J/ψ-N interaction and J/ψ- nuclei

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High-energy hadron physics with hadron beams

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0. Quark masses. Lightest charmed mesons.
1. The case of the D·bar-N interaction.
2. J/ψ and J/ψ-N mass spectrum, and J/ψ size.
3. J/ψ-N interaction
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Quark masses*

$m_u \approx 1.5 \sim 3.3$ MeV

$m_d \approx 3.5 \sim 6.0$ MeV

$m_s \approx 66 \sim 126$ MeV

m » $\Lambda_{QCD} \approx (1 \sim 4) \cdot 100$ MeV:

perturbative treatments of m_q become possible

→ Effective field theoretical (EFT) treatments of QCD (even nonrelativistic QCD) become possible**

$m_c \approx 1.16 \sim 1.34$ GeV

*PDF: The u-, d-, and s-quark masses are estimates of so-called \current-quark masses," in a mass- independent subtraction scheme such as MS. The ratios mu/md and ms /md are extracted from pion and kaon masses using chiral symmetry. The estimates of d and u masses are not without controversy and remain under active investigation. Within the literature there are even suggestions that the u quark could be essentially massless. The s-quark mass is estimated from SU(3) splittings in hadron masses. We have normalized the MS masses at a renormalization scale of ¹ = 2 GeV. Results quoted in the literature at ¹ = 1 GeV have been rescaled by dividing by 1:35.

***cf. N. Brambilla & A. Vairo, Rev. Mod. Phys. 77, 1423 (2005).*

Lightest charmed mesons

(Lightest) charmed mesons: $\Gamma \approx 10^{-4}$ eV.

$m_c + m_d \approx 1.2$ GeV

D^+ ($c\ \underline{d}$), D^o ($c\ \underline{u}$), D^{--} ($\underline{c}\ d$), $\underline{D}^o$ ($\underline{c}\ u$): $I(J^P) = ½(0^{--})$, $m_D \approx 1.87$ GeV

D_s^+ ($c\ \underline{s}$), D^{--} ($\underline{c}\ s$) : $I(J^P) = 0(0^{--})$, $m_{Ds} \approx 1.97$ GeV

(Lightest) C$\underline{C}$ mesons: C$\underline{C}$ in 1S states.

$2m_c \approx 2.3 \sim 2.7$ GeV

η_c ($c\ \underline{c}$) : $I(J^P) = 0(0^{--})$, $m_{\eta c} \approx 2.98$ GeV, $\Gamma \approx 27$ MeV

J/ψ ($c\ \underline{c}$) : $I(J^P) = 0(1^{--})$, $m_{J/\psi} \approx 3.10$ MeV, $\Gamma \approx 93$ eV

Note: $2m_u + m_d \approx 6.5 \sim 13$ MeV, while $M_p \approx 938.3$ MeV.

1. The case of D·bar-N interaction

Attractive. Probably strong enough to form $\underline{D}$-N bound states.

One π-exchange interaction: S.Yasui & K.Sudoh, PRD(2009).

Bound state: I = 0 and $J^P = ½^{--}$

E_B = 1.4 MeV → a = +4.7 fm

and R =3.8 fm

with the coupled channels of

$$|\bar{D}N\rangle = c_0^D(|D^- p\rangle - |\bar{D}^0 n\rangle) + c_1^D(|D^{*-} p\rangle - |\bar{D}^{*0} n\rangle)$$

$m_{\underline{D}}{}^{o} - m_{\underline{D}}{}^{-} \approx$ 5 MeV

$m_{\underline{D}}{}^{*} - m_{\underline{D}} \approx$ 140 MeV

→ D·bar nuclear bound sates:

Coupled atomic + nuclear bound states of charmed mesons

with the meson-nucleon bound-states of I = 0 and $J^P = ½^{--}$

→ nuclear shell structure possibly destroyed?

But hold the horse.

Quark-meson coupling model: (Guichon, Fleck-Benz-Shimizu-Yazaki,Saito-Thomas)

→K.Saito, K.Tsushima, A.W.Thomas, PPNP(2007):

Non-interacting N bag model in Rel. Mean Field (QHD) model,

σ, ω, ρ coupling to q, Q, ~self-consistintly at the N and nuclear levels.

Tsushima,Lu,Thomas,Saito,Landau, PRC(1999)

D · bar mass shift at ~ nuclear matter (at the center of Pb): $\delta m_{\underline{D}} \approx - 45$ MeV

QCD sum rule: A.Hayashigaki, PLB(2000) on D, noting $\delta m_D \approx \delta m_{\underline{D}} \approx - 50$ MeV

Yasui - Sudoh $\underline{D}$N scattering length roughly corresponds to:

$a = + 4.7\text{fm} \rightarrow \delta m_D = - 17.4\text{MeV}\ (\Lambda=1.27\text{GeV})$

$- 22.4\text{MeV}\ (\Lambda=1.00\text{GeV})$

However, at the LO meson-baryon interaction,

Chiral SU(3) → SU(4) model:

A.Mishra, Bratkovskaya,Shaffer-Bielich,Schramm,Stöcker, PRC(2004)

$\delta m_{\underline{D}}$ = even down to ~ −150MeV

Hofmann-Lutz (coupled-equation) model:

Includes all $J^P = ½^-$ pseudoscalar-baryon states consisting of u, d, s, c with s-wave interactions using the universal vector coupling strength:

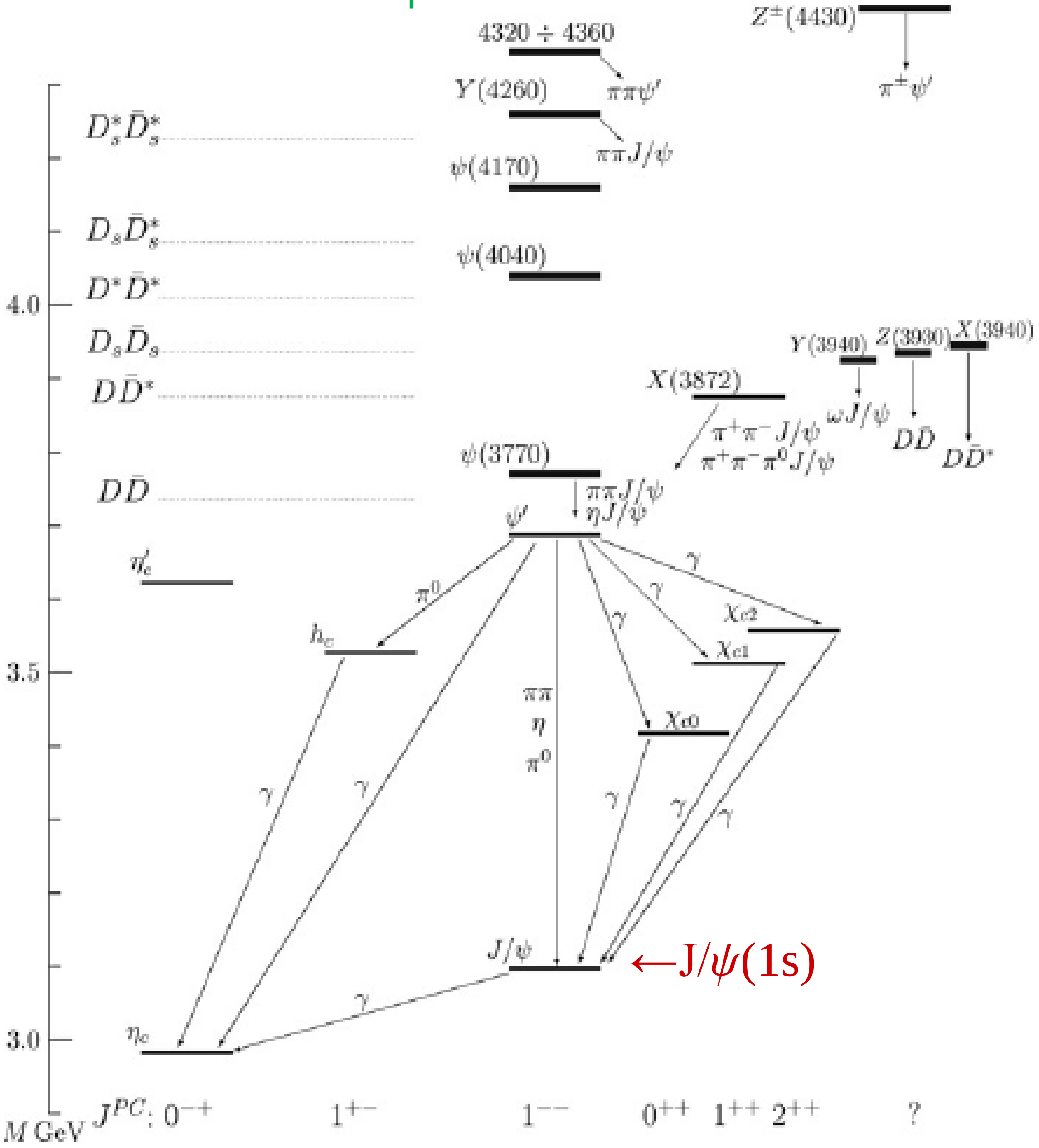
M.F.M.Lutz & C.L.Korpa,PL(2006); J.Hofmann & Lutz,NPA(2005)

$\delta m_{\underline{D}} = +17$ MeV

Strong coupling of various channels makes the strength of the $\underline{D}$-N interaction much uncertain.

2. J/ψ and J/ψ - N mass spectrum, and J/ψ size

C-C·bar meson mass spectrum



M.B. Voloshin / Progress in Particle and Nuclear Physics 61 (2008) 455–511

←J/ψ(1s)

J/ψ(1s):
I=0, G= -, J=1, PC= - -
M=3097MeV,
Γ=0.093MeV

Like ϕ(1020) of s s·bar
but with Γ=4.3MeV
Decaying to K's.

η_c(1s):
Γ=27MeV
May not be pure c c·bar?

N + J/ψ couples little to other hadronic channels:

J/ψ have a lonely life with N.

1) The J/ψ mass is below the D - D·bar mass by more than 60 MeV.

2) The proton - J/ψ mass is below the Λ_c - D·bar mass by about 120 MeV:

Mass (Λ_c + Dbar) ≈ 4.1561 ± 0.0002 GeV
Mass (p + J/ψ) ≈ 4.0352 ± 0.0001 GeV

All other OZI-allowed hadronic states with the same quantum number of N + J/ψ have higher masses.

3) The J/ψ mass is above the η_c(1s) mass by 117 MeV, but a transition to η_c(1s) involves a spin flip of c or c·bar. Because of the large mass, the transition is expected to be rare.

4) Coupling to OZI-non-allowed channels is expected to be small:

S.J. Brodsky & G. A. Miller, PL B412, 125 (1997).

* $N + J/\psi \rightarrow N + J/\psi + \pi + \pi$ Isospin allowed via two-pion exchanges but down by the order of $(m_\pi / 4\pi f_\pi)^2 \approx 1\ \%$.

* $J/\psi \rightarrow e^+ + e^-$ $5.94 \pm 0.06\ \%$

$\mu^+ + \mu^-$ $5.93 \pm 0.06\ \%$

$\rho + \pi$ $1.69 \pm 0.15\ \%$: the largest two-body hadronic branching ratio ($\rho\ \pi$ puzzle: ρ has c-cbar component?)

but $N + J/\psi \rightarrow (N+\rho+\pi) \rightarrow N + J/\psi$ unlikely with the order of $10^{-4}\ \%$ interaction strength.

* Also $N + J/\psi \rightarrow (N+D+ D\cdot\text{bar}) \rightarrow N + J/\psi$ unlikely with about 0.4 % interaction strength.

J/ψ is small:

At short distances, the non-relativistic C and C·bar in J/ψ interact through the color singlet (P_0) part of the Coulombic potential

$$V(r) = -\frac{4}{3}\frac{\alpha_s(1/r)}{r}P_0 + \frac{2}{3}\frac{\alpha_s(1/r)}{r}P_8 .$$

The Bohr radius of this C-C·bar bound state is

$$a_o = (3/2)\,[m_c\,\alpha_s(1/a_0)]^{-1} .$$

Numerically

$$\alpha_s(\Lambda_Q) \approx 0.5 \sim 0.6 \qquad [\alpha_s(q) = g(q)^2/4\pi]$$

$$a_o \approx 0.3\ \mathrm{fm} \qquad (1/a_0 \equiv \Lambda_Q \approx 0.75 \sim 0.64\ \mathrm{GeV})$$

N.B. $\Lambda_Q \equiv 1/a_0$.

Note: $-4/3 = t_1^a \cdot t_2^a$ for the color singlet pair.

4. J/ψ-N interaction is definitely attractive through QCD van der Waals (two gluon exchange) interaction:

The J/ψ-N amplitude at the threshold in Born approximation is expressed in the second order of the color dipole coupling $\hat{H}_{\rm int} = -(t_1^{\,a} - t_2^{\,a})\mathbf{r}\cdot\mathbf{E}^a$:

$$f_{\rm B} = -\frac{m_{\rm red}}{2\pi}\frac{2\pi}{3}\alpha_s \left\langle \varphi \left| r^i \frac{1}{H^{(8)}+\epsilon} r^j \right| \varphi \right\rangle_{{\rm J}/\psi} \langle K_2 | E_i^a E_j^a | K_1 \rangle_{\rm N} \;(K_1 = K_2)$$

$$= -\frac{m_{\rm red}}{2\pi}\, 4\alpha_{{\rm J}/\psi} \left\langle \frac{1}{2}\mathbf{E}_a\cdot\mathbf{E}_a \right\rangle_{\rm N}$$

Here,

J/ψ chromo-polarizability: $\alpha_{{\rm J}/\psi} \approx d_2\, a_0^{\,3}/4$ [$d_2 = 7\cdot(4\pi/27)$, Wilson coefficient (1S) ;

c-c·bar octet state propagator: $(H^{(8)} + \varepsilon)^{-1}$. (Peskin, $N_c \rightarrow \infty$)]

$f_{\rm B}$ is expressed in the forms of multi-pole expansion*,

of operator product expansion,

and (QCD) EFT/HQ formulation **

*K.Gottfried (1978), M.B.Voloshin (1979),M.Peshkin (1979); G.Bhanot & Peshkin (1979), T.M.Yan (1980), A.B.Kaidalov & P.E.Volkovitsky (1992).

**M. Luke, A. V. Manohar, & M. J. Savage (1992), S.J.Brodsky and G. A. Miller (1997).

Approximation (thus the source of uncertainties) on the two major factors evaluated at Λ_Q :

1) The J/ψ chromo-polarizability:

$\alpha_{J/\psi} \approx d_2\, a_0^{3}/4 \approx 0.9\ \mathrm{GeV}^{-3}$ ($N_c \rightarrow \infty$; M.Peshkin(1979))

$\approx 2.0\ \mathrm{GeV}^{-3}$ and up (A.Sibirtsev & M.B.Voloshin (2005)).

2) The N matrix element of the gluon operator:

$$\langle \tfrac{1}{2}\mathbf{E^a}\cdot\mathbf{E^a}\rangle_N \approx (4\pi^2/9)\langle\, T_\mu{}^{\mu}\rangle_N + 2\pi\, \alpha_s(1/a_0)\langle T_G{}^{00}\rangle$$

$$\approx (3V_2\,/8 + \pi\,/\,9\alpha_s)\; m_N \approx m_N$$

Here, $T(\Lambda_Q)$ =the energy-momentum tensor

$V_2(\Lambda_Q) \approx 0.5$, the gluon momentum fraction in N

Note, however, neglect of the second term (formally in NLO) leads to

$\approx (1/4)\; m_N$ (A.B.Kaidalov & P.E.Volkovitsky(1992))

So, we have found the Born approximation of the J/ψ - N scattering amplitude at the threshold. It is

$$a^B_{j/\psi} = 2m_{red}\int d^3 r V(r)$$

in terms of the local J/ψ - N potential V(r).

By writing $$V(r) = V_0 \cdot [V_N \delta^3(r)] = \delta m [V_N \delta^3(r)]$$

obtain $$\delta m = \frac{a^B_{j/\psi}}{2m_{red}} \frac{1}{V_N} \to \frac{a^B_{j/\psi}}{2m_{red}} \rho_0$$ with $\rho_0 = 0.172\ \mathrm{fm}^{-3}$

by neglecting the Fermi motion and possible modification of V(r) in the presence of other nucleons.

$a_{J/\psi\text{-}N}^B \to a_{J/\psi\text{-}N}$ or $\sigma_{J/\psi}$ is a different matter.

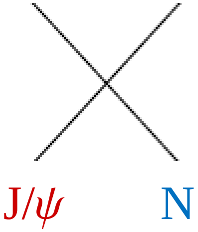
How to $a_{J/\psi\text{-}N}^{B} \rightarrow a_{J/\psi\text{-}N}$

1) Assume the form of V(r): $V(r) = V_0 \exp(-r^2/R^2)$

R ~ the nucleon size, 0.8 fm (Brodsky & Miller, 1997)

$a_{J/\psi\text{-}N}^{B} = -0.19$ fm → $a_{J/\psi\text{-}N} = -0.24$ fm by solving Sch. Eq.

2) Apply the LO NR J/ψ-N EFT:



$$V(r) = \frac{\pi^2}{m_{red}\Lambda} c_0(\Lambda)\delta^3(r)$$

Since $a_{J/\psi\text{-}N}^{B} = \frac{\pi}{2\Lambda} c_0(\Lambda)$, $a_{J/\psi\text{-}N} = \left(\frac{1}{a_{j/\psi}^{B}} + \frac{\Lambda}{\pi}\right)^{-1} = -0.22$ fm

for $\Lambda = 1/R = 0.25$ GeV

The EFT treatment reveals the regularization dependence of $a_{J/\psi\text{-}N}{}^B$,
$a_{J/\psi\text{-}N}{}^B = a_{J/\psi\text{-}N}{}^B(\Lambda)$, or the intrinsic ambiguity with δm:
For the J/ψ scattering amplitude, write

$$V_N\delta^3(r) = \frac{1}{\Lambda^3}\delta^3(r) \qquad \text{in} \quad V(r) = V_0\cdot[V_N\delta^3(r)] = \delta m[V_N\delta^3(r)]$$

The point is simply that $a_{J/\psi\text{-}N}$ is an observable and independent of Λ,
but $a_{J/\psi\text{-}N}{}^B$ is not.

The difference between $a_{J/\psi\text{-}N}$ and $a_{J/\psi\text{-}N}{}^B$ in our J/ψ-N case is expected to be small as the interaction being weak:

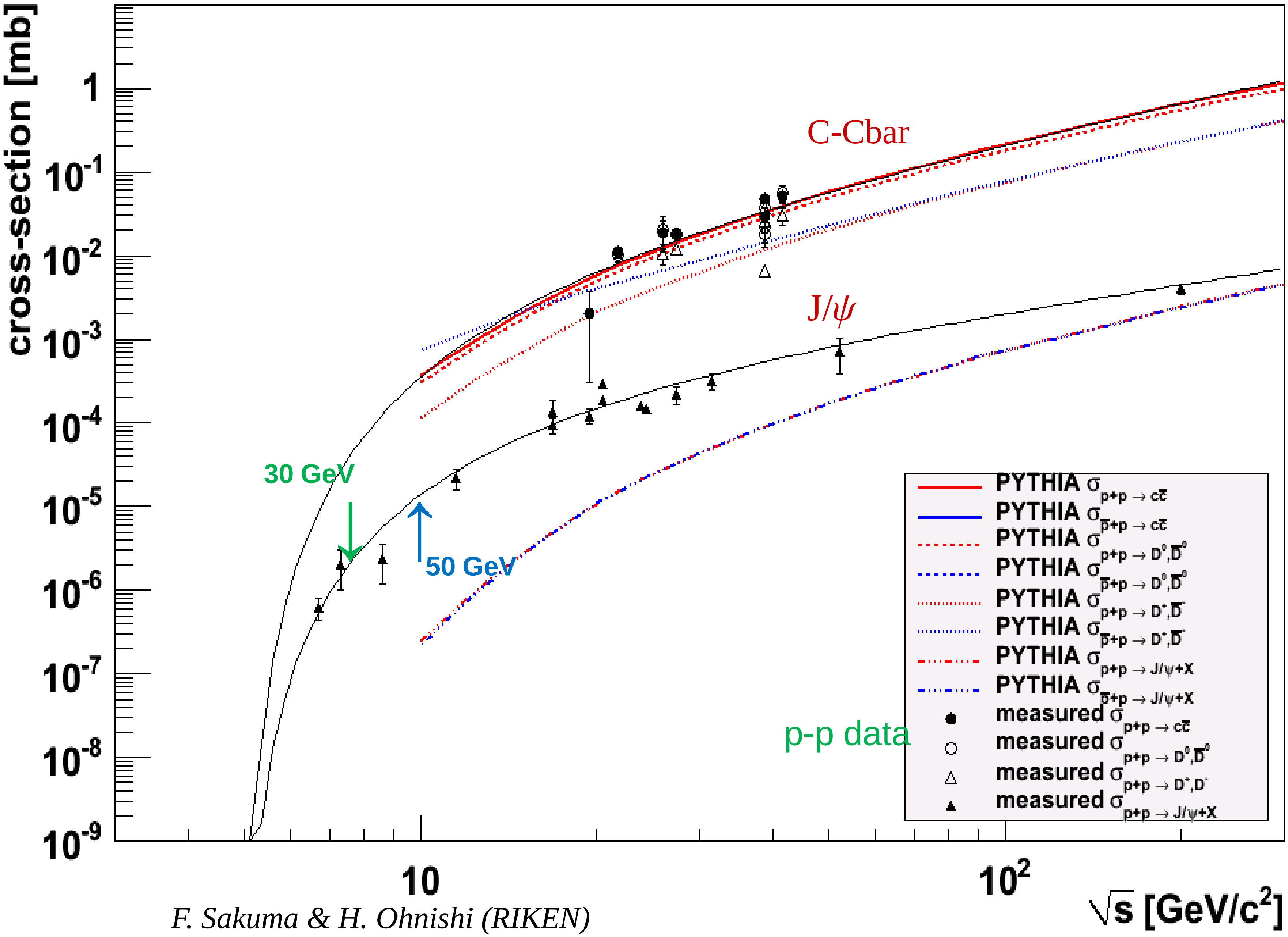
$$a_{J/\psi\text{-}N}{}^B = -0.19\text{ fm} \quad \rightarrow \quad a_{J/\psi\text{-}N} = -0.24\text{ fm} \quad \text{(Brodsky \& Miller, 1997)}$$
$$= -0.22\text{ fm} \quad \text{(EFT, R.S.)}$$

δm (MeV) and the spin-averaged $a_{J/\psi\text{-}N}$ (fm) calculations (All with ~):

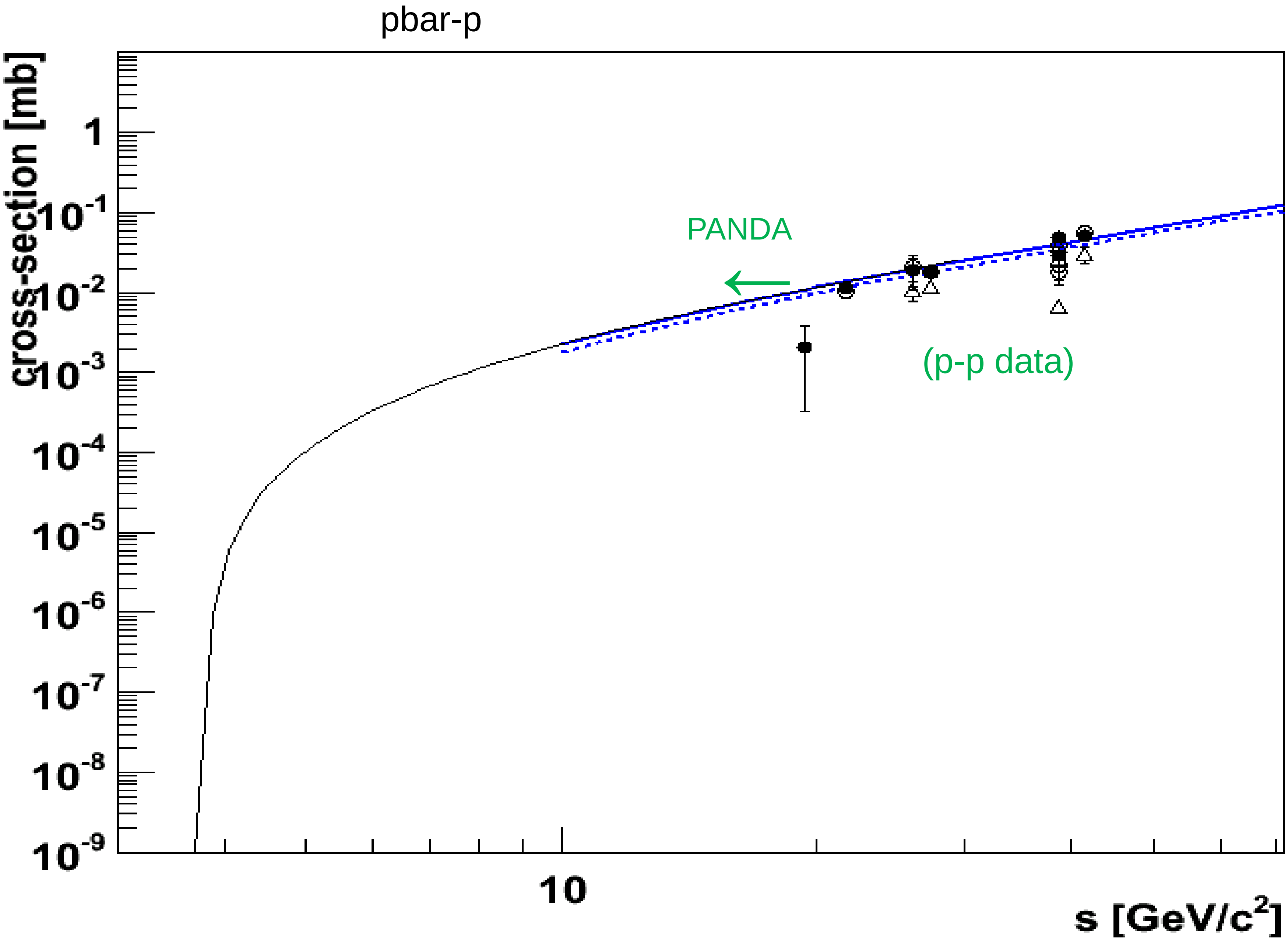
pQCD		
− (8 ~ 11)		Luke,Manohar & Savage (1992)
	− 0.24	Brodsky,Miller (1997)
−8±3		Lee,Ko (2003)
−11	−0.2	deTeramond,Epinoza, & Ortega-Rodriguez (1998)*
−3	−0.06	Kaidalov & Volkovitsky(1992)
≤ −21		Sibirtsev,Voloshin(2005)
Sum rule		
−7	−0.2	Klingl,Kim,Lee,Morath,Weise,(1999)
−(4~7)	≈ −0.1	Hayashigaki(1999)
Lattice**		
	− 0.71±0.48	Yokokawa,Sasaki,Hatsuda,Hayashigaki(2006)
exp. analysis		
	~0.1 (magnitude)	(γ prod.) Hüfner et al.(2000)
−11	−0.2	*(p-p A_{NN})

**A new, more precise lattice calculation is underway (private comm. S. Sasaki)

4. J/ψ production

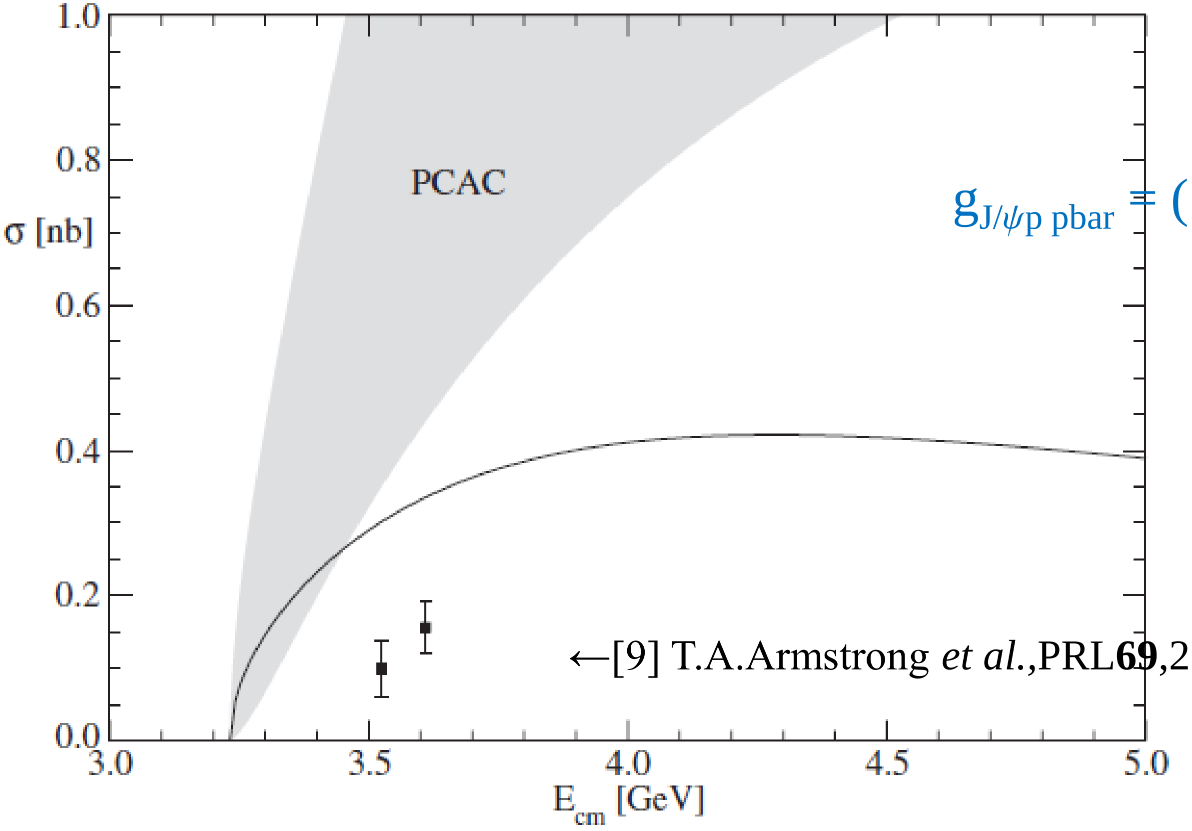


F. Sakuma & H. Ohnishi (RIKEN)



F. Sakuma & H. Ohnishi (RIKEN)

- p-bar p → π^o J/ψ cross sections from J/ψ → p-bar p π^o



$g_{J/\psi p\ pbar} = (1.62\pm0.03)\cdot10^{-3}$

←[9] T.A.Armstrong *et al.*,PRL**69**,2337(1992).

FIG. 4. Theoretical and experimental cross sections for $p\bar{p} \to \pi^0 J/\psi$. The theoretical predictions are the constant amplitude result Eq. (7) (solid) and the range of PCAC cross sections, from Eq. (8) (filled). The experimental points are from E760 [9].

A.Lundborg,T.Barnes,U.Wiedner,PRD**73,**096003(2006).

Some possible experiments

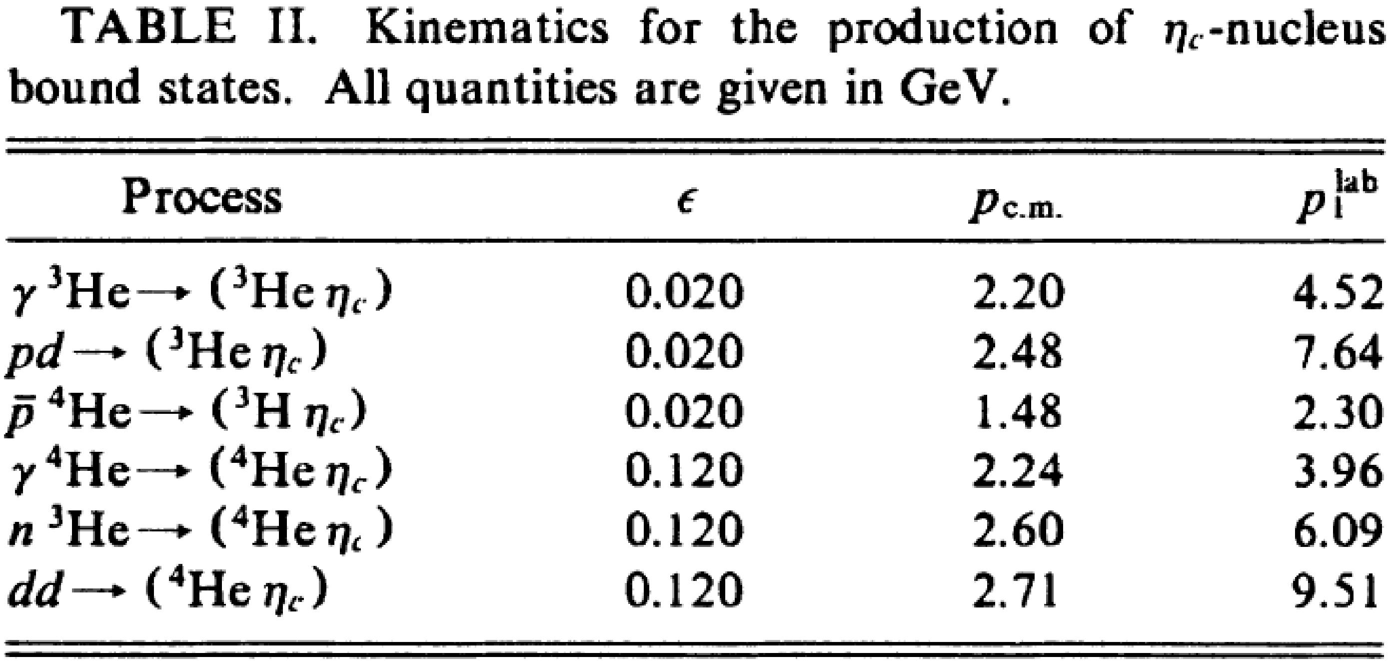


TABLE II. Kinematics for the production of η_c-nucleus bound states. All quantities are given in GeV.

Process	ϵ	$p_{\mathrm{c.m.}}$	p_1^{lab}
$\gamma\,{}^3\mathrm{He} \to ({}^3\mathrm{He}\,\eta_c)$	0.020	2.20	4.52
$pd \to ({}^3\mathrm{He}\,\eta_c)$	0.020	2.48	7.64
$\bar{p}\,{}^4\mathrm{He} \to ({}^3\mathrm{H}\,\eta_c)$	0.020	1.48	2.30
$\gamma\,{}^4\mathrm{He} \to ({}^4\mathrm{He}\,\eta_c)$	0.120	2.24	3.96
$n\,{}^3\mathrm{He} \to ({}^4\mathrm{He}\,\eta_c)$	0.120	2.60	6.09
$dd \to ({}^4\mathrm{He}\,\eta_c)$	0.120	2.71	9.51

S.J.Brodsky, I.Schmidt, & G.F.deTeramond, PRL 64, 1011(1990)

$\pi^+ d \to J/\psi\, p_1\, p_2$

S.J.Brodsky & G.A.Miller, PLB 412, 125 (1997)

$\bar{p}\,{}^4\mathrm{He} \to \pi(\text{all charges}) + 3\text{nucleons}_{J/\psi}$

R.S.

5. J/ψ -nuclei

How attractive is the nuclear interaction to form a bound state with nuclei?:

A simple estimate

For a mass μ particle in a square-well potential *V* of the radius *R*:

$$V \le -\frac{1}{2\mu}\left(\frac{\pi}{2R}\right)^2$$

The equality is for the unitary limit ($E_B = 0$).

Let's

$$R = (1.12\,fm)A^{1/3} = \left(\frac{3}{4\pi\rho_o}\right)^{1/3} A^{1/3} \qquad \text{with } \rho_o = 0.172\,fm^{-3}$$

We get

$$V \le -(20.4\ \text{MeV})\ A^{-2/3} \qquad \text{for } \mu = m_D \approx 1.87\ \text{GeV}$$

$$\le -(12.3\ \text{MeV})\ A^{-2/3} \qquad \text{for } \mu = m_{J/\psi} \approx 3.10\ \text{GeV}$$

J/*ψ*-nucleus folded potential

The approximation is

$$V_{J/\psi-A}(r) \approx \int d^3r' V_{J/\psi-N}(r-r')\rho_A(r') \, .$$

If the J/*ψ* interaction is weak, the standard "lowest-order impulse approximation" in nuclear physics is

$$V_{J/\psi-A}(r) = \frac{2\pi}{m_{red}} a_{J/\psi-N}\rho_A(r) \, .$$

Note that if the interaction should be strong enough to form a bound state, $a_{J/\psi}$ diverges and then changes its sign, $- \rightarrow +$, as the strength increases. $a_{J/\psi} \rightarrow \pm\infty$ diverges; $\sigma_{J/\psi} \rightarrow \infty$ unless inelastic process also occurs.

J/ψ nuclei using folded potentials

* *Nuclear-Bound Quarkonium*, S.J.Brodsky, I.Schmidt, & G.F.deTeramond,PRL(1990).
Comment: D.A.Wasson, PRL(1991).

* *Heavy-Quarkonia interactions with nucleons and nuclei,*
A.B.Kaidalov & P.E.Volkovitsky, PRL(1992)

* *Is J/ψ-nucleon scattering dominated by the gluonic van der Waals interaction?*
S.J.Brodsky & G.A.Miller, PLB(1997)

* *Proton-proton spin correlations at charm threshold and quarkonium bound to nuclei ,*
G.F.deTeramond, R.Espinoza, & M.Ortega-Rodriguez, PRD(1998).

Quark-meson coupling model

* *Nucleon and hadron structure changes in the nuclear medium and the impact on observables*, K.Sato, K.Ysushima, & A.W.Thomas, PPNP(2007).

* *Binding of D,D and J/ψ mesons in nuclei, K.Tsushima,* arXiv:0907.0244v1 [nucl-th].

New nuclear structure with J/ψ?

A small (0.2 ~0.3 fm), heavy (~3m_N), spin 1 and negative parity J/ψ placed in a nucleus with

v_N > $v_{J/\psi}$: ~ Nucleons move around J/ψ (Born-Oppenheimer)

For example, a J/ψ would sit in the middle of four nucleons in $^4\mathrm{He}_{J/\psi}$, squeezing the ^{4}He structure, while the nuclear ompressibility coefficient is

$$b_{\mathrm{comp}} \equiv \rho^2\partial^2(E/A) / \partial \rho^2 \equiv K/9 \approx 13\mathrm{MeV}.$$

The spin/parity 1^-: Effects on shell structure in heavier nuclei?

The real picture depends on the magnitude of $V_{J/\psi\text{-}N}$, $E_{B,J/\psi}$,

and $K.E._{J/\psi} = V_{J/\psi\text{-}N} + E_{B,J/\psi}$.

6. NLO effect and nuclear interaction of the excited c-c·bar mesons

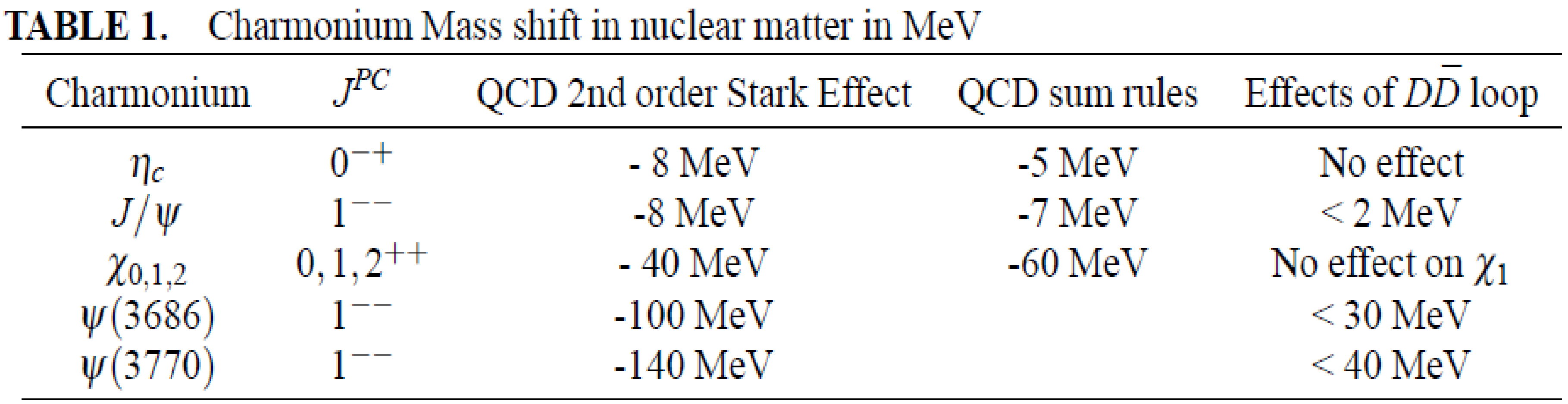


TABLE 1. Charmonium Mass shift in nuclear matter in MeV

Charmonium	J^{PC}	QCD 2nd order Stark Effect	QCD sum rules	Effects of $D\bar{D}$ loop
η_c	0^{-+}	- 8 MeV	-5 MeV	No effect
J/ψ	1^{--}	-8 MeV	-7 MeV	<2 MeV
$\chi_{0,1,2}$	$0,1,2^{++}$	- 40 MeV	-60 MeV	No effect on χ_1
$\psi(3686)$	1^{--}	-100 MeV		<30 MeV
$\psi(3770)$	1^{--}	-140 MeV		<40 MeV

S.H.Lee, arXiv:nucl-th/0310080
T.Song & S. H. Lee, PRD 72, 034002 (2005).

The issue of the coupling to other channels including inelastic ones.

Strong coupling of ψ’ to J/ψ

$$V_{\psi'} \approx -21\ \text{MeV} \times \left[\frac{1+C}{2}\,\frac{\alpha_{\psi'}}{2\ \text{GeV}^{-3}}\right]$$

$$\Gamma_{\psi' J/\psi} = |\mathcal{T}_{\psi' J/\psi}|^2 \frac{p_f}{32\pi(M_{\psi'}+m_N)M_{\psi'}m_N}\,\rho_N$$

$$\approx 70\ \text{MeV}\left[\frac{1+C}{2}\right]^2 \frac{[\alpha_{\psi'}}{2\ \text{GeV}^{-3}}]^2|F(q^2)|^2$$

$$\sigma(\psi' + N \to J/\psi + N) = \frac{1}{p_i}\,\frac{|\mathcal{T}_{\psi' J/\psi}|^2 p_f}{16\pi(M_{\psi'}+m_N)^2}$$

$$\approx 16\ \text{mb}\left[\frac{1\text{GeV}}{p_i}\right]\left[\frac{1+C}{2}\right]^2$$

$$\times\ |F(q^2)|^2,$$

A. Sibirtsev & M.B.Voloshin, PRD 71, 076005(2005)