「J-PARCハドロン物理の将来研究計画を考える」研究会

J-PARCと格子QCD

– Nuclear Bound Charmoninum –

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Nuclear-Bound Charmonium

- Brodsky, Schmidt, de Teramond, PRL 64 (1990) 1011
  - Different quark flavors: (up, down vs. charm)
    - Attractive QCD van der Waals interaction
    - No Pauli blocking = No short-range repulsion
  - The formation of charmonium bound to nuclei ($A \geq 3$)
    - A genuine QCD effect at the nuclear level

Nuclear-Bound Charmonium

- Brodsky, Schmidt, de Teramond, PRL 64 (1990) 1011
  - Assumption 1: interaction between cc^{bar} and nucleon (N)
    - $$V_{(c\bar{c})N}(r) = -\gamma \frac{e^{-\alpha r}}{r} \qquad (\gamma = 0.4 - 0.6,\ \alpha = 0.6\ \mathrm{GeV})$$
    - parameters determined by the Pomeron model
  - Assumption 2: interaction between cc^{bar} and nucleus (A)
    - the potential strength is linear in A (Pomeron model)

Nuclear-Bound Charmonium

- Dependence of $c\bar{c}$ and nucleus interaction
  - the binding energy of η_c - ^{3}He [MeV]

γ	Original work	Folding model[1]	4-body calculation[2]
0.4	-3.0	—	-1.4
0.6	-19.0	- 0.8	-12.6

Folding potential

$$V_{(c\bar{c})A}(r) = \int V_{(c\bar{c})N}(r - r')\rho_A(r')d^3r'$$

[1] Wasson et al., PRL 67 (91) 2237

[2] Belyaev et al., NPA 780 (06) 100

Charmonium-Nucleon interaction

- Charmonium-Nucleon interaction = “Multi-gluon exchange”
  - Color van der Waals interaction given by two-gluon exchange
    - Attractive long-range potential behaves like $1/r^n$ $(n \geq 6)$
    - the scattering length $a = 0.24$ fm (Brodsky-Miller[1])
  - QCD sum rules: $a = 0.1$ fm (Hayashigaki[2])
  - Lattice QCD: $a = 0.71 \pm 0.48$ fm (Yokokawa-Sasaki-Hatsuda-Hayashigaki[3])

Note that “a>0” means attractive

[1] Brodsky, Miller, PLB 412 (97) 125

[2] Hayashigaki., PTP 101 (99) 923

[3] Yokokawa et al., PRD 74 (06) 034504

$c\bar{c}$-Nucleon potential

$$V_{(c\bar{c})N}(r) = -\gamma \frac{e^{-\alpha r}}{r} \qquad (\gamma = 0.4 - 0.6,\ \alpha = 0.6\ \text{GeV})$$

Born approx. $a_B = -2M_{\text{red}} \int drr^2 V_{(c\bar{c})N}(r) = 2M_{\text{red}}\gamma/\alpha^2$

γ	a Born		
0.4	0.16 fm		
0.6	0.47 fm		

a = 0.24 fm (color ven der Waals)

a = 0.1 fm (QCD sum rules)

a = 0.71±0.48 fm (Lattice QCD)

$c\bar{c}$-Nucleon potential

$$V_{(c\bar{c})N}(r) = -\gamma \frac{e^{-\alpha r}}{r} \qquad (\gamma = 0.4 - 0.6,\ \alpha = 0.6\ \mathrm{GeV})$$

- Bound state formation condition $D = 2M_{\mathrm{red}}\gamma/\alpha > 1.679798$

γ	a_{Born}		D
0.4	0.16 fm		0.477
0.6	0.47 fm		1.430

$c\bar{c}$-Nucleon potential

$$V_{(c\bar{c})N}(r) = -\gamma \frac{e^{-\alpha r}}{r} \qquad (\gamma = 0.4 - 0.6,\ \alpha = 0.6\ \text{GeV})$$

γ=0.6 is too strong for chanominum-nucleon interaction

γ	a Born	a	D
0.4	0.16 fm	0.21 fm	0.477
0.6	0.47 fm	1.65 fm	1.430

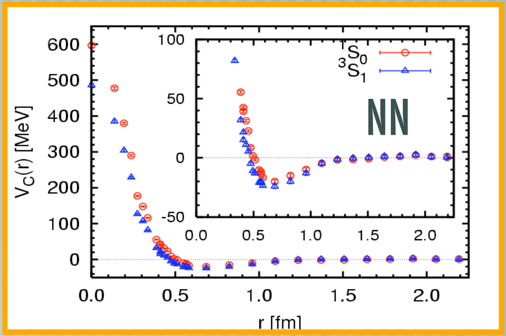
a = 0.24 fm (color ven der Waals)

a = 0.1 fm (QCD sum rules)

a = 0.71±0.48 fm (Lattice QCD)

Toward more realistic prediction

- Measure $c\bar{c}$ - Nucleon potentials in lattice QCD
  - momentum-dep. of phase shift (interaction range r)
  - Wave Function Approach (CP-PACS)
  - c.f. NN potential (Ishii-Aoki-Hatsuda)



- Exact few-body calculations with the realistic $c\bar{c}$ - N potential
  - Gaussian Expansion Method (Hiyama-Kino-Kamimura)

Backup Files

Lattice results (quench approx.)

- Yokokawa, Sasaki, Hatsuda, Hayashigaki, PRD 74 (06) 034504
  - Interaction of charmonia with light hadrons is always attractive
  - the cc^{bar} - pion scattering length is very small (a = 0.012 ± 0.004 fm) as consistent with the soft-pion theorem.
  - the cc^{bar} - Nucleon (rho) scattering length is an order of magnitude larger than that in the cc^{bar} - pion channel

$$0 < a^{(c\bar{c})\pi} \ll a^{(c\bar{c})\rho} < a^{(c\bar{c})N}$$

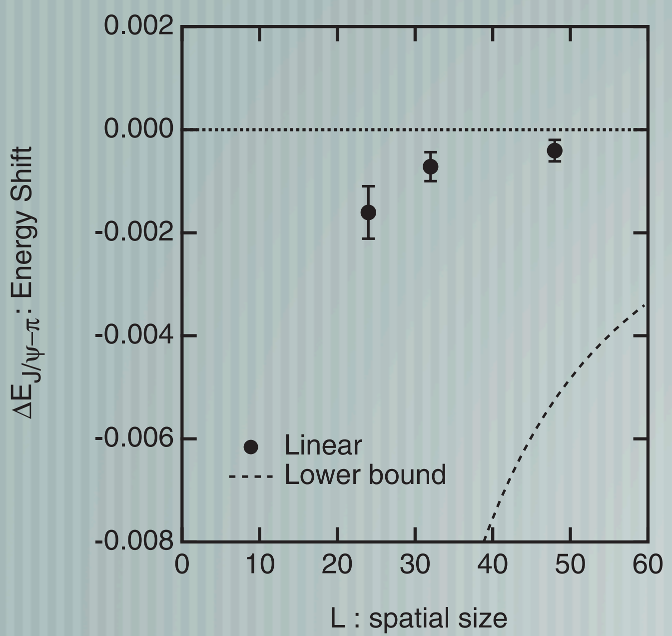
  - No appreciable spin-dependence: cc^{bar} = η_c or J/ψ

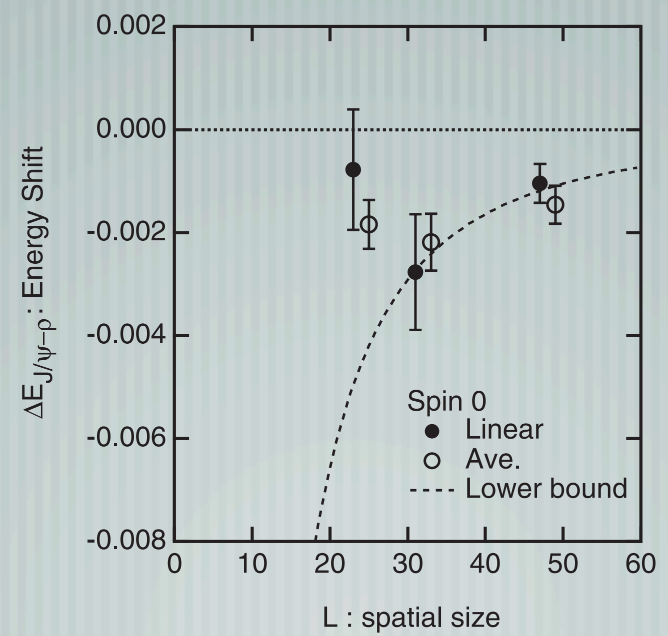
Lattice results (quench approx.)

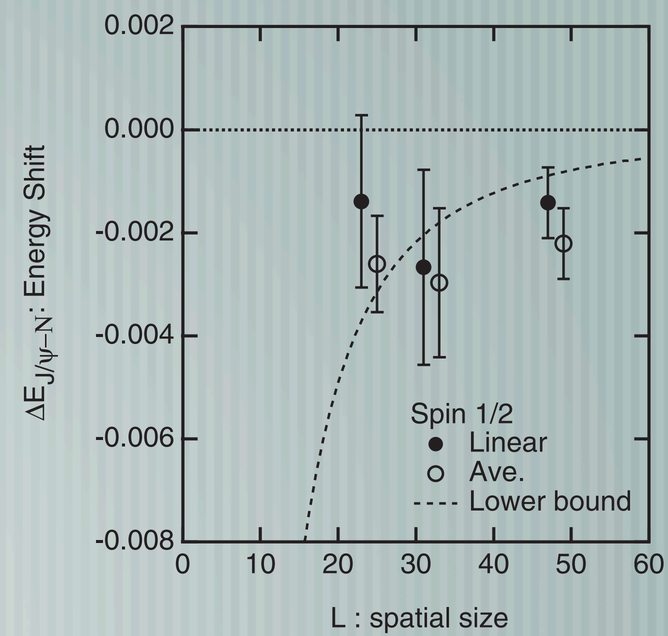
β	a [fm]	a^{-1} [GeV]	Lattice size ($L^3 \times T$)	$\sim La$ [fm]	Statistics
6.2	0.06775	2.913	$24^3 \times 48$	1.6	161
			$32^3 \times 48$	2.2	169
			$48^3 \times 48$	3.2	53

Lüscher finite size formula

$$\Delta E = -\frac{2\pi a_0}{\mu L^3}\left(1 + c_1 \frac{a_0}{L} + c_2\left(\frac{a_0}{L}\right)^2\right) + O(L^6)$$







Channel	Spin	From PSF a_0 [fm]	From PSF σ_{el} [mb]	From LLE a_0 [fm]	From LLE σ_{el} [mb]
J/ψ-π	1	0.0119 ± 0.0039	$0.018^{+0.013}_{-0.010}$	0.0119 ± 0.0025	$0.018^{+0.008}_{-0.007}$
J/ψ-ρ	0	0.32 ± 0.12	$12.9^{+11.0}_{-7.6}$	0.23 ± 0.06	$6.6^{+4.2}_{-3.2}$
	1	0.25 ± 0.10	$7.9^{+7.3}_{-4.9}$	0.19 ± 0.06	$4.6^{+3.3}_{-2.4}$
	2	0.21 ± 0.09	$5.5^{+5.6}_{-3.7}$	0.17 ± 0.06	$3.5^{+2.8}_{-2.0}$
	SAV	0.23 ± 0.08	$6.8^{+6.1}_{-4.2}$	0.18 ± 0.05	$4.1^{+2.9}_{-2.1}$
J/ψ-N	1/2	0.57 ± 0.42	41^{+83}_{-38}	0.35 ± 0.15	15^{+15}_{-10}
	3/2	0.88 ± 0.63	96^{+188}_{-89}	0.43 ± 0.16	23^{+20}_{-14}
	SAV	0.71 ± 0.48	64^{+116}_{-57}	0.39 ± 0.14	20^{+16}_{-12}

Channel	Spin	From PSF a_0 [fm]	From PSF σ_{el} [mb]	From LLE a_0 [fm]	From LLE σ_{el} [mb]
η_c-π	0	0.0113 ± 0.0035	$0.016^{+0.011}_{-0.008}$	0.0112 ± 0.0024	$0.016^{+0.008}_{-0.006}$
η_c-ρ	1	0.21 ± 0.11	$5.3^{+7.5}_{-4.3}$	0.16 ± 0.05	$3.4^{+2.5}_{-1.8}$
η_c-N	1/2	0.70 ± 0.66	62^{+172}_{-62}	0.39 ± 0.14	19^{+16}_{-11}

$L^3 \times T$		$a_0^{\eta_c\text{-}\pi}$	$a_0^{\eta_c\text{-}\rho}$	$a_0^{\eta_c\text{-}N}$
$24^3 \times 48$	Physical	0.15(5)	−0.25(48)	1.10(1.29)
	Chiral	−0.0025(15)	−0.25(48)	1.09(1.28)
$32^3 \times 48$	Physical	0.15(5)	2.8(1.6)	8.8(9.2)
	Chiral	−0.0013(9)	2.7(1.6)	8.7(9.0)
$48^3 \times 48$	Physical	0.33(17)	3.4(1.8)	12.4(10.5)
	Chiral	−0.0014(14)	3.4(1.8)	12.2(10.2)

$$a_0^{H\text{-}\pi} = -\left(1 + \frac{M_\pi}{M_H}\right)^{-1} \frac{M_\pi}{4\pi f_\pi^2} \vec{I}_\pi \cdot \vec{I}_H + O(M_\pi^2),$$

where $\vec{I}_\pi$ ($\vec{I}_H$) is the isospin vector of π (H)

$\vec{I}_\pi \cdot \vec{I}_H = 0$ **for isoscalar hadron**

Possible Experiments

- Production of η_c-nucleus bound states
  - **$p + d \rightarrow (^3He\ \eta_c)$**
  - **$p^{bar} + {}^4He \rightarrow (^3He\ \eta_c)$**
- ***Missing mass analysis (M_X) on $^3He + X$**
- ***Invariant mass analysis ($M_{\gamma\gamma}$) on $^3He + \gamma\gamma$**