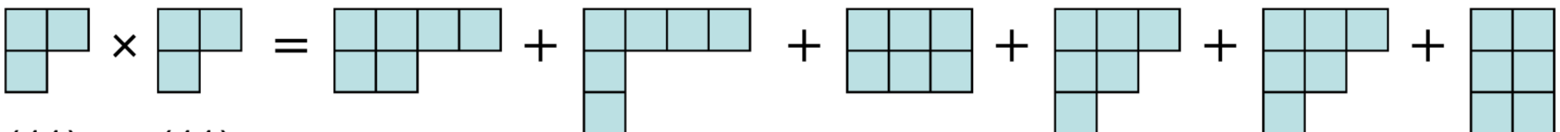
μ = 0 : complete Pauli-forbidden state

μ ~ 0 : almost Pauli-forbidden state

2-baryon system

Overlap components： (color) × (spin-flavor) × $(0s)^6$

Two octet-baryon(B_8B_8) state



(11)	(11)	(22)	(30)	(03)	$(11)_s$	$(11)_a$	(00)
8	8	27	10	10*	8_s	8_a	1

$$\dim(\lambda\mu) = \frac{1}{2}(\lambda+1)(\mu+1)(\lambda+\mu+2)$$

B_8B_8 states : $\underset{8}{(11)} \times \underset{8}{(11)} = \underset{27}{(22)} + \underset{10}{(30)} + \underset{10^*}{(03)} + \underset{8s}{(11)_s} + \underset{8a}{(11)_a} + \underset{1}{(00)}$

S	B_8B_8(isospin)	$\mathcal{P}=+1$(symmetric) ^1E or ^3O	$\mathcal{P}=-1$(antisymmetric) ^3E or ^1O	norm eigenvalue ^1S	norm eigenvalue ^3S
0	$NN(0)$	–	(03)	–	$\frac{10}{9}$
	$NN(1)$	(22)	–	$\frac{10}{9}$	–
−1	ΛN	$\frac{1}{\sqrt{10}}[(11)_s+3(22)]$	$\frac{1}{\sqrt{2}}[-(11)_a+(03)]$	1	1
	$\Sigma N(\frac{1}{2})$	$\frac{1}{\sqrt{10}}[3(11)_s-(22)]$	$\frac{1}{\sqrt{2}}[(11)_a+(03)]$	$\frac{1}{9}$	1
	$\Sigma N(\frac{3}{2})$	(22)	(30)	$\frac{10}{9}$	$\frac{2}{9}$
−2	$\Lambda\Lambda$	$\frac{1}{\sqrt{5}}(11)_s+\frac{9}{2\sqrt{30}}(22)+\frac{1}{2\sqrt{2}}(00)$	–	1	–
	$\Xi N(0)$	$\frac{1}{\sqrt{5}}(11)_s-\sqrt{\frac{3}{10}}(22)+\frac{1}{\sqrt{2}}(00)$	$(11)_a$	$\frac{4}{3}$	$\frac{8}{9}$
	$\Xi N(1)$	$\sqrt{\frac{3}{5}}(11)_s+\sqrt{\frac{2}{5}}(22)$	$\frac{1}{\sqrt{3}}[-(11)_a+(30)+(03)]$	$\frac{4}{9}$	$\frac{20}{27}$
	$\Sigma\Lambda$	$-\sqrt{\frac{2}{5}}(11)_s+\sqrt{\frac{3}{5}}(22)$	$\frac{1}{\sqrt{2}}[(30)-(03)]$	$\frac{2}{3}$	$\frac{2}{3}$
	$\Sigma\Sigma(0)$	$\sqrt{\frac{3}{5}}(11)_s-\frac{1}{2\sqrt{10}}(22)-\sqrt{\frac{3}{8}}(00)$	–	$\frac{7}{9}$	–
	$\Sigma\Sigma(1)$	–	$\frac{1}{\sqrt{6}}[2(11)_a+(30)+(03)]$	–	$\frac{22}{27}$
	$\Sigma\Sigma(2)$	(22)	–	$\frac{10}{9}$	–
−3	$\Xi\Lambda$	$\frac{1}{\sqrt{10}}[(11)_s+3(22)]$	$\frac{1}{\sqrt{2}}[-(11)_a+(30)]$	1	$\frac{5}{9}$
	$\Xi\Sigma(\frac{1}{2})$	$\frac{1}{\sqrt{10}}[3(11)_s-(22)]$	$\frac{1}{\sqrt{2}}[(11)_a+(30)]$	$\frac{1}{9}$	$\frac{5}{9}$
	$\Xi\Sigma(\frac{3}{2})$	(22)	(03)	$\frac{10}{9}$	$\frac{10}{9}$
−4	$\Xi\Xi(0)$	–	(30)	–	$\frac{2}{9}$
	$\Xi\Xi(1)$	(22)	–	$\frac{10}{9}$	–

M. Oka, K. Shimizu and K. Yazaki, NPA464 (1987) 700.

TABLE 4

The eigenvalues of the normalization kernel in eq. (3.3) for $S=-1$ two-baryon (BB) system

$S=-1$

I	J	BB	Eigenvalues (uncoupled)	Eigenvalues (coupled)
$\frac{1}{2}$	0	$N\Lambda$	1	0 $\frac{10}{9}$
		$N\Sigma$	$\frac{1}{9}$	
$\frac{1}{2}$	1	$N\Lambda$	1	$\frac{8}{9}$ $\frac{10}{9}$
		$N\Sigma$	1	
$\frac{3}{2}$	0	$N\Sigma$	$\frac{10}{9}$	
$\frac{3}{2}$	1	$N\Sigma$	$\frac{2}{9}$	

Eigenvalues of single and coupled channels are given.

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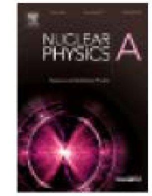

Hyperon single-particle potentials calculated from SU_6 quark-model baryon–baryon interactions

M. Kohno [a], Y. Fujiwara [b], T. Fujita [b], C. Nakamoto [c], Y. Suzuki [d]

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https://doi.org/10.1016/S0375-9474(00)00164-0

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Abstract

Using the SU_6 quark-model baryon–baryon interaction recently developed by the Kyoto –Niigata group, we calculate NN, ΛN and ΣN G -matrices in ordinary nuclear matter. This is the first attempt to discuss the Λ and Σ single-particle potentials in nuclear medium, based on the realistic quark-model potential. The Λ potential has the depth of more than 40 MeV, which is more attractive than the value expected from the experimental data of Λ -hypernuclei. The Σ potential turns out to be repulsive, the origin of which is traced back to the strong Pauli repulsion in the $\Sigma N(I=3/2)\,{}^3S_1$ state.

Sigma-Nucleus Potential in $A = 28$

H. Noumi *et al.*

Phys. Rev. Lett. **89**, 072301 (2002) - Published 30 July 2002

Hide Abstract −

We have studied the (π−,K+) reaction on a silicon target to investigate the sigma-nucleus potential. The inclusive spectrum was measured at a beam momentum of 1.2 GeV/c with an energy resolution of 3.3 MeV (FWHM) by employing the superconducting kaon spectrometer system. The spectrum was compared with theoretical calculations within the framework of the distorted-wave impulse approximation, which demonstrates that a strongly repulsive sigma-nucleus potential with a nonzero size of the imaginary part reproduces the observed spectrum.

3バリオン系でのクォーク・パウリ効果

RGMノルム核の固有値を求めて、quark-Pauli effectを調べる

中性子星核物質における問題意識との関連

コアにおけるハイペロンやK凝縮の
出現による状態方程式の軟化

⇒ 斥力の不足（２体では記述し得ない？）

⇒ multi-baryon系におけるquark縮退圧効果？

どの3バリオン系が、全体として強いパウリ斥力を感じるのか

Formulation

9-quark 3-baryon wave-function

$$\Psi_{Sa}((0s)^9 : B_1 B_2 B_3) = \Psi^{(\mathrm{orb})}(B_1 B_2 B_3)\Psi^{(\mathrm{SF})}_{Sa}(B_1 B_2 B_3)\Psi^{(\mathrm{color})}(B_1 B_2 B_3)$$

$$|(0s)^9\rangle \sim \Psi^{(\mathrm{orb})}(B_1 B_2 B_3)$$

$$\Psi^{(\mathrm{color})}(B_1 B_2 B_3) = C(123)C(456)C(789)$$

We assume the color-singlet for 3*q*-cluster

$$\Psi^{(\mathrm{SF})}_{Sa}(B_1 B_2 B_3) = \sum_{S_{12}(\lambda_{12}\mu_{12})\rho_{12}(\lambda\mu)\rho} G(a_1 a_2 a_3, Sa; S_{12}(\lambda_{12}\mu_{12})\rho_{12}(\lambda\mu)\rho) \times \left[[W^{[3]}(123)W^{[3]}(456)]_{S_{12}(\lambda_{12}\mu_{12})\rho_{12}} W^{[3]}(789)\right]_{S(\lambda\mu)\rho a}.$$

Eigen-value equation

$$\sum_{B_1'B_2'B_3'} \langle \Psi_{Sa}((0s)^9 : B_1B_2B_3)|\frac{1}{6}\mathcal{A}|\Psi_{Sa}((0s)^9 : B_1'B_2'B_3')\rangle C(Sa; B_1'B_2'B_3') = \mu_{Sa} C(Sa; B_1B_2B_3)$$

Antisymmetrizer

$\mu_{Sa} = 0$: Pauli forbidden state

$\mu_{Sa} \sim 0$: almost Pauli forbidden state

⇓

so much repulsive that μ_{Sa} is smaller

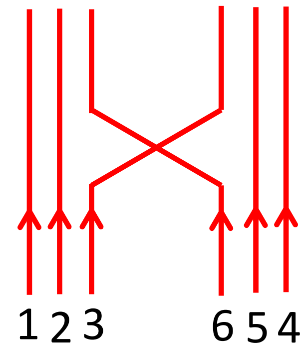
Antisymmetrizer

2-baryon system

Antisymmetrizer $\mathcal{A} = (1 - \mathcal{P})(1 - 9\, P_{36})$

baryon-exchange operator

quark -exchange operator



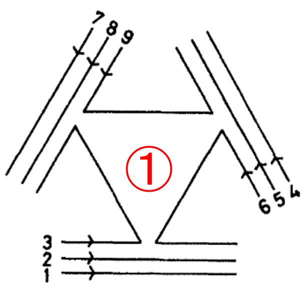
20 terms

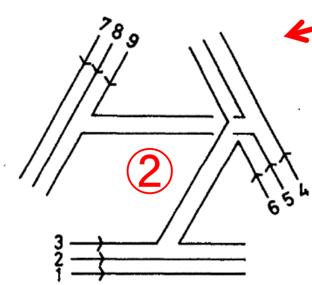
3-baryon system

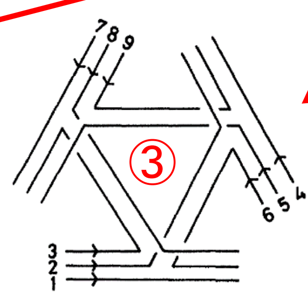
$$
\begin{aligned}
\mathcal{A} \ = \ & [1 \\
& -9\,(P_{36} + P_{69} + P_{93}) \\
& +27\,(P_{369} + P_{396}) \\
& +54\,(P_{36}P_{59} + P_{69}P_{83} + P_{93}P_{26})\,] \times \left[\sum_{\mathcal{P}=1}^{6} (-1)^{\pi(\mathcal{P})}\mathcal{P}\right] \\
& -216\, P_{26}P_{59}P_{83}
\end{aligned}
$$

D-term

2B-term







762 terms

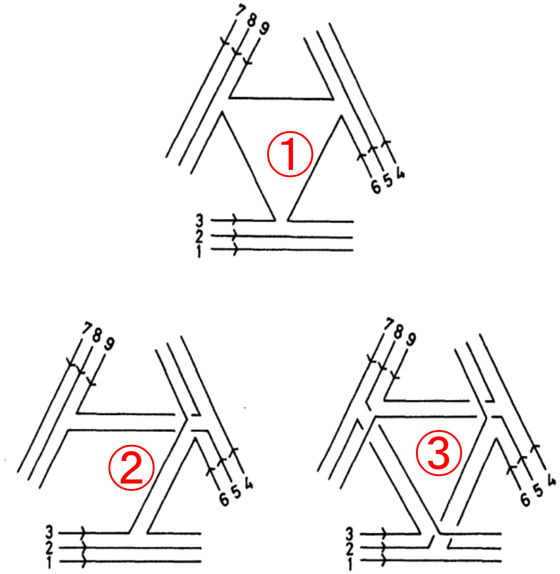
3-baryon system

kernel の構成　(color) × (spin-flavor) × (orbital)

各バリオンのcolor-singlet condition

D−term	2B−term	① 3Ba	② 3Bb	③ 3Bc
1	$\frac{1}{3}$	$\frac{1}{9}$	$\frac{1}{9}$	0

③3Bc を考える必要なし



Total Spin ½ case

$\Lambda n n$ $\Sigma^- n n$ $\Lambda\Lambda n$ $\Xi^- n n$ $\Sigma^-\Sigma^- n$ $\Xi^-\Xi^- n$

Y	I	$B_8B_8B_8$	uncoupled	coupled
3	$\frac{1}{2}$	NNN	$\frac{100}{81}$	–
2	0	ΛNN	$\frac{25}{27}$	$0, \frac{100}{81}$
		ΣNN	$\frac{25}{81}$	
	1	ΛNN	$\frac{25}{27}$	$0, \frac{200}{243}, \frac{100}{81}$
		$\Sigma NN_{v=1}$	$\frac{50}{81}$	
		$\Sigma NN_{v=2}$	$\frac{125}{243}$	
	2	ΣNN	$\frac{4}{81}$	–
1	$\frac{1}{2}$	$\Xi NN_{v=1}$	$\frac{25}{27}$	$0, 0, 0, 0, \frac{200}{243}, \frac{100}{81}, \frac{130}{81}$
		$\Xi NN_{v=2}$	$\frac{35}{81}$	
		$\Lambda\Lambda N$	$\frac{5}{6}$	
		$\Sigma\Sigma N_{v=1}$	$\frac{85}{162}$	
		$\Sigma\Sigma N_{v=2}$	$\frac{35}{243}$	
		$\Sigma\Lambda N_{v=1}$	$\frac{5}{9}$	
		$\Sigma\Lambda N_{v=2}$	$\frac{20}{81}$	
	$\frac{3}{2}$	ΞNN	$\frac{10}{27}$	$0, 0, \frac{4}{81}, \frac{200}{243}, \frac{100}{81}$
		$\Sigma\Sigma N_{v=1}$	$\frac{73}{162}$	
		$\Sigma\Sigma N_{v=2}$	$\frac{235}{486}$	
		$\Sigma\Lambda N_{v=1}$	$\frac{5}{18}$	
		$\Sigma\Lambda N_{v=2}$	$\frac{85}{162}$	
	$\frac{5}{2}$	$\Sigma\Sigma N$	$\frac{4}{81}$	–

Y	I	$B_8B_8B_8$	uncoupled	coupled
0	0	$\Xi\Lambda N_{v=1}$	$\frac{5}{6}$	$0, 0, 0, \frac{200}{243}, \frac{130}{81}$
		$\Xi\Lambda N_{v=2}$	$\frac{55}{54}$	
		$\Xi\Sigma N_{v=1}$	$\frac{5}{54}$	
		$\Xi\Sigma N_{v=2}$	$\frac{55}{486}$	
		$\Sigma\Sigma\Lambda$	$\frac{10}{27}$	
	1	$\Xi\Lambda N_{v=1}$	$\frac{33}{54}$	$0, 0, 0, 0, 0, \frac{4}{81}, \frac{200}{243}, \frac{100}{81}, \frac{130}{81}$
		$\Xi\Lambda N_{v=2}$	$\frac{17}{162}$	
		$\Xi\Sigma N_{v=1}$	$\frac{11}{162}$	
		$\Xi\Sigma N_{v=2}$	$\frac{17}{27}$	
		$\Xi\Sigma N_{v=3}$	$\frac{673}{1458}$	
		$\Xi\Sigma N_{v=4}$	$\frac{295}{729}$	
		$\Sigma\Lambda\Lambda$	$\frac{4}{9}$	
		$\Sigma\Sigma\Lambda$	$\frac{23}{81}$	
		$\Sigma\Sigma\Sigma$	$\frac{19}{27}$	
	2	$\Xi\Sigma N_{v=1}$	$\frac{1}{3}$	$0, \frac{4}{81}, \frac{200}{243}, \frac{100}{81}$
		$\Xi\Sigma N_{v=2}$	$\frac{125}{243}$	
		$\Sigma\Sigma\Lambda$	$\frac{13}{27}$	
		$\Sigma\Sigma\Sigma$	$\frac{7}{9}$	

Y	I	$B_8B_8B_8$	uncoupled	coupled
−1	$\frac{1}{2}$	$\Xi\Xi N_{v=1}$	$\frac{17}{81}$	$0, 0, 0, 0, \frac{4}{81}, \frac{200}{243}, \frac{130}{81}$
		$\Xi\Xi N_{v=2}$	$\frac{73}{81}$	
		$\Xi\Lambda\Lambda$	$\frac{1}{2}$	
		$\Xi\Sigma\Sigma_{v=1}$	$\frac{83}{162}$	
		$\Xi\Sigma\Sigma_{v=2}$	$\frac{17}{243}$	
		$\Xi\Sigma\Lambda_{v=1}$	$\frac{1}{36}$	
		$\Xi\Sigma\Lambda_{v=2}$	$\frac{83}{324}$	
	$\frac{3}{2}$	$\Xi\Xi N$	$\frac{34}{81}$	$0, 0, \frac{4}{81}, \frac{200}{243}, \frac{100}{81}$
		$\Xi\Sigma\Sigma_{v=1}$	$\frac{35}{162}$	
		$\Xi\Sigma\Sigma_{v=2}$	$\frac{253}{486}$	
		$\Xi\Sigma\Lambda_{v=1}$	$\frac{1}{3}$	
		$\Xi\Sigma\Lambda_{v=2}$	$\frac{50}{81}$	
	$\frac{5}{2}$	$\Xi\Sigma\Sigma$	$\frac{100}{81}$	–
−2	0	$\Xi\Xi\Lambda$	$\frac{1}{27}$	$0, \frac{4}{81}$
		$\Xi\Xi\Sigma$	$\frac{1}{81}$	
	1	$\Xi\Xi\Lambda$	$\frac{13}{27}$	$0, \frac{4}{81}, \frac{200}{243}$
		$\Xi\Xi\Sigma_{v=1}$	$\frac{26}{81}$	
		$\Xi\Xi\Sigma_{v=2}$	$\frac{17}{243}$	
	2	$\Xi\Xi\Sigma$	$\frac{100}{81}$	–
−3	$\frac{1}{2}$	$\Xi\Xi\Xi$	$\frac{4}{81}$	–

Total Spin ½ case

Y	I	$B_8B_8B_8$	uncoupled	coupled
3	$\frac{1}{2}$	NNN	$\frac{100}{81}$	–
2	0	ΛNN	$\frac{25}{27}$	$0\,,\ \frac{100}{81}$
		ΣNN	$\frac{25}{81}$	
	1	ΛNN	$\frac{25}{27}$	$0\,,\ \frac{200}{243}\,,\ \frac{100}{81}$
		$\Sigma NN_{v=1}$	$\frac{50}{81}$	
		$\Sigma NN_{v=2}$	$\frac{125}{243}$	
	2	ΣNN	$\frac{4}{81}$	–
1	$\frac{1}{2}$	$\Xi NN_{v=1}$	$\frac{25}{27}$	$0\,,\ 0\,,\ 0\,,\ 0\,,\ \frac{200}{243}\,,\ \frac{100}{81}\,,\ \frac{130}{81}$
		$\Xi NN_{v=2}$	$\frac{35}{81}$	
		$\Lambda\Lambda N$	$\frac{5}{6}$	
		$\Sigma\Sigma N_{v=1}$	$\frac{85}{162}$	
		$\Sigma\Sigma N_{v=2}$	$\frac{35}{243}$	
		$\Sigma\Lambda N$ [illegible]	[illegible]	
		$\Sigma\Lambda N$ [illegible]	[illegible]	
	$\frac{3}{2}$	ΞNN	$\frac{10}{27}$	$0\,,\ 0\,,\ \frac{4}{81}\,,\ \frac{200}{243}\,,\ \frac{100}{81}$
		$\Sigma\Sigma N_{v=1}$	$\frac{73}{162}$	
		$\Sigma\Sigma N_{v=2}$	$\frac{235}{486}$	
		$\Sigma\Lambda N_{v=1}$	$\frac{5}{18}$	
		$\Sigma\Lambda N_{v=2}$	$\frac{85}{162}$	
	$\frac{5}{2}$	$\Sigma\Sigma N$	$\frac{4}{81}$	–

Y	I	$B_8B_8B_8$	uncoupled	coupled
0	0	$\Xi\Lambda N_{v=1}$	$\frac{5}{6}$	$0\,,\ 0\,,\ 0\,,\ \frac{200}{243}\,,\ \frac{130}{81}$
		$\Xi\Lambda N_{v=2}$	$\frac{55}{54}$	
		$\Xi\Sigma N_{v=1}$	$\frac{5}{54}$	
		$\Xi\Sigma N_{v=2}$	$\frac{55}{486}$	
		$\Sigma\Sigma\Lambda$	$\frac{10}{27}$	
	1	$\Xi\Lambda N_{v=1}$	$\frac{33}{54}$	$0\,,\ 0\,,\ 0\,,\ 0\,,\ 0\,,\ \frac{4}{81}\,,\ \frac{200}{243}\,,\ \frac{100}{81}\,,\ \frac{130}{81}$
		$\Xi\Lambda N_{v=2}$	$\frac{17}{162}$	
		$\Xi\Sigma N_{v=1}$	$\frac{11}{162}$	
		$\Xi\Sigma N_{v=2}$	$\frac{17}{27}$	
		$\Xi\Sigma N_{v=3}$	$\frac{673}{1458}$	
		$\Xi\Sigma N_{v=4}$	$\frac{295}{729}$	
		[illegible]	[illegible]	
		$\Sigma\Sigma\Sigma$	$\frac{19}{27}$	
	2	$\Xi\Sigma N_{v=1}$	$\frac{1}{3}$	$0\,,\ \frac{4}{81}\,,\ \frac{200}{243}\,,\ \frac{100}{81}$
		$\Xi\Sigma N_{v=2}$	$\frac{125}{243}$	
		$\Sigma\Sigma\Lambda$	$\frac{13}{27}$	
		$\Sigma\Sigma\Sigma$	$\frac{7}{9}$	

Y	I	$B_8B_8B_8$	uncoupled	coupled
−1	$\frac{1}{2}$	$\Xi\Xi N_{v=1}$	$\frac{17}{81}$	$0\,,\ 0\,,\ 0\,,\ 0\,,\ \frac{4}{81}\,,\ \frac{200}{243}\,,\ \frac{130}{81}$
		$\Xi\Xi N_{v=2}$	$\frac{73}{81}$	
		$\Xi\Lambda\Lambda$	$\frac{1}{2}$	
		$\Xi\Sigma\Sigma_{v=1}$	$\frac{83}{162}$	
		$\Xi\Sigma\Sigma_{v=2}$	$\frac{17}{243}$	
		$\Xi\Sigma\Lambda_{v=1}$	$\frac{1}{36}$	
		$\Xi\Sigma\Lambda_{v=2}$	$\frac{83}{324}$	
	$\frac{3}{2}$	$\Xi\Xi N$	$\frac{34}{81}$	$0\,,\ 0\,,\ \frac{4}{81}\,,\ \frac{200}{243}\,,\ \frac{100}{81}$
		$\Xi\Sigma\Sigma_{v=1}$	$\frac{35}{162}$	
		$\Xi\Sigma\Sigma_{v=2}$	$\frac{253}{486}$	
		$\Xi\Sigma\Lambda_{v=1}$	$\frac{1}{3}$	
		$\Xi\Sigma\Lambda_{v=2}$	$\frac{50}{81}$	
	$\frac{5}{2}$	$\Xi\Sigma\Sigma$	$\frac{100}{81}$	–
−2	0	$\Xi\Xi\Lambda$	$\frac{1}{27}$	$0\,,\ \frac{4}{81}$
		$\Xi\Xi\Sigma$	$\frac{1}{81}$	
	1	$\Xi\Xi\Lambda$	$\frac{13}{27}$	$0\,,\ \frac{4}{81}\,,\ \frac{200}{243}$
		$\Xi\Xi\Sigma_{v=1}$	$\frac{26}{81}$	
		$\Xi\Xi\Sigma_{v=2}$	$\frac{17}{243}$	
	2	$\Xi\Xi\Sigma$	$\frac{100}{81}$	–
−3	$\frac{1}{2}$	$\Xi\Xi\Xi$	$\frac{4}{81}$	–

Λnn

$\Sigma^- nn$

$\Lambda\Lambda n$

$\Xi^- nn$

$\Sigma^-\Sigma^- n$

$\Xi^-\Xi^- n$

Strong Pauli-repulsion

Total Spin 3/2 case

Y	I	$B_8B_8B_8$	uncoupled	coupled
2	0	ΛNN	$\frac{25}{27}$	–
	1	ΣNN	$\frac{35}{243}$	–
1	$\frac{1}{2}$	ΞNN	$\frac{50}{81}$	$\frac{35}{243}$, $\frac{5}{9}$, $\frac{25}{27}$
		$\Sigma\Sigma N$	$\frac{95}{243}$	
		$\Sigma\Lambda N$	$\frac{50}{81}$	
	$\frac{3}{2}$	$\Sigma\Sigma N$	$\frac{31}{486}$	$\frac{1}{27}$, $\frac{35}{243}$
		$\Sigma\Lambda N$	$\frac{19}{162}$	
0	0	$\Xi\Lambda N$	$\frac{20}{27}$	$\frac{35}{243}$, $\frac{5}{9}$, $\frac{35}{27}$
		$\Xi\Sigma N$	$\frac{140}{243}$	
		$\Sigma\Sigma\Sigma$	$\frac{55}{81}$	
	1	$\Xi\Lambda N$	$\frac{34}{81}$	$\frac{1}{27}$, $\frac{35}{243}$, $\frac{5}{9}$, $\frac{25}{27}$
		$\Xi\Sigma N_{v=1}$	$\frac{134}{729}$	
		$\Xi\Sigma N_{v=2}$	$\frac{565}{729}$	
		$\Sigma\Sigma\Lambda$	$\frac{23}{81}$	
	2	$\Xi\Sigma N$	$\frac{35}{243}$	–
−1	$\frac{1}{2}$	$\Xi\Xi N$	$\frac{14}{81}$	$\frac{1}{27}$, $\frac{35}{243}$, $\frac{5}{9}$
		$\Xi\Sigma\Sigma$	$\frac{95}{243}$	
		$\Xi\Sigma\Lambda$	$\frac{14}{81}$	
	$\frac{3}{2}$	$\Xi\Sigma\Sigma$	$\frac{355}{486}$	$\frac{35}{243}$, $\frac{25}{27}$
		$\Xi\Sigma\Lambda$	$\frac{55}{162}$	
−2	0	$\Xi\Xi\Lambda$	$\frac{1}{27}$	–
	1	$\Xi\Xi\Sigma$	$\frac{35}{243}$	–

$\Sigma^-\Lambda n$

$\Xi^-\Sigma^- n$

$\Xi^-\Sigma^-\Lambda$

Total Spin 3/2 case

Y	I	$B_8B_8B_8$	uncoupled	coupled
2	0	ΛNN	$\frac{25}{27}$	–
	1	ΣNN	$\frac{35}{243}$	–
1	$\frac{1}{2}$	ΞNN	$\frac{50}{81}$	$\frac{35}{243}, \frac{5}{9}, \frac{25}{27}$
		$\Sigma\Sigma N$	$\frac{95}{243}$	
		$\Sigma\Lambda N$	$\frac{50}{81}$	
	$\frac{3}{2}$	$\Sigma\Sigma N$	$\frac{31}{486}$	$\frac{1}{27}, \frac{35}{243}$
		$\Sigma\Lambda N$	$\frac{19}{162}$	
0	0	$\Xi\Lambda N$	$\frac{20}{27}$	$\frac{35}{243}, \frac{5}{9}, \frac{35}{27}$
		$\Xi\Sigma N$	$\frac{140}{243}$	
		$\Sigma\Sigma\Sigma$	$\frac{55}{81}$	
	1	$\Xi\Lambda N$	$\frac{34}{81}$	$\frac{1}{27}, \frac{35}{243}, \frac{5}{9}, \frac{25}{27}$
		$\Xi\Sigma N_{v=1}$	$\frac{134}{729}$	
		$\Xi\Sigma N_{v=2}$	$\frac{565}{729}$	
		$\Sigma\Sigma\Lambda$	$\frac{23}{81}$	
	2	$\Xi\Sigma N$	$\frac{35}{243}$	–
−1	$\frac{1}{2}$	$\Xi\Xi N$	$\frac{14}{81}$	$\frac{1}{27}, \frac{35}{243}, \frac{5}{9}$
		$\Xi\Sigma\Sigma$	$\frac{95}{243}$	
		$\Xi\Sigma\Lambda$	$\frac{14}{81}$	
	$\frac{3}{2}$	$\Xi\Sigma\Sigma$	$\frac{355}{486}$	$\frac{35}{243}, \frac{25}{27}$
		$\Xi\Sigma\Lambda$	$\frac{55}{162}$	
−2	0	$\Xi\Xi\Lambda$	$\frac{1}{27}$	–
	1	$\Xi\Xi\Sigma$	$\frac{35}{243}$	–

$\Sigma^-\Lambda n$

$\Xi^-\Sigma^-n$

$\Xi^-\Sigma^-\Lambda$

Strong Pauli-repulsion

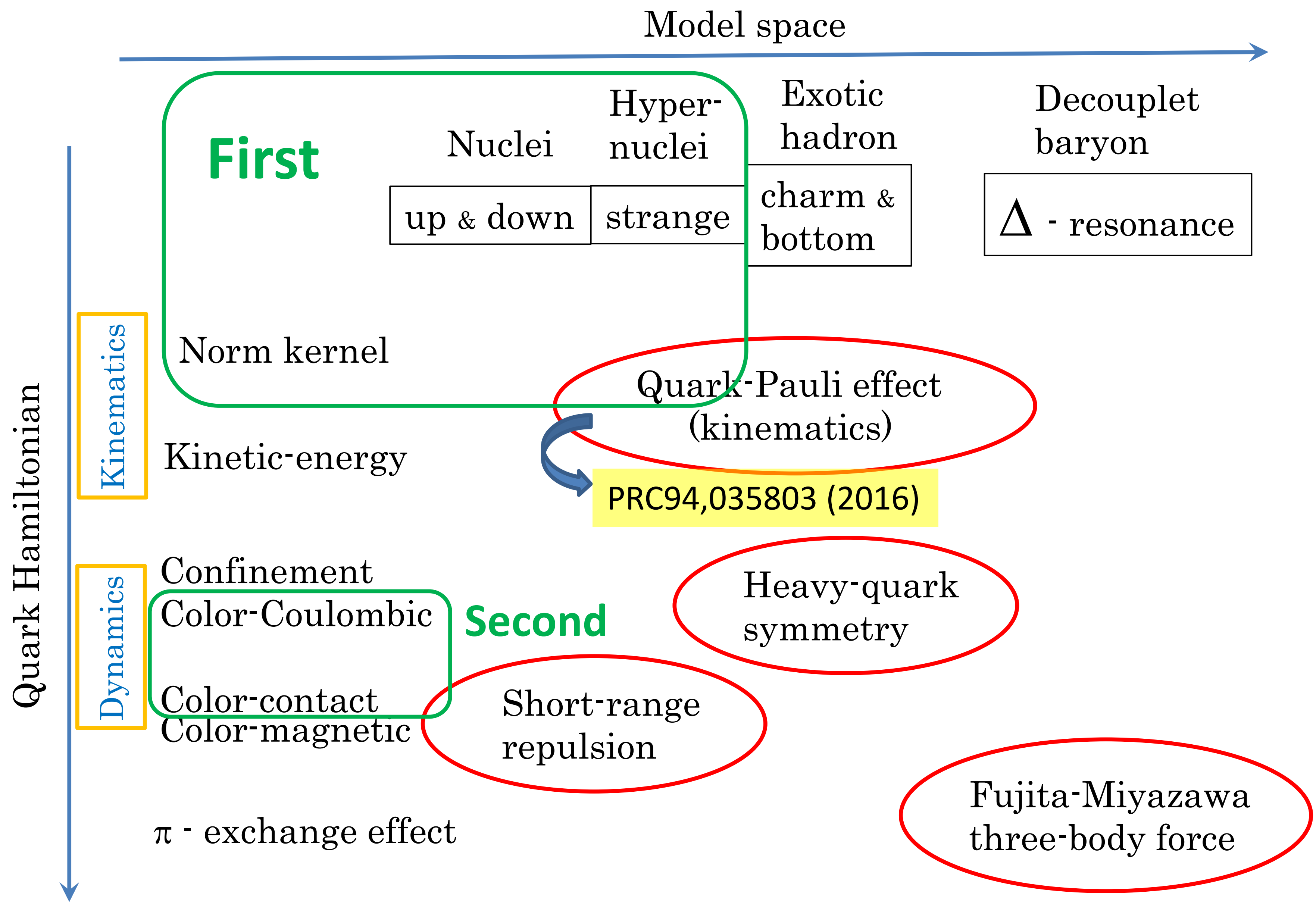
３体バリオン系における クォーク･パウリ効果のまとめ

$(0s)^9$ configuration において反対称化演算子の固有値方程式を解くことによって、３バリオン系におけるquark-Pauliの効果について調べた。

ΛNN系については、quark-Pauli効果は小さい
⇒　重い中性子星を支えるために必要とされる斥力として、
　　バリオンの構造的斥力効果はその役割を担えない

ΣNN(I=2)系、ΣΣN(I=5/2)系は、almost Pauli-forbidden state
⇒　Σ^-が中性子星内部に現れるのを邪魔する働きをする

PRC94,035803 (2016)


Model space
Quark Hamiltonian
Kinematics
Dynamics
First
Nuclei
Hyper-
nuclei
Exotic
hadron
Decouplet
baryon
up & down
strange
charm &
bottom
Δ - resonance
Norm kernel
Kinetic-energy
Quark-Pauli effect
(kinematics)
PRC94,035803 (2016)
Confinement
Color-Coulombic
Second
Heavy-quark
symmetry
Color-contact
Color-magnetic
Short-range
repulsion
Fujita-Miyazawa
three-body force
π - exchange effect

３．ノルム核に比例する３体バリオン相関

Resonating-group method (RGM) equation

3-baryon system

$$\left[-\frac{\hbar^2}{2\mu_1}\Delta_{R_{12}}-\frac{\hbar^2}{2\mu_2}\Delta_{R_{12-3}}\right]\chi(\vec{R}_{12},\vec{R}_{12-3})+\int\int \underline{K(\vec{R}'_{12},\vec{R}'_{12-3};\vec{R}_{12},\vec{R}_{12-3})}\chi(\vec{R}'_{12},\vec{R}'_{12-3})d\vec{R}'_{12}d\vec{R}'_{12-3}=\varepsilon\chi(\vec{R}_{12},\vec{R}_{12-3})$$

↓

Exchange RGM kernel

(non-local potential)

Diagonal element $K(\vec{R}_{12},\vec{R}_{12-3};\vec{R}_{12},\vec{R}_{12-3})$ を評価することで、
定性的な3体効果を調べる

We can now write down the RGM equation for the relative-motion function $\chi_\alpha(\boldsymbol{r})$ as

$$\left[\varepsilon_\alpha+\frac{\hbar^2}{2\mu_\alpha}\left(\frac{\partial}{\partial \boldsymbol{R}}\right)^2\right]\chi_\alpha(\boldsymbol{R})=\sum_{\alpha'}\int d\boldsymbol{R}' G_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')\chi_{\alpha'}(\boldsymbol{R}')\,, \tag{3·17}$$

where the relative energy ε_α in the channel α is related to the total energy E of the system through $\varepsilon_\alpha=E-E^{\rm int}_{a_1}-E^{\rm int}_{a_2}$, and the exchange kernel $G_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')$ is given by

$$G_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')=\sum_\Omega \mathcal{M}^{(\Omega)}_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')-\varepsilon_\alpha\mathcal{M}^N_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')\,. \tag{3·18}$$

The summation in Eq. (3·18) is over $\Omega=K$, CC, MC, GC, sLS, aLS and T of Eq. (3·4), among which the central components $\Omega=K$, CC, MC and GC need subtraction of the internal-energy contributions through

$$\mathcal{M}^{(\Omega)}_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')=\mathcal{M}^{(\Omega)\rm exch}_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')-(E^{(\Omega)}_{a_1}+E^{(\Omega)}_{a_2})\mathcal{M}^N_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')\,. \tag{3·19}$$

In Eqs. (3·18) and (3·19), $\mathcal{M}^N_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')$ and $\mathcal{M}^{(\Omega)\rm exch}_{\alpha\alpha'}(\boldsymbol{R},\boldsymbol{R}')$ are the exchange normalization and interaction (of the type Ω) kernels, respectively, and the internal energies are subtracted in the prior form. The exchange kernel in Eq. (3·19), which is derived analytically for each piece of the interaction, has the advantage that it is free from the internal-energy contribution. In particular, the mass term of the kinetic-energy operator T_i and the confinement potential with $\Omega=Cf$ exactly cancel out between the exchange part and the internal-energy contribution in Eq. (3·19).

Quark-Hamiltonian

$$H^{\mathrm{K+conf.+FB}} = \sum_i \frac{1}{2m_i}\boldsymbol{p}_i^2$$

confinement

$$+\sum_{i<j}\left(\lambda_i^c\cdot\lambda_j^c\right)v_c(r_{ij})$$

Color-Coulombic

$$+\sum_{i<j}\frac{1}{4}\alpha_S\hbar c\left(\lambda_i^c\cdot\lambda_j^c\right)\frac{1}{r_{ij}}$$

Color-contact

$$+\sum_{i<j}\frac{1}{4}\alpha_S\hbar c\left(\lambda_i^c\cdot\lambda_j^c\right)\left\{-\frac{\pi\hbar^2}{2c^2}\left(\frac{1}{m_i^2}+\frac{1}{m_j^2}\right)\delta(r_{ij})\right\}$$

Color-magnetic

$$+\sum_{i<j}\frac{1}{4}\alpha_S\hbar c\left(\lambda_i^c\cdot\lambda_j^c\right)\left\{-\frac{2\pi\hbar^2}{3m_im_jc^2}\delta(r_{ij})\left(\boldsymbol{\sigma}_i\cdot\boldsymbol{\sigma}_j\right)\right\}$$

（FSBを無視すれば）
Norm kernelの
Spin-flavor factorが
使える

Diagonal exchange RGM kernel

$$K(\vec{R}_{12}, \vec{R}_{12-3}; \vec{R}_{12}, \vec{R}_{12-3})$$

$$= \frac{1}{3!} \left\langle \phi(1,2,3)_{SI} \delta(\vec{R}_{12} - \vec{R}_a) \delta(\vec{R}_{12-3} - \vec{R}_b) \right.$$

$$\left. \times \left| \sum_{i<j} (\lambda_i \cdot \lambda_j) \frac{1}{r_{ij}} \left(\mathcal{A} - \sum_{\mathcal{P}=1}^{6} (-1)^{\pi(\mathcal{P})} \mathcal{P} \right) \right| \phi(1,2,3)_{SI} \delta(\vec{R}_{12} - \vec{R}_a) \delta(\vec{R}_{12-3} - \vec{R}_b) \right\rangle$$

反対称化演算子 $\mathcal{A}$ $= [1$ D-term

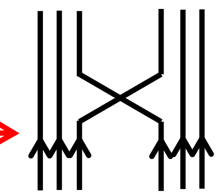
$-9\,(P_{36} + P_{69} + P_{93})$ 2B-term

$+27\,(P_{369} + P_{396})$

$+54\,(P_{36}P_{59} + P_{69}P_{83} + P_{93}P_{26})] \times \left[\sum_{\mathcal{P}=1}^{6} (-1)^{\pi(\mathcal{P})} \mathcal{P} \right]$

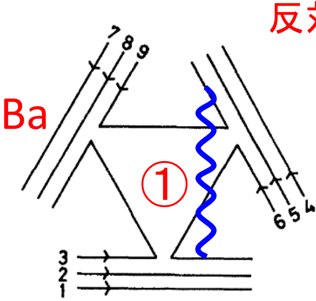
$-216\,P_{26}P_{59}P_{83}$

3体効果！

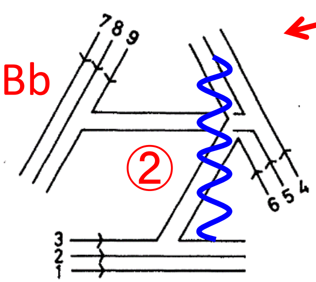


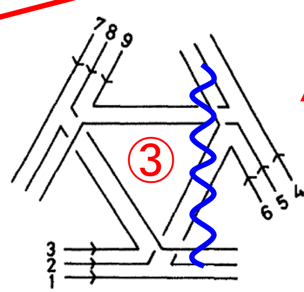
baryon-exchange operator

3Ba



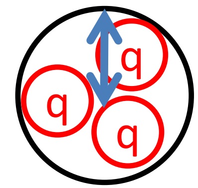
3Bb





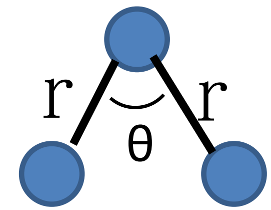
3Bc

Width parameter $b = 0.6$ fm
Quark mass $mc^2 = 313$ MeV とする。



NNN
ΛNN(I=0,1)
ΣNN(I=2)
ΞNN(I=3/2)
ΞΞΞ(I=1/2)

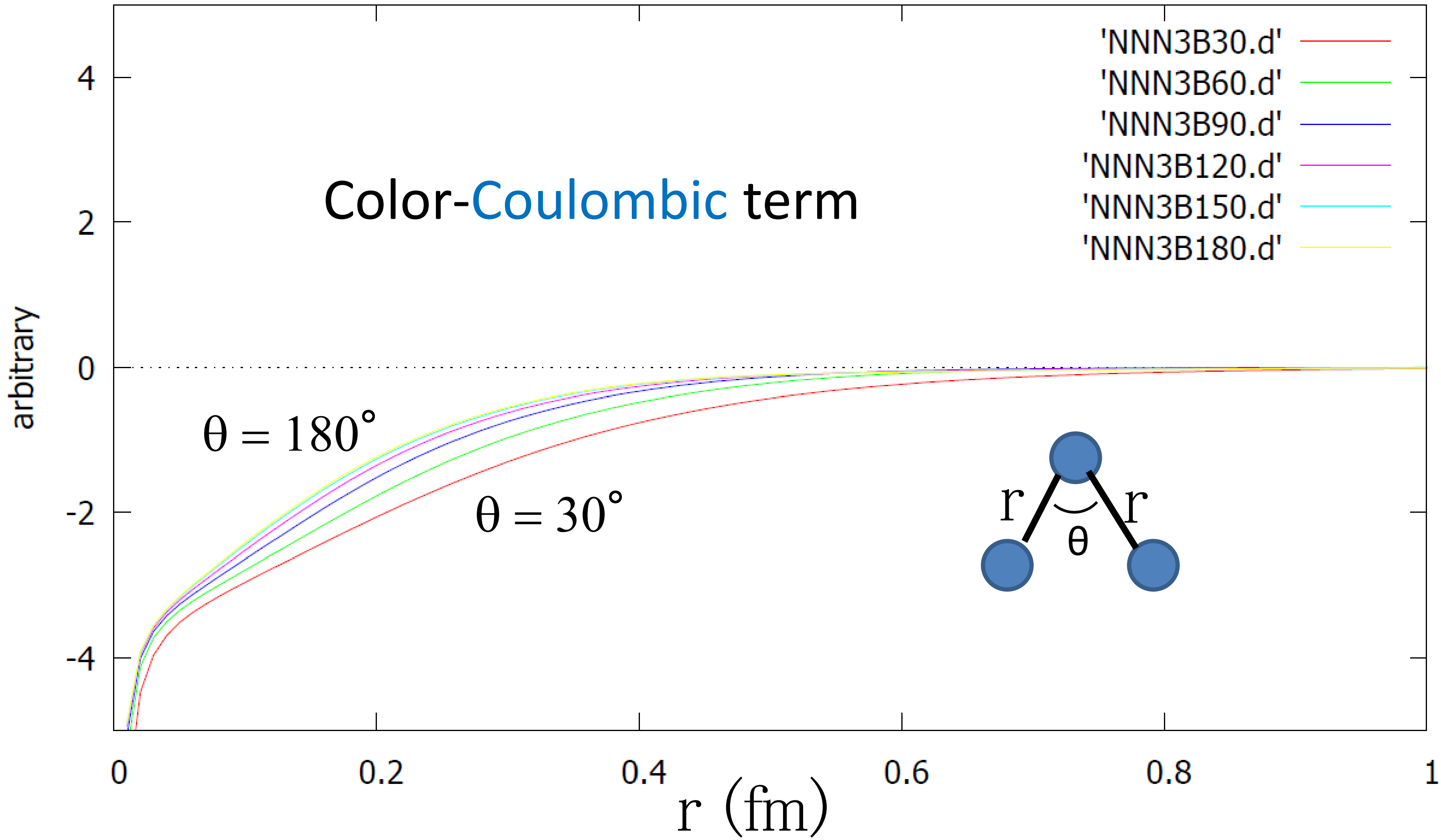
の各系について、
二等辺三角形状態
について調べる



大きさは共通の量を計算するだけで任意の単位とし、
kernelの定性的特徴を調べる

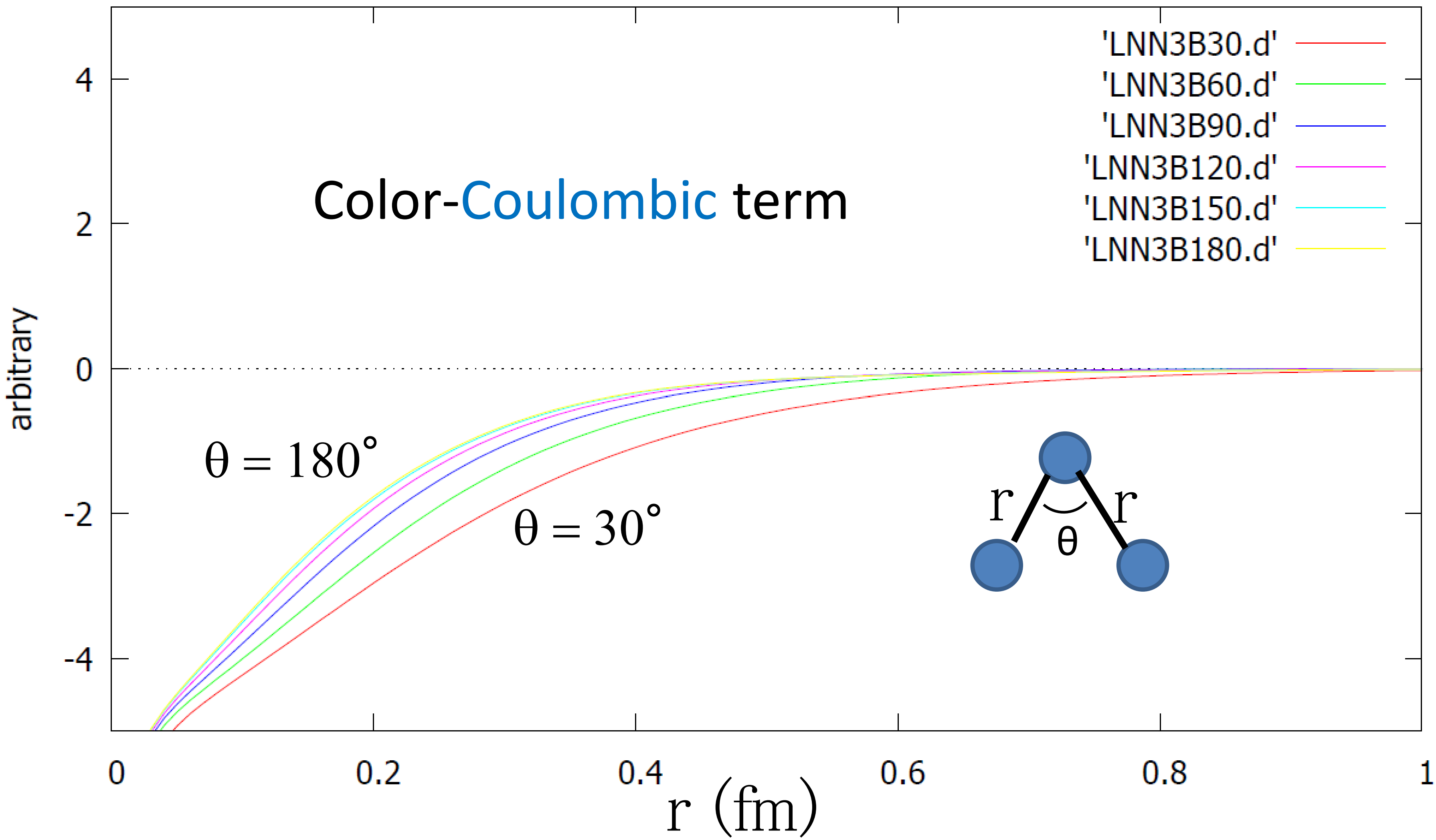
一部、発散する項は除く

NNN(I = 1/2)



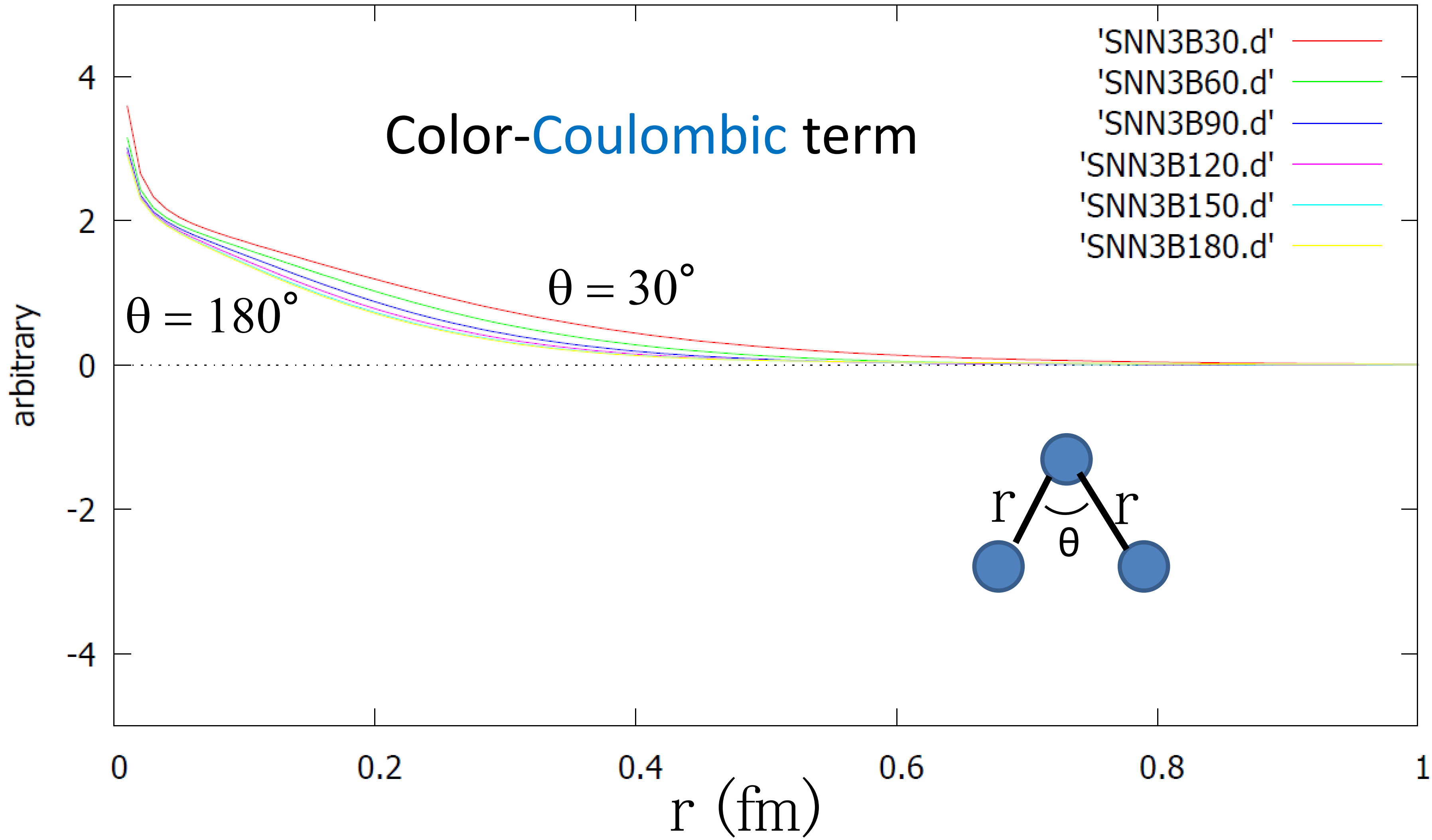
'NNN3B30.d'
'NNN3B60.d'
'NNN3B90.d'
'NNN3B120.d'
'NNN3B150.d'
'NNN3B180.d'
Color-Coulombic term
θ = 180°
θ = 30°
r
r
θ
arbitrary
4
2
0
-2
-4
0
0.2
0.4
0.6
0.8
1
r (fm)

ΛNN



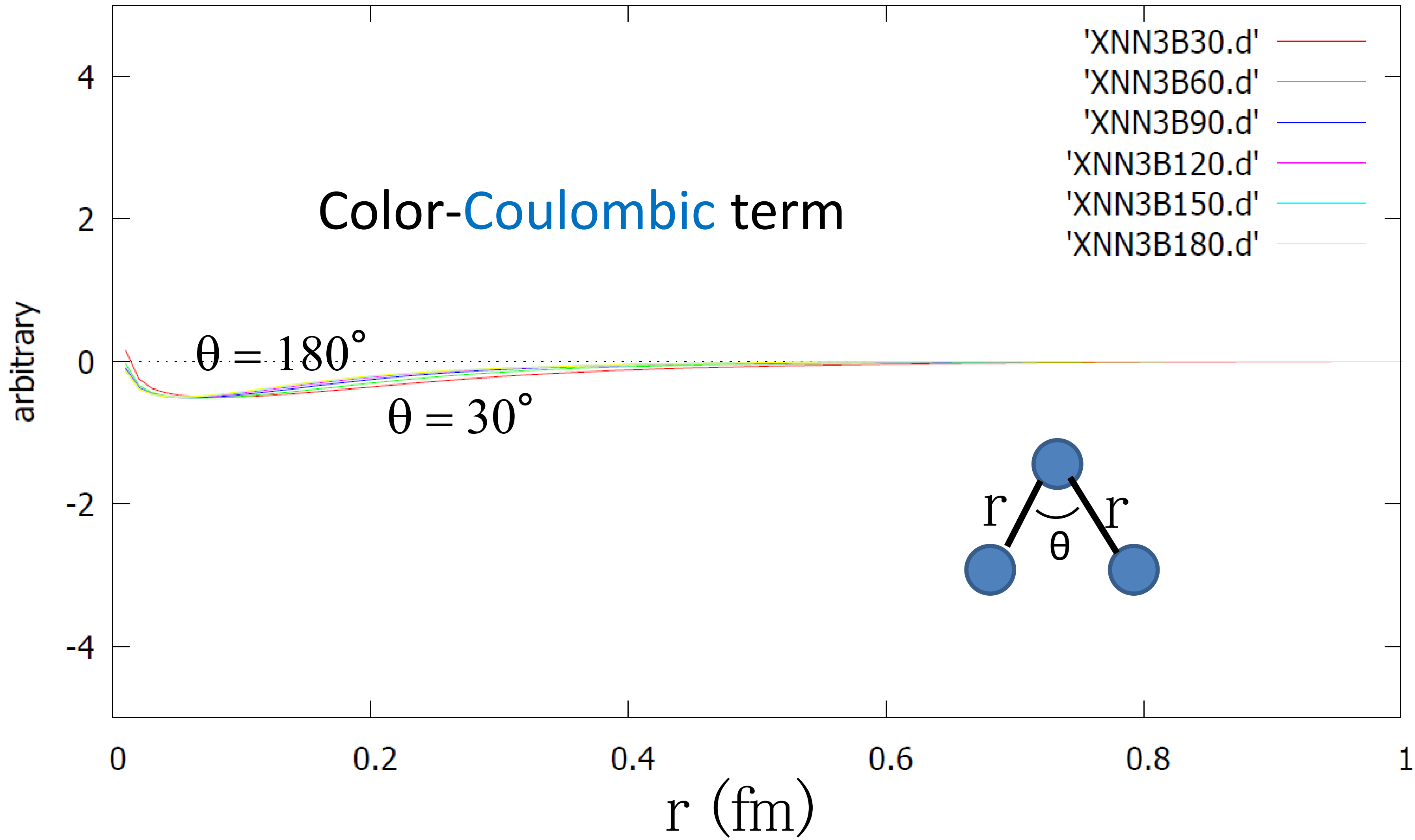
4
2
0
-2
-4
arbitrary
'LNN3B30.d'
'LNN3B60.d'
'LNN3B90.d'
'LNN3B120.d'
'LNN3B150.d'
'LNN3B180.d'
Color-Coulombic term
θ = 180°
θ = 30°
r
r
θ
0
0.2
0.4
0.6
0.8
1
r (fm)

ΣNN (I = 2)



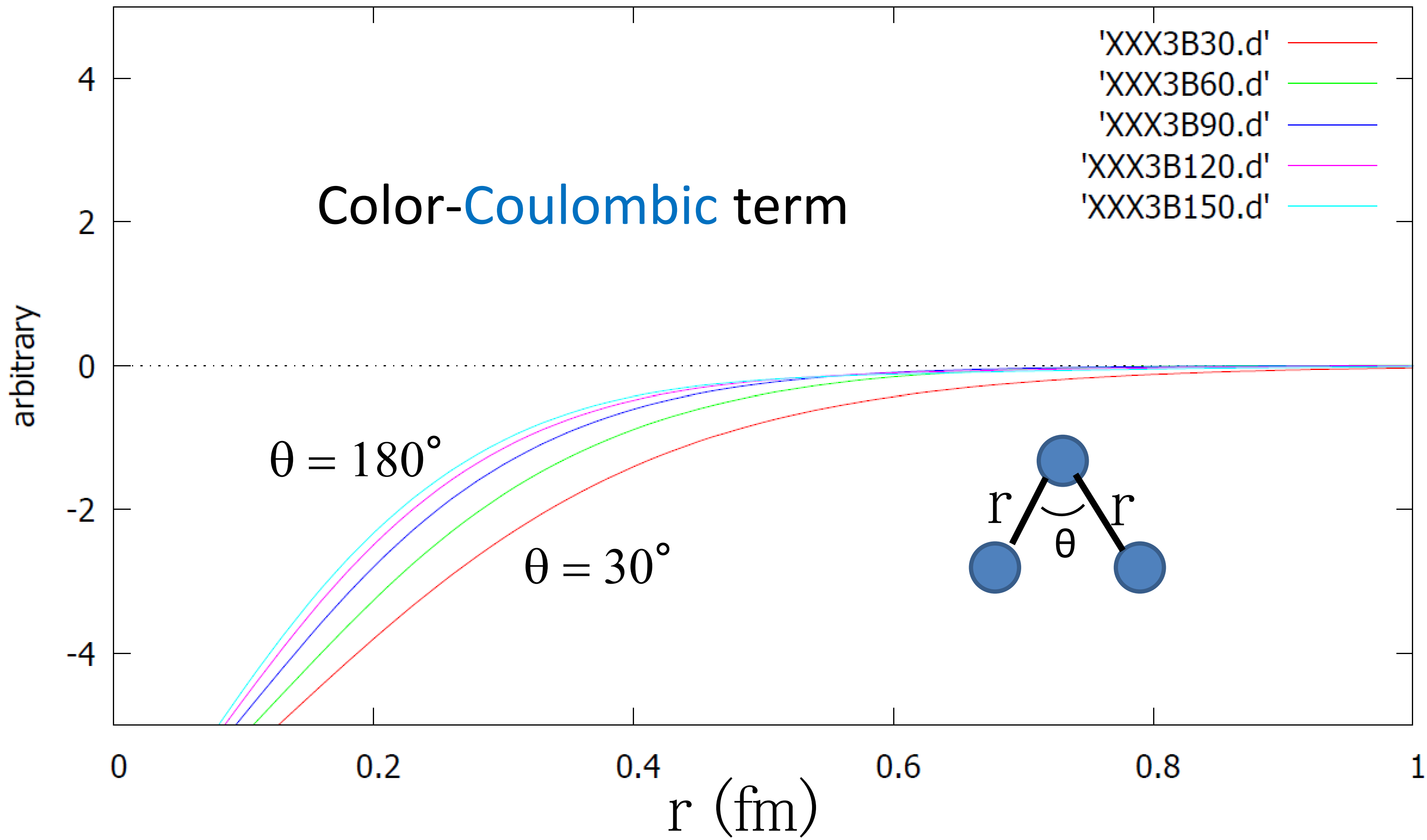
'SNN3B30.d'
'SNN3B60.d'
'SNN3B90.d'
'SNN3B120.d'
'SNN3B150.d'
'SNN3B180.d'
Color-Coulombic term
θ = 30°
θ = 180°
arbitrary
4
2
0
-2
-4
0
0.2
0.4
0.6
0.8
1
r (fm)
r
r
θ

ΞNN (I = 3/2)



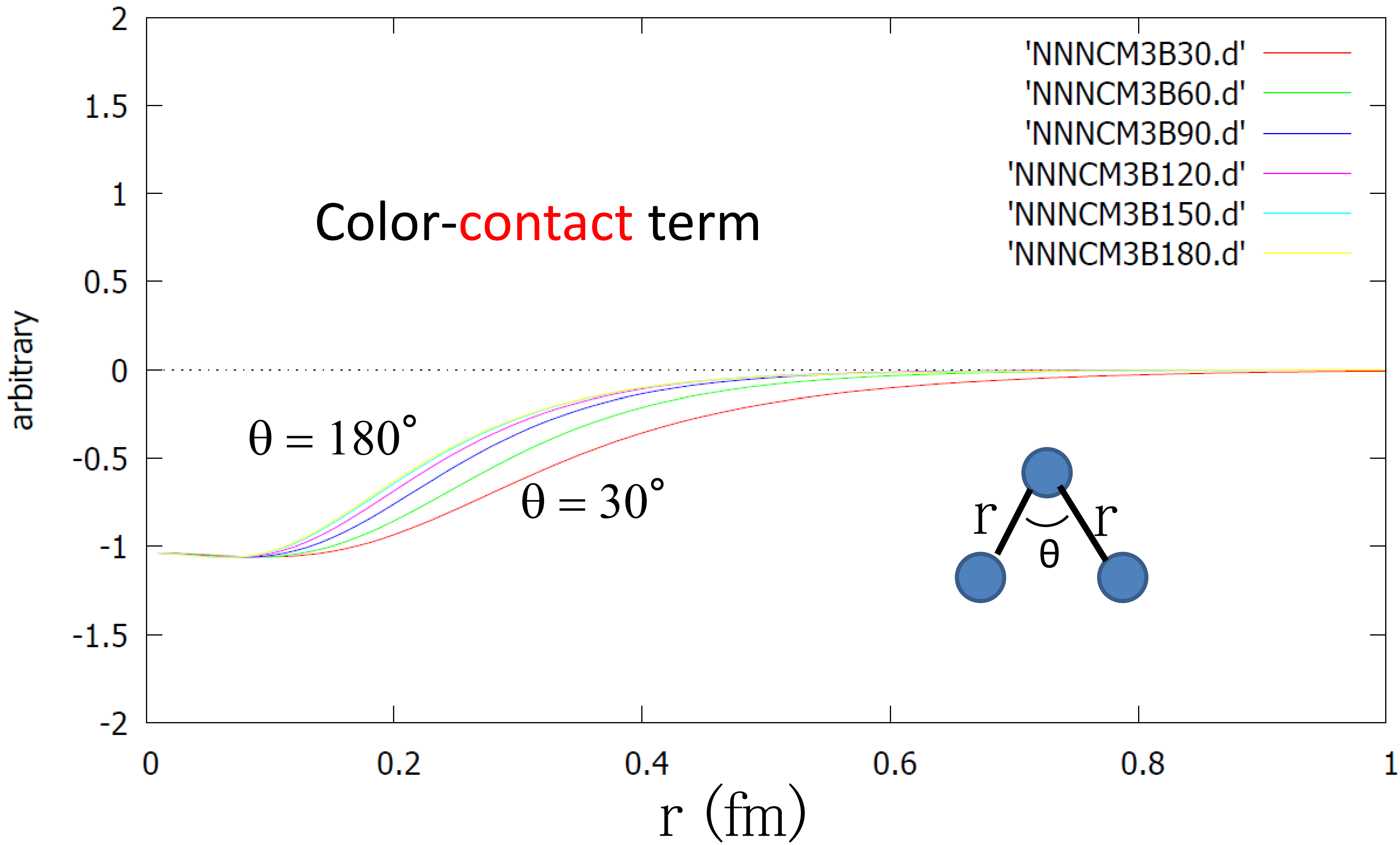
4
2
0
-2
-4
arbitrary
0
0.2
0.4
0.6
0.8
1
r (fm)
'XNN3B30.d'
'XNN3B60.d'
'XNN3B90.d'
'XNN3B120.d'
'XNN3B150.d'
'XNN3B180.d'
Color-Coulombic term
θ = 180°
θ = 30°
r
r
θ

ΞΞΞ (I = 1/2)



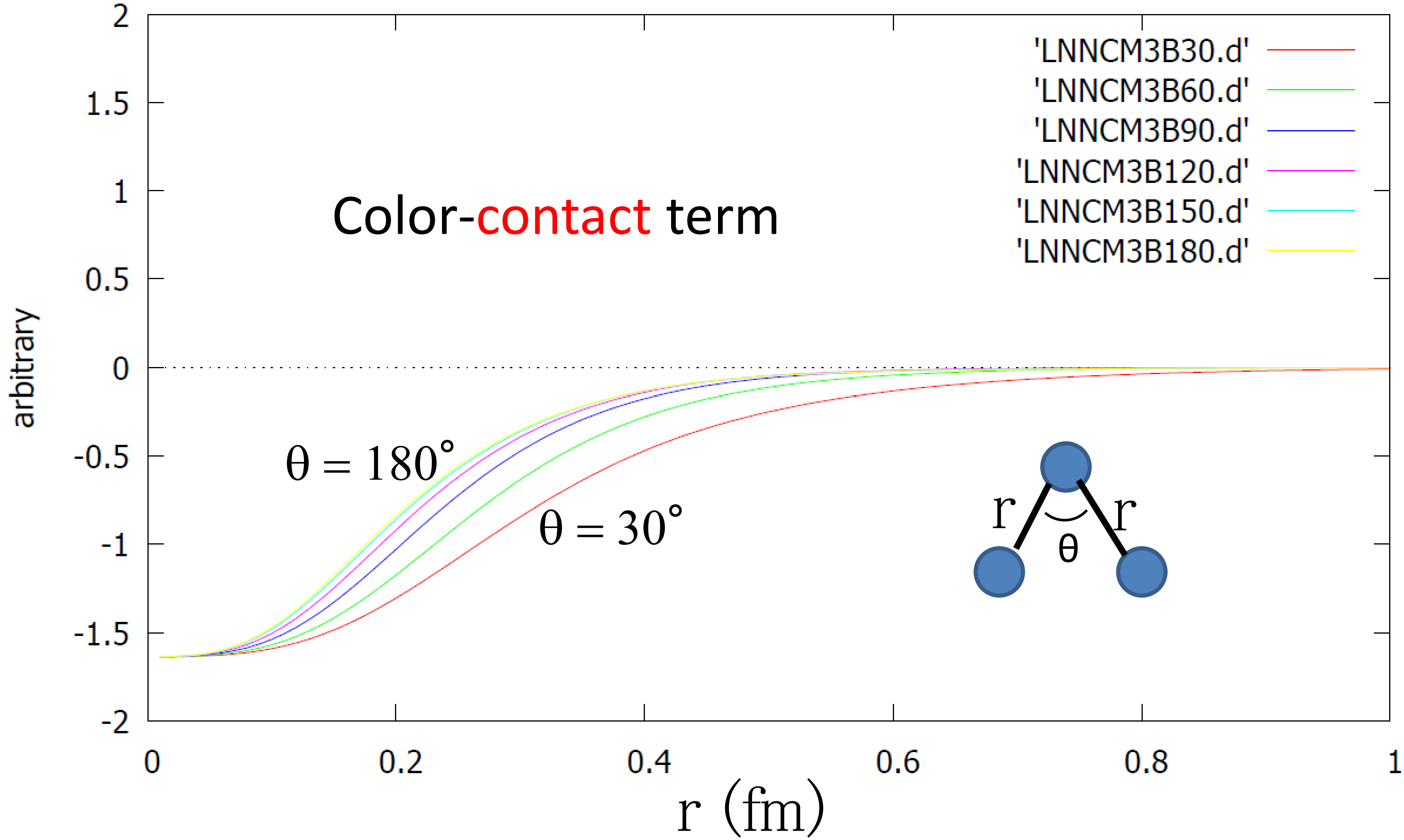
'XXX3B30.d'
'XXX3B60.d'
'XXX3B90.d'
'XXX3B120.d'
'XXX3B150.d'
Color-Coulombic term
θ = 180°
θ = 30°
r
r
θ
arbitrary
4
2
0
-2
-4
0
0.2
0.4
0.6
0.8
1
r (fm)

NNN(I = 1/2)



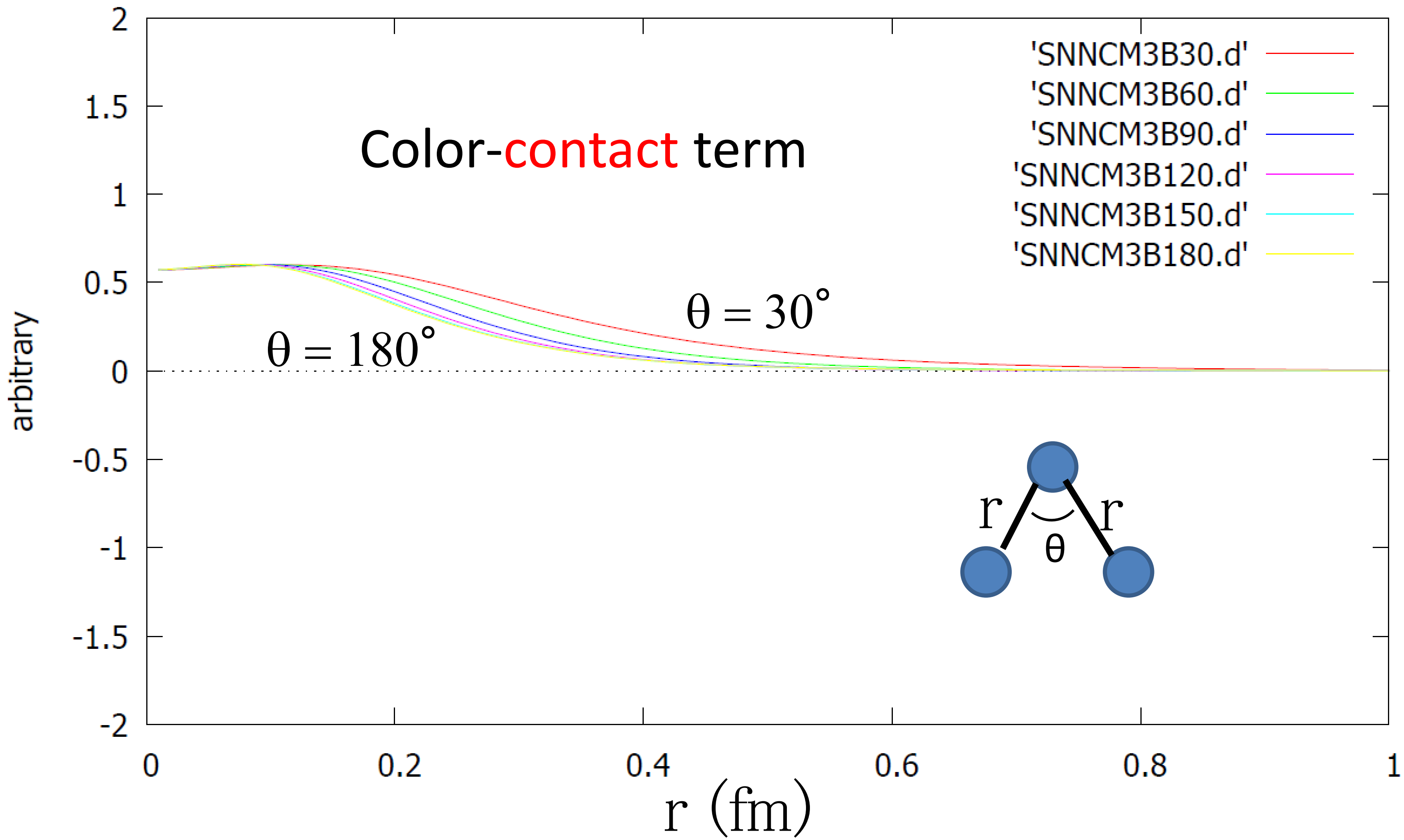
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
arbitrary
0
0.2
0.4
0.6
0.8
1
r (fm)
'NNNCM3B30.d'
'NNNCM3B60.d'
'NNNCM3B90.d'
'NNNCM3B120.d'
'NNNCM3B150.d'
'NNNCM3B180.d'
Color-contact term
θ = 180°
θ = 30°
r
r
θ

ΛNN



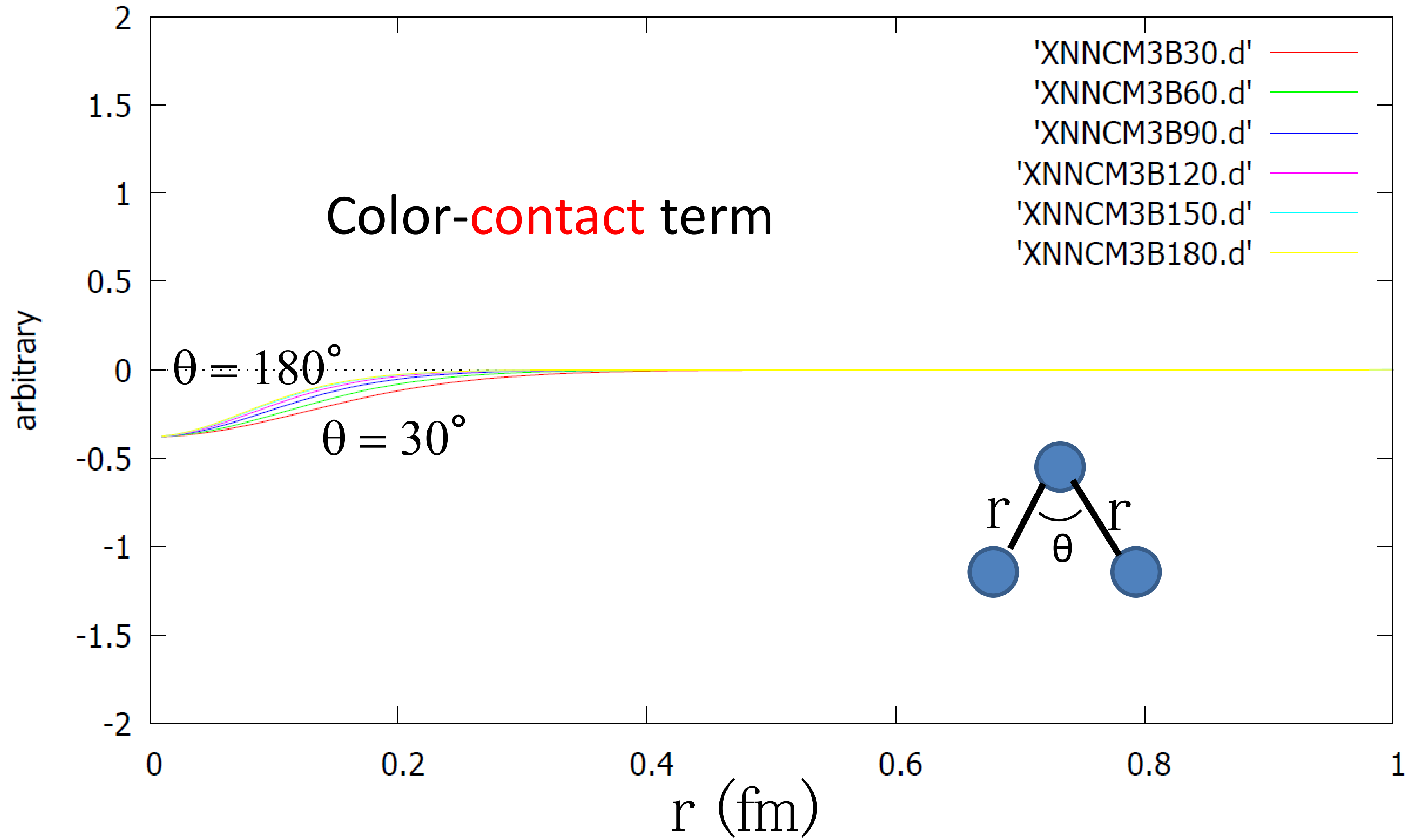
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
0.2
0.4
0.6
0.8
1
arbitrary
r (fm)
'LNNCM3B30.d'
'LNNCM3B60.d'
'LNNCM3B90.d'
'LNNCM3B120.d'
'LNNCM3B150.d'
'LNNCM3B180.d'
Color-contact term
θ = 180°
θ = 30°
r
r
θ

ΣNN (I = 2)



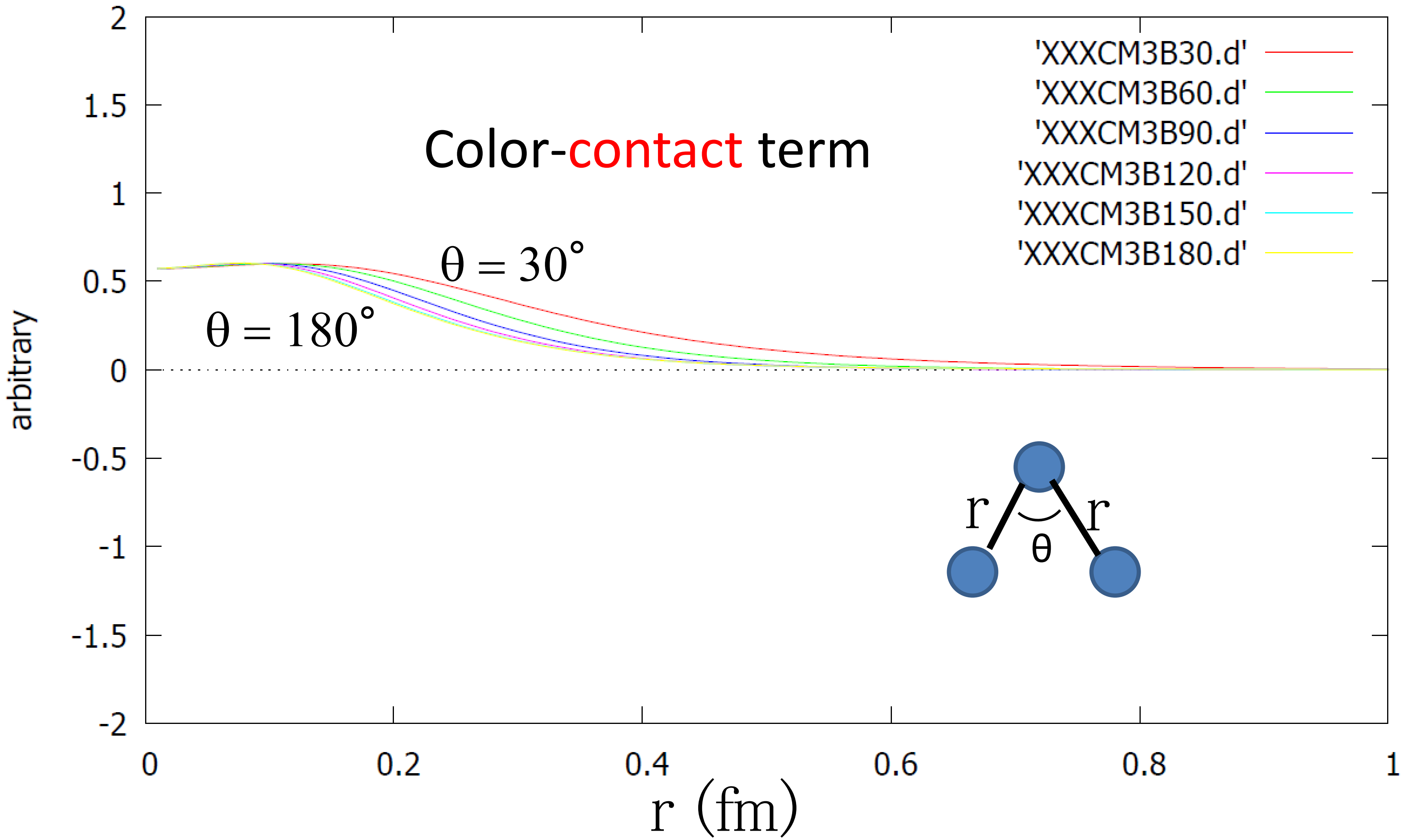
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
0.2
0.4
0.6
0.8
1
arbitrary
r (fm)
'SNNCM3B30.d'
'SNNCM3B60.d'
'SNNCM3B90.d'
'SNNCM3B120.d'
'SNNCM3B150.d'
'SNNCM3B180.d'
Color-contact term
θ = 30°
θ = 180°
r
r
θ

ΞNN (I = 3/2)



2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
0
0.2
0.4
0.6
0.8
1
arbitrary
r (fm)
'XNNCM3B30.d'
'XNNCM3B60.d'
'XNNCM3B90.d'
'XNNCM3B120.d'
'XNNCM3B150.d'
'XNNCM3B180.d'
Color-contact term
θ = 180°
θ = 30°
r
r
θ

ΞΞΞ (I = 1/2)



2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
arbitrary
0
0.2
0.4
0.6
0.8
1
r (fm)
Color-contact term
'XXXCM3B30.d'
'XXXCM3B60.d'
'XXXCM3B90.d'
'XXXCM3B120.d'
'XXXCM3B150.d'
'XXXCM3B180.d'
θ = 30°
θ = 180°
r
r
θ

4. Summary & Future

- exchange RGM kernelのdiagonal elementの評価を通して、3-baryon系におけるcolor-Coulomb項およびcolor-contact項の定性的特徴について調べた

	NNN(1/2)	ΛNN(1)	ΣNN(2)	ΞNN(3/2)	ΞΞΞ(1/2)
Coulomb	引力	引力	斥力	～0	引力
contact	引力	引力	斥力	～0	斥力

- Linear (θ=180°)になるにつれて3体効果は弱くなる

Future

- 内部エネルギーへの寄与の除去
- kinetic, confinement, color-magnetic 各項の評価
- effective local potentialとしての評価が必要？