Kondo effect for charm hadrons in nuclear matter

arXiv:1607.07948 [hep-ph]
(accepted in PRC)

Shigehiro YASUI
Tokyo Institute of Technology
in collaboration with K. Sudoh

1. Charm nucleus and Kodo effect
2. Kondo effect for D_s^- and D_s^{*-} meson
3. Kondo effect in atomic nucleus S.Y., Phys. Rev. C93, 065204 (2016)
4. Conclusion

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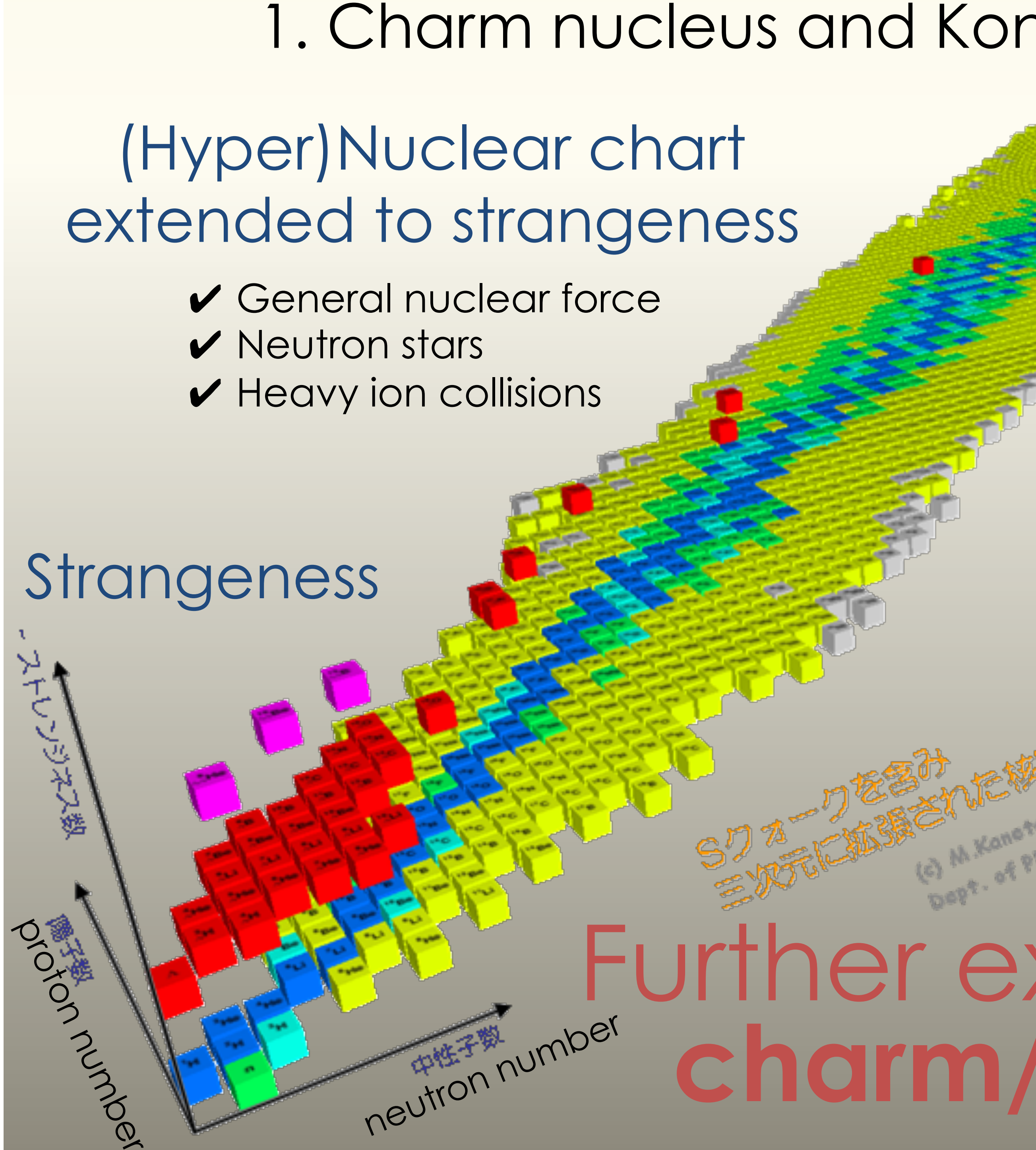
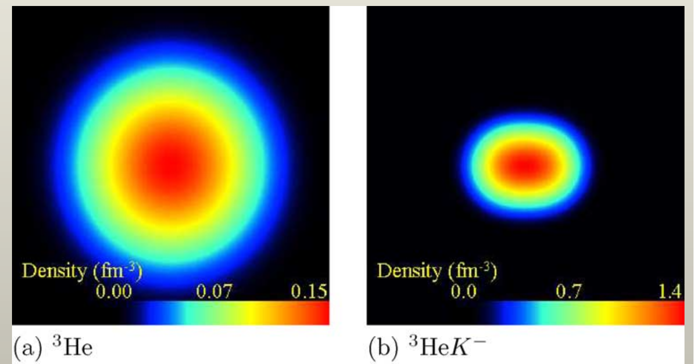
1. Charm nucleus and Kondo effect

(Hyper)Nuclear chart extended to strangeness

- ✔ General nuclear force
- ✔ Neutron stars
- ✔ Heavy ion collisions

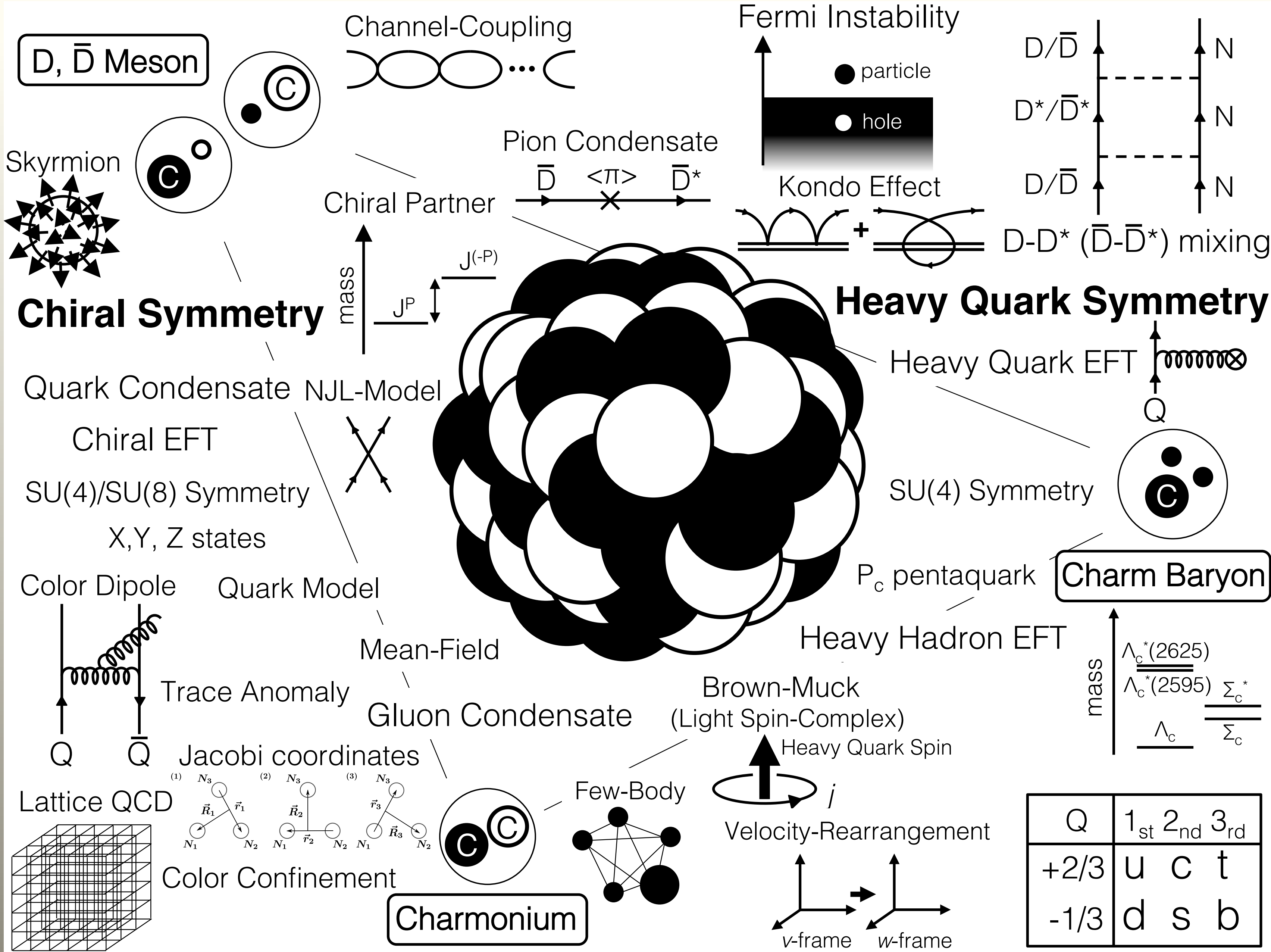


Anti-K mesic nuclei



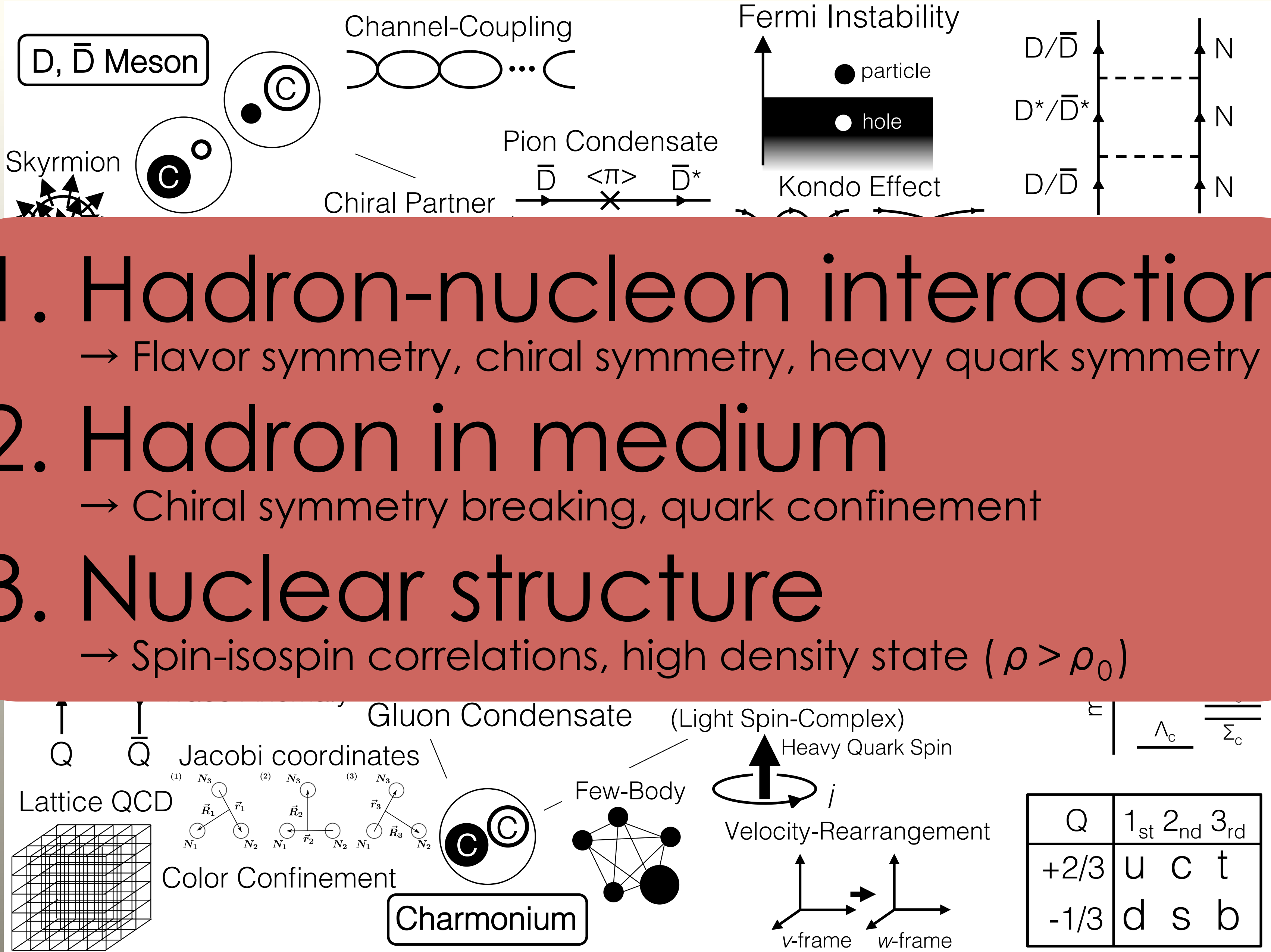
Further extension to **charm/bottom?**

1. Charm nucleus and Kondo effect



Q	1st 2nd 3rd
+2/3	u c t
-1/3	d s b

1. Charm nucleus and Kondo effect



1. Hadron-nucleon interaction

→ Flavor symmetry, chiral symmetry, heavy quark symmetry

2. Hadron in medium

→ Chiral symmetry breaking, quark confinement

3. Nuclear structure

→ Spin-isospin correlations, high density state ($\rho > \rho_0$)

1. Charm nucleus and Kondo effect

Review : “Heavy Hadrons in Nuclear Matter” (107 pages)

Heavy Hadrons in Nuclear Matter

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arXiv:1606.08685v1 [hep-ph] 28 Jun 2016

Abstract

Current studies on heavy hadrons in nuclear medium are reviewed with a summary of the basic theoretical concepts of QCD, namely chiral symmetry, heavy quark spin symmetry, and the effective Lagrangian approach. The nuclear matter is an interesting place to study the properties of heavy hadrons from many different points of view. We emphasize the importance of the following topics: (i) charm/bottom hadron-nucleon interaction, (ii) structure of charm/bottom nuclei, and (iii) QCD vacuum properties and hadron modifications in nuclear medium. We pick up three different groups of heavy hadrons, quarkonia (J/ψ, Υ), heavy-light mesons ($D/\bar{D}$, $\bar{B}/B$) and heavy baryons (Λ_c, Λ_b). The modifications of those hadrons in nuclear matter provide us with important information to investigate the essential properties of heavy hadrons. We also give the discussions about the heavy hadrons, not only in nuclear matter with infinite volume, but also in atomic nuclei with finite baryon numbers, to serve future experiments.

Contents

1 Introduction

It is an important problem to understand hadron properties based on the fundamental theory of the strong interaction, Quantum Chromodynamics (QCD). Due to the non-trivial features of the QCD dynamics at low energies, the hadron physics shows us many interesting and even unexpected non-trivial phenomena. The fact that hadronic phenomena are so rich implies that various studies from many different views are useful and indispensable to reveal the nature of the hadron dynamics. Not only isolated hadrons but also hadronic matter under extreme conditions of high temperature, of high baryon density, and of many different flavors provide important hints to understand the hadron dynamics.

One of familiar forms of hadronic matter is the atomic nucleus, the composite system of protons and neutrons. The nuclear physics has been developed so far, based on various phenomenological approaches (shell models, collective models, and so on). Recently, ab-initio calculations are being realized such that many-body nuclear problems are solved starting from the bare nucleon-nucleon interaction determined phenomenologically with high precision [1–3]. Yet a large step forward has been made; the lattice QCD has derived the nucleon-nucleon interaction [4, 5]. Thus the so far missing path from QCD to nucleus is now being exploited.

Nevertheless, if we look at the problem, for instance, neutron stars, we confront with a difficulty in explaining the so-called twice of the solar mass problem. Because of the high density environment in

What is *new* property of charm nuclei？

1. Charm nucleus and Kondo effect

- Heavy mass of charm hadron

m_c=1.3 GeV and m_b=4.7 GeV

- Heavy Quark Symmetry (HQS)

Hadron spin = light quark spin x heavy quark spin

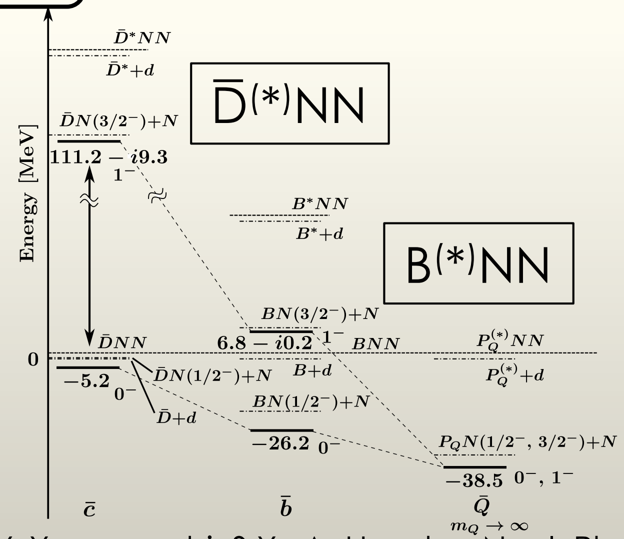
1. Charm nucleus and Kondo effect

Few-body study

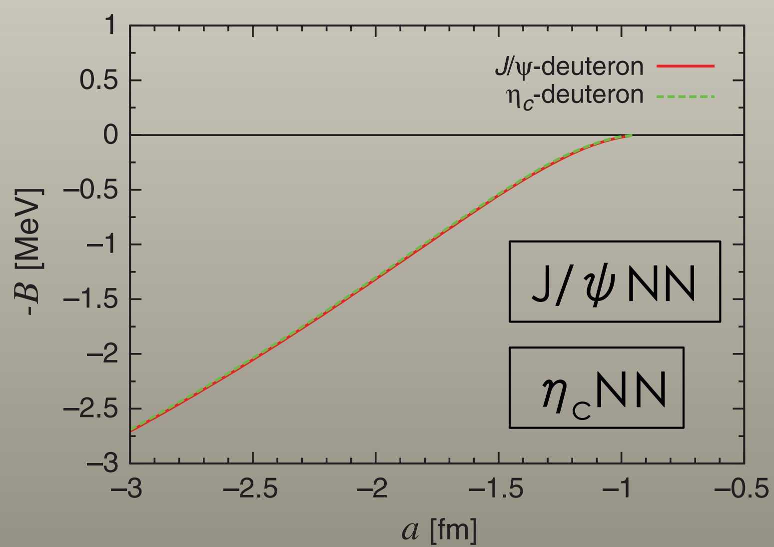
DNN

	HN1R $J=1$	$J=0$	Minnesota $J=0$	Av18 $J=0$
	Unbound	Bound	Bound	Bound
B	208	225	251	209
M_B	3537	3520	3494	3536
$\Gamma_{\pi Y_c N}$	—	26	38	22
E_{kin}	338	352	438	335
$V(NN)$	0	-2	19	-5
$V(DN)$	-546	-575	-708	-540
T_{nuc}	113	126	162	117
E_{NN}	113	124	181	113
P(odd)	75.0%	14.4%	7.4%	18.9%

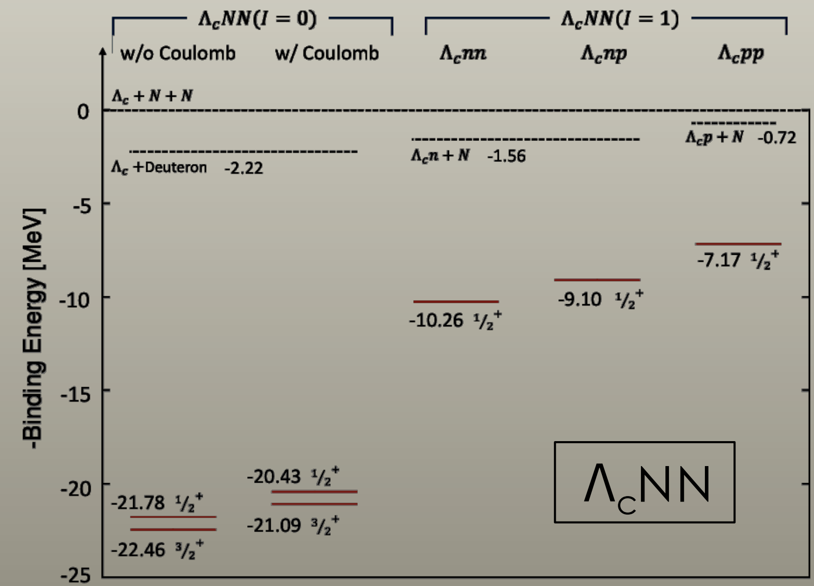
M. Bayer, C. W. Xiao, T. Hyodo, A. Dote, M. Oka, E. Oset, Phys. Rev. C86, 044004 (2012)



Y. Yamaguchi, S.Y., A. Hosaka, Nucl. Phys. A927, 110 (2014)



A. Yokota, E. Hiyama, M. Oka, Pog. Ther. Exp. Phys. 2013, 113D01



S. Maeda, M. Oka, A. Yokota, E. Hiyama, Y-R. Liu, Pog. Ther. Exp. Phys. 2016, 023D02

1. Charm nucleus and Kondo effect

Heavy-light meson

$\bar{D}$ meson

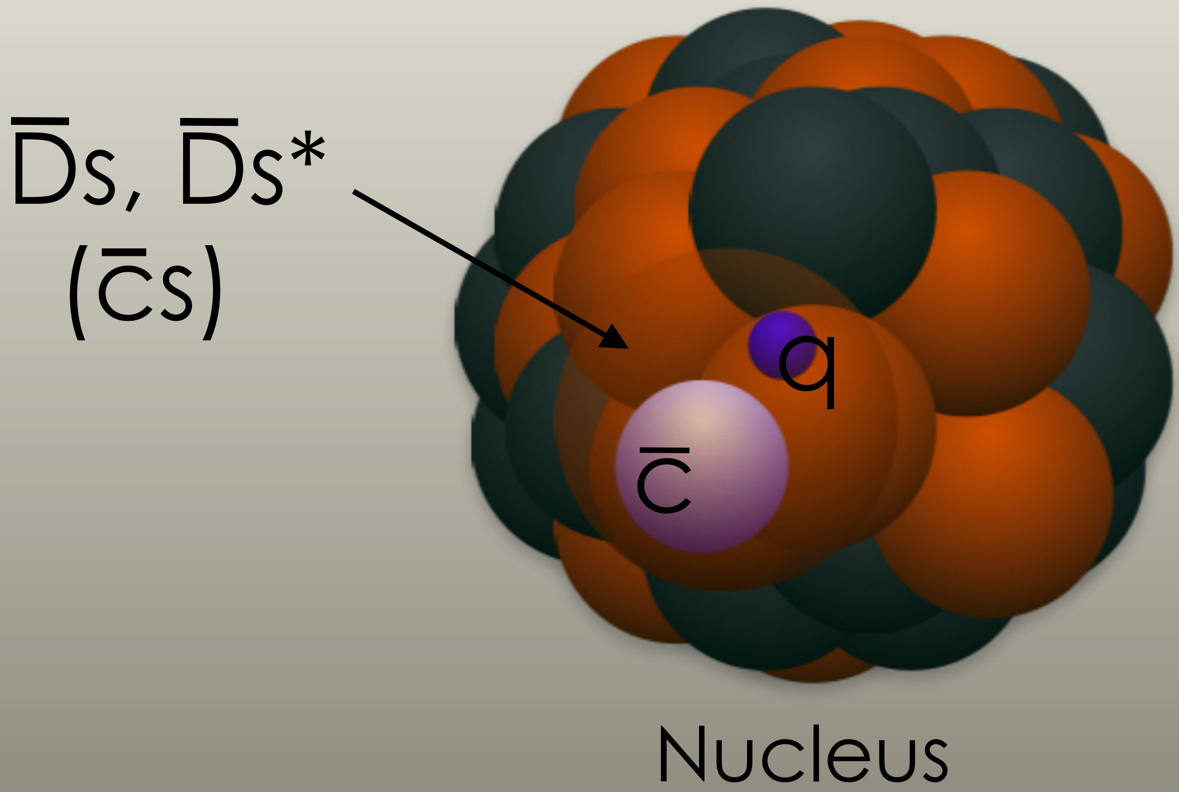
$\bar{Q}q$

1. Charm nucleus and Kondo effect

Heavy-light meson

Kondo effect

“Heavy impurity” nuclear physics



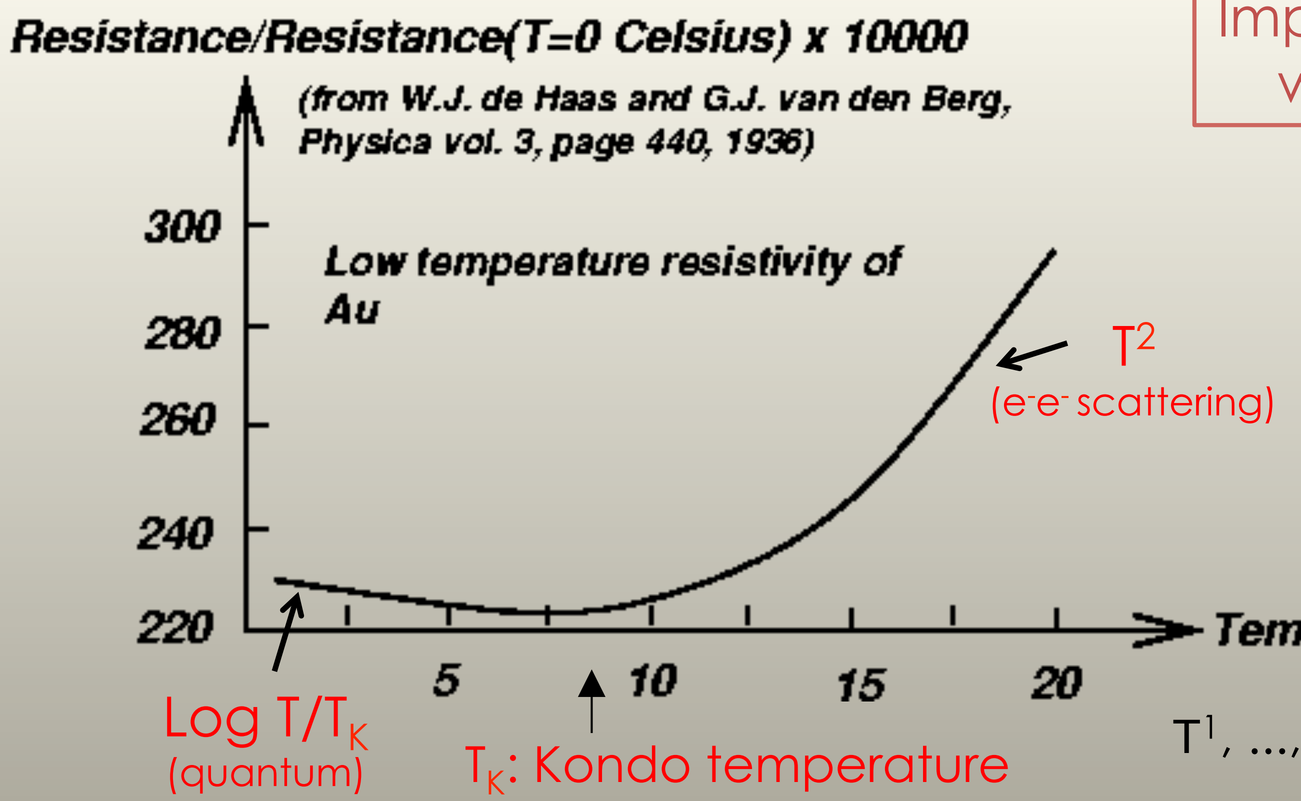
1. Charm nucleus and Kondo effect

What's "Kondo effect" ?

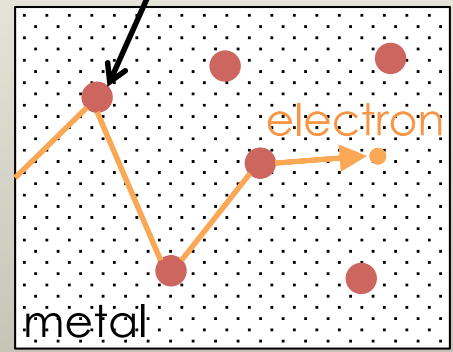
1. Charm nucleus and Kondo effect

1. Charm nucleus and Kondo effect

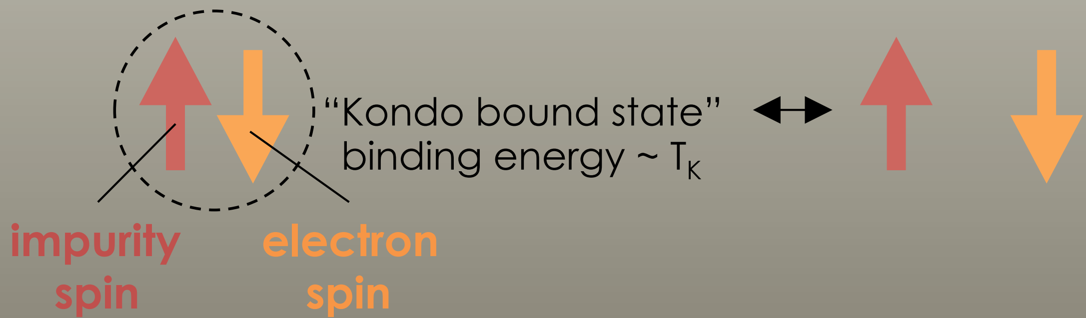
Original Work: J. Kondo (Prog. Theor. Phys. 32, 37 (1964))



Impurity atom with spin ½
with $T^a \cdot T^a$ interaction

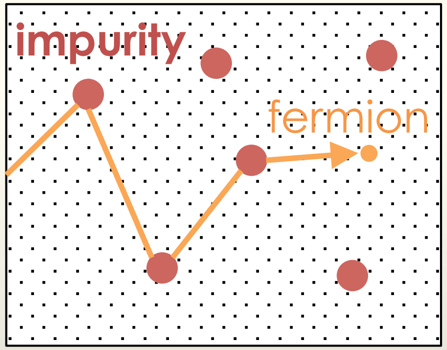


$T^1, \ldots, T^{n^2-1}$: generators of SU(n)
(n=2 for spin ½)



1. Charm nucleus and Kondo effect

Original Work: J. Kondo (Prog. Theor. Phys. 32, 37 (1964))



Heavy impurity

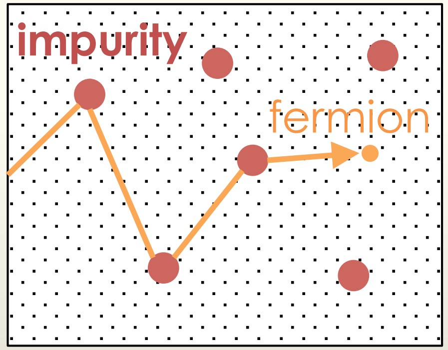
① **Fermi surface**
(degenerate state)

② **Loop effect**
(particle-hole creation)

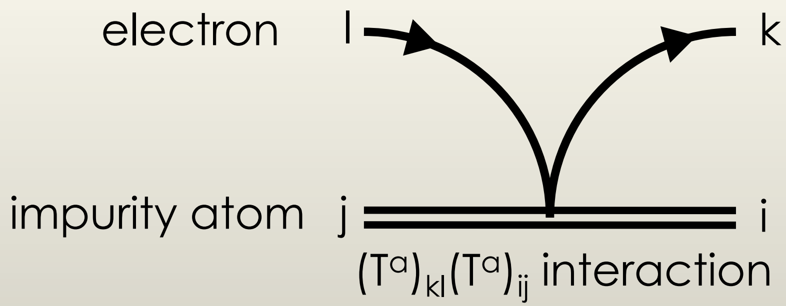
③ **Non-Abelian int.**
(SU(n) symmetry)

1. Charm nucleus and Kondo effect

Original Work: J. Kondo (Prog. Theor. Phys. 32, 37 (1964))



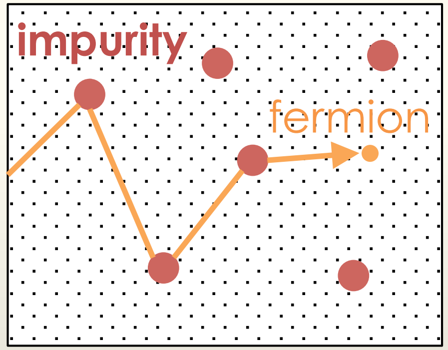
Scattering amplitude:



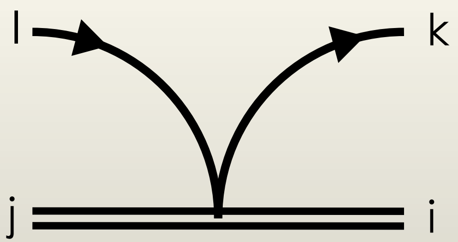
k, l, i, j= ↑ , ↓ in SU(n) (n=2 for spin ½)
T^1, ..., T^{n^2-1}: generators of SU(n)

1. Charm nucleus and Kondo effect

Original Work: J. Kondo (Prog. Theor. Phys. 32, 37 (1964))

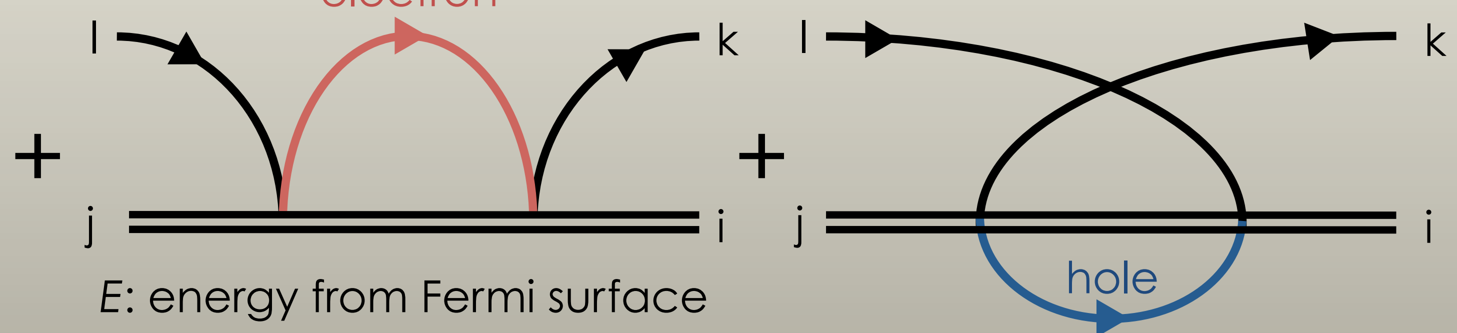


Scattering amplitude:



$(T^a)_{kl}(T^a)_{ij}$ interaction

k, l, i, j= ↑ , ↓ in SU(n) (n=2 for spin ½)
T^1, ..., T^{n^2-1}: generators of SU(n)



E: energy from Fermi surface

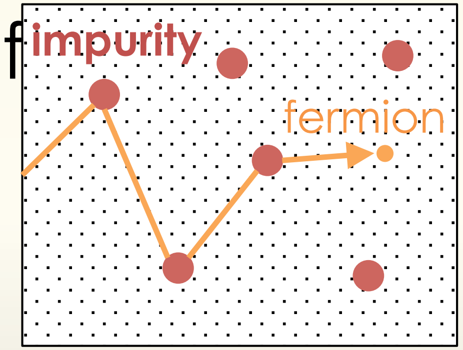
$$\times\left(-\frac{1}{n}\right)\int_{E>0}\frac{1}{E}\mathrm{d}E\sum(T^a)_{kl}(T^a)_{ij}$$

$$\times\int_{E>0}\left(\frac{n}{2}\frac{1}{-E}\frac{1}{n}\right)\mathrm{d}E\sum_a(T^a)_{kl}(T^a)_{ij}$$

Log E divergence for infrared limit (E→0) for ***any small coupling***

→ Logarithmic divergence in resistance of electron

1. Charm nucleus and Kondo ef



Application of Kondo effect to
Hadron/nuclear physics

Fermi gas	electron gas	**nuclear matter** (p,n)	**quark matter** (u,d,s)
Heavy impurity	spin-atoms	**D/B mesons**	**c/b quarks**
Fermi surface (degenerate state)	✔	✔	✔
Loop effect (particle-hole creation)	electron-hole	**nucleon-hole**	**quark-hole**
Non-Abelian int. (SU(n) symmetry)	$SU(2)_{spin}$	$\mathbf{SU(2)_{isospin}}$	$\mathbf{SU(3)_{color}}$

1. **NJL-type:** S.Y., K.Sudoh, Phys. Rev. C88, 015201 (2013)
2. **QCD Kondo**: K. Hattori, K. Itakura, S. Ozaki, S.Y., Phys. Rev. D92, 065003 (2015)
3. **Magnetic catalysis QCD Kondo effect**: S. Ozaki, K. Itakura, Y. Kuramoto, Phys. Rev. D94, 074013 (2016)
4. **Kondo effect in atomic nucleus**: S.Y., Phys. Rev. C93, 065204 (2016)
5. **Kondo effect of Ds meson**: S.Y., arXiv:1607.07948 [hep-ph]
6. **QCD Kondo phase**: S.Y., K. Suzuki, K. Itakura, arXiv:1604.09229 [hep-ph]
7. **Single heavy-quark QCD Kondo cloud**, S.Y., arXiv:1608.06450 [hep-ph]
8. **Conformal theory**, T. Kumura, S. Ozaki, arXiv:1611.07284 [cond-mat]
9. **QCD Kondo effect and color superconductivity**, T. Kanazawa, S. Uchino, Phys. Rev. D94, 114005 (2016)
10. **Topology and stability of QCD Kondo phase**, S.Y., K. Suzuki, K. Itakura, submitted to arXiv

$\bar{D}^0(\bar{c}u)$ $D^-(\bar{c}d)$ $\boxed{D_s^-(\bar{c}s)}$

2. Kondo effect for D_s^- and D_s^{*-} meson

	$\bar{D}s/\bar{D}s^*$ ($\bar{c}s$)	$\bar{D}/\bar{D}^*$ ($\bar{c}u,\bar{c}d$)
Electric charge (Coulomb-assisted bound state)	-1	0, -1
Long life-time of vector-meson	< 1.9 MeV	< 2.1 MeV, 0.834 MeV
Short-distance repulsion	No	Yes
Non-Abelian interaction	*spin*	*spin+isospin*

2. Kondo effect for D_s^- and D_s^{*-} meson

S.Y., arXiv:1607.07948 [hep-ph]

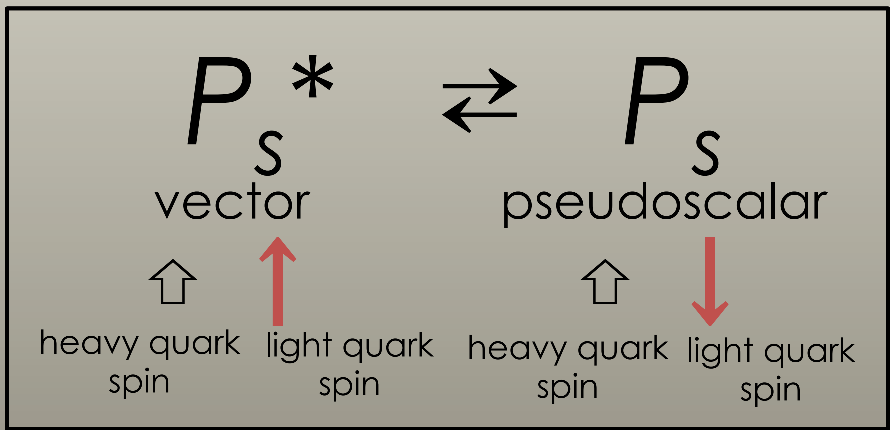
① Interaction of $\bar{D}s$ ($\bar{D}s^*$) meson and nucleon

φ : nucleon field

$$\mathcal{L}_{\rm int} = c_s \varphi^\dagger \varphi \left(\delta^{ij} P^{*i\dagger}_{sv} P^{*j}_{sv} + P^\dagger_{sv} P_{sv} \right)$$ spin-nonexchange term

$$+ c_t \sum_k \varphi^\dagger \sigma^k \varphi \left(\epsilon^{ijk} P^{*i\dagger}_{sv} P^{*j}_{sv} - \left(P^{*k\dagger}_{sv} P_{sv} - P^\dagger_{sv} P^{*k}_{sv} \right) \right)$$ spin-exchange term

heavy quark limit ($m_Q \to \infty$)

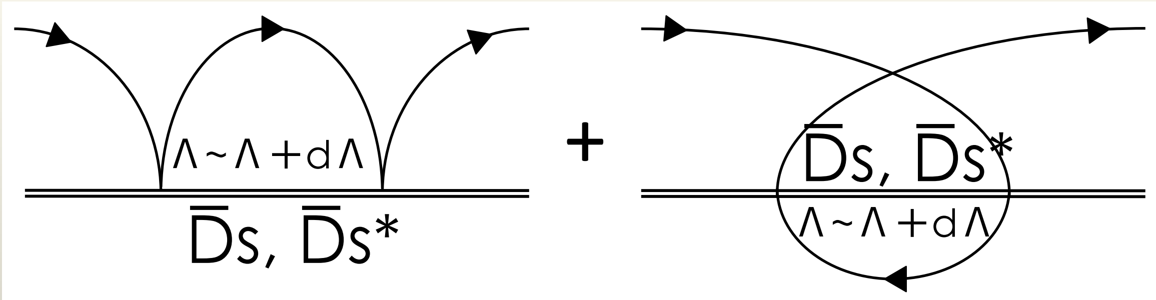


2. Kondo effect for D_s^- and D_s^{*-} meson

S.Y., K. Sudoh, arXiv:1607.07948 [hep-ph]

② Renormalization group equation

nucleon



nucleon (hole)

bare $\bar{D}s$, $\bar{D}s^*$

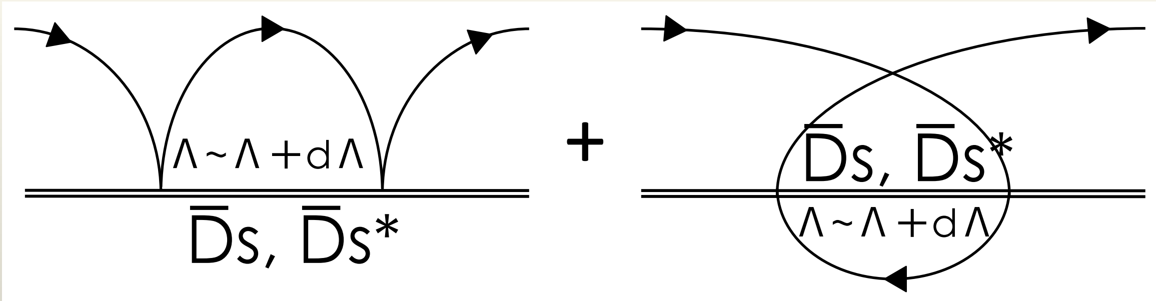
$\bar{D}s$, $\bar{D}s^*$ dressed by nucleon/hole

2. Kondo effect for D_s^- and D_s^{*-} meson

S.Y., K. Sudoh, arXiv:1607.07948 [hep-ph]

② Renormalization group equation

nucleon

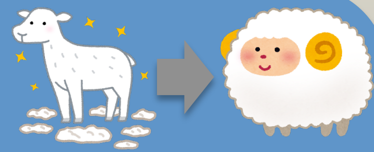


nucleon (hole)

$$\ell = -\ln \Lambda / k_{\mathrm{F}}$$

(Λ : loop momentum)

spin-nonexchange term $$\frac{\mathrm{d}}{\mathrm{d}\ell} c_s(\ell) = 0$$

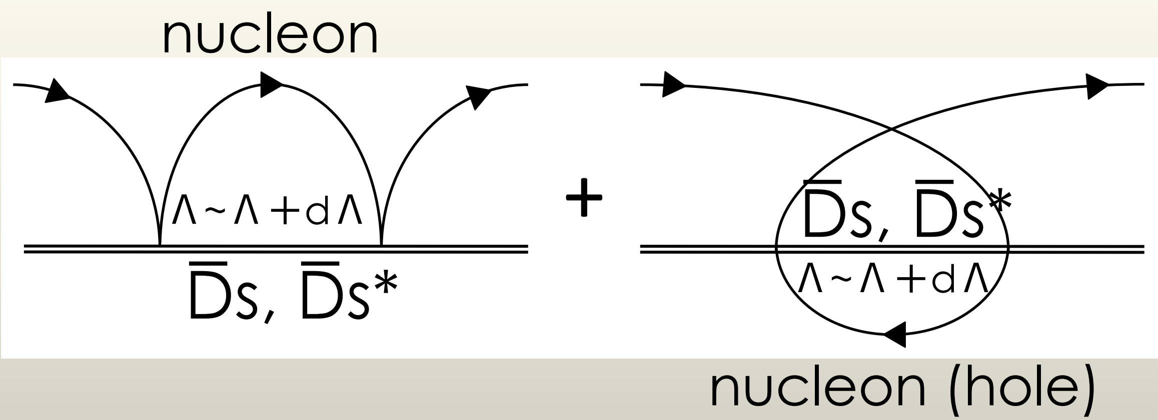


spin-exchange term $$\frac{\mathrm{d}}{\mathrm{d}\ell} c_t(\ell) = \frac{m k_{\mathrm{F}}}{2\pi^2} c_t(\ell)^2$$

2. Kondo effect for D_s^- and D_s^{*-} meson

S.Y., K. Sudoh, arXiv:1607.07948 [hep-ph]

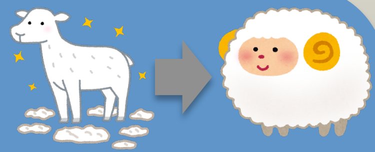
② Renormalization group equation



$$\ell = -\ln \Lambda / k_{\mathrm{F}}$$

(Λ: loop momentum)

spin-nonexchange term $c_s(\ell) = c_s$



spin-exchange term $$c_t(\ell) = \frac{c_t}{1 - \dfrac{mk_{\mathrm{F}}}{2\pi^2} c_t \ell}$$

$c_t > 0$

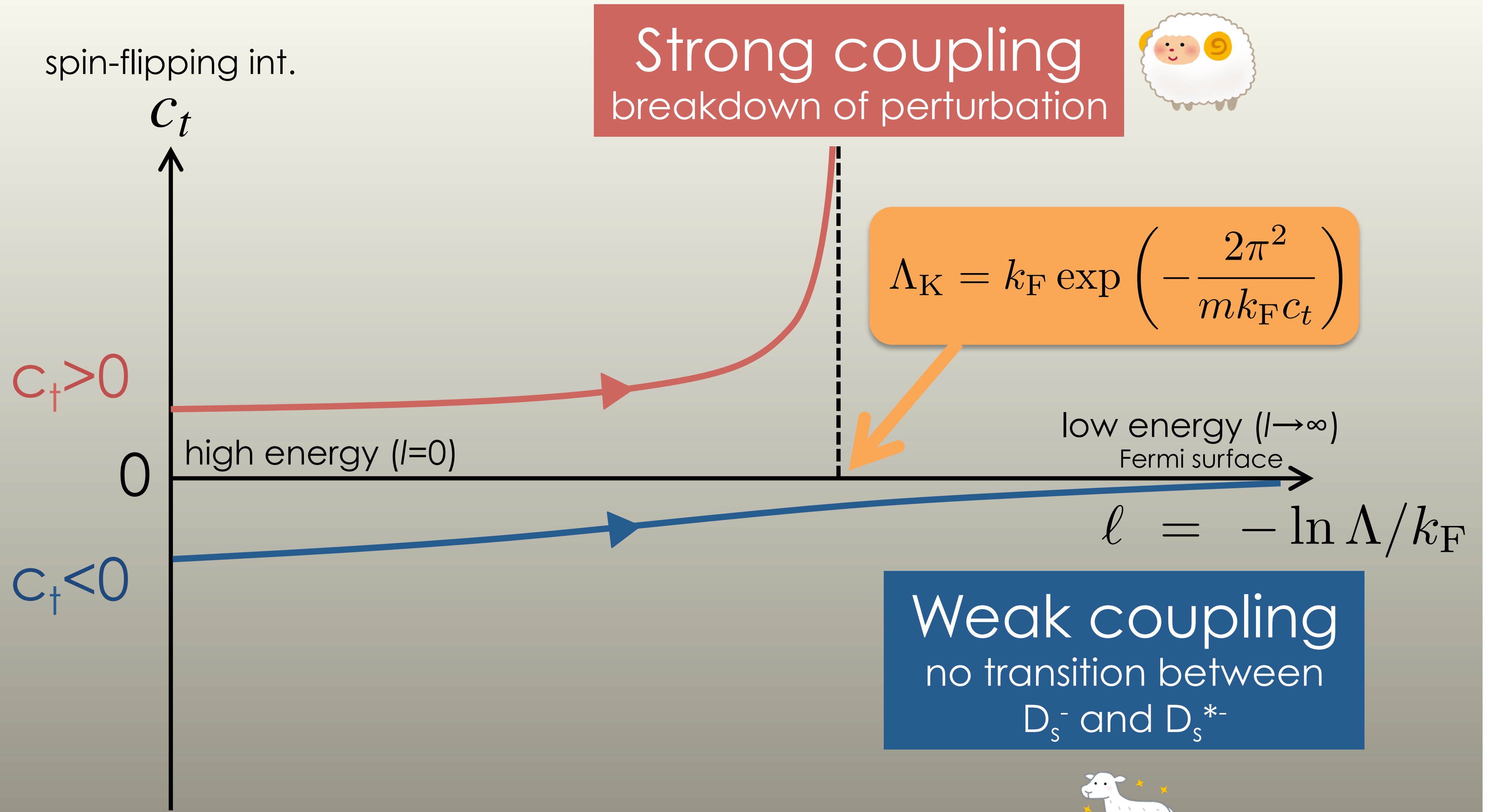
Kondo scale
(infrared singularity)

$$\Lambda_{\mathrm{K}} = k_{\mathrm{F}} \exp\left(-\frac{2\pi^2}{mk_{\mathrm{F}} c_t}\right)$$

2. Kondo effect for D_s^- and D_s^{*-} meson

S.Y., K. Sudoh, arXiv:1607.07948 [hep-ph]

② Renormalization group equation



2. Kondo effect for D_s^- and D_s^{*-} meson

S.Y., K. Sudoh, arXiv:1607.07948 [hep-ph]

③ Mean-field approach **($c_t>0$)**

Kondo scale → non-perturbative treatment

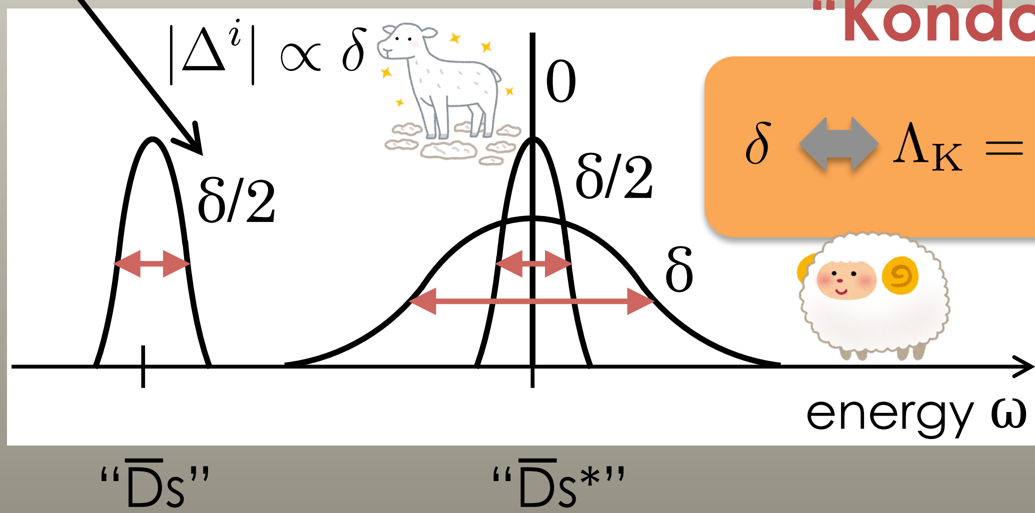
$$\bar{D}_s^{(*)} \leftrightarrow \frac{1}{2}\psi_\sigma^i$$

s quark field
(σ: light-spin, i:heavy-quark spin)

$$\Delta^i \equiv -2\frac{C_t}{4}\sum_{\boldsymbol{k},\sigma}\langle \psi_\sigma^{i\dagger}\varphi_{\boldsymbol{k}\sigma}\rangle$$

gap: mixing of s quark and nucleon

Spectral function $\rho(\omega)$



"Kondo resonance"

$$\delta \Leftrightarrow \Lambda_{\mathrm{K}} = k_{\mathrm{F}} \exp\left(-\frac{2\pi^2}{mk_{\mathrm{F}}c_t}\right)$$

→ Research spectral function of D_s^{bar} meson in nucleus!

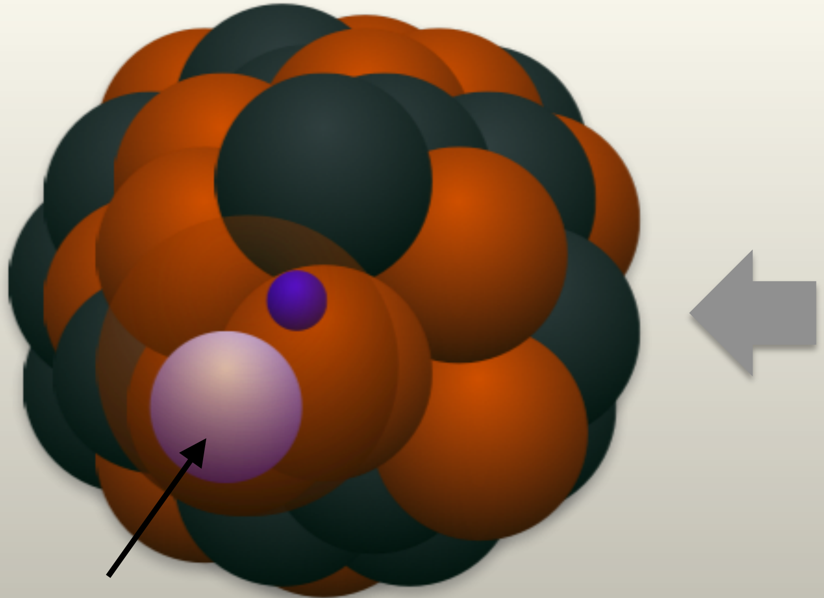
$\bar{D}^0(\bar{c}u)$ $D^-(\bar{c}d)$ $D_s^-(\bar{c}s)$

3. Kondo effect in atomic nuclei

S.Y., Phys. Rev. C93, 065204 (2016)

"simple model" for atomic nucleus

-shell model-like picture-



$\bar{\mathrm{D}}$ meson isospin 1/2

$\bar{D}^0(\bar{c}u)$

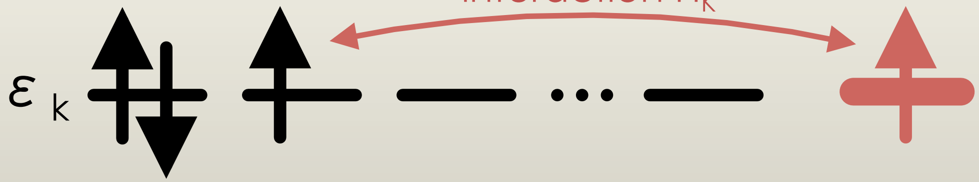
$D^-(\bar{c}d)$

nucleon sector (N states)

↑/↓ for proton/neutron

$\bar{\mathrm{D}}$ sector

interaction H_K



$k = 1 \quad 2 \quad 3 \quad \cdots \quad N$

cf. We consider one shell space. But this method can be extended to multi-shells.

$$H = H_0 + H_{\mathrm{K}}$$

$$H_0 = \sum \epsilon_k c_{k\sigma}{}^\dagger c_{k\sigma}$$ kinetic term

$$H_{\mathrm{K}} = g \sum \left(c_{k'\downarrow}{}^\dagger c_{k\uparrow} T_+ + c_{k'\uparrow}{}^\dagger c_{k\downarrow} T_- + \left(c_{k'\uparrow}{}^\dagger c_{k\uparrow} - c_{k'\downarrow}{}^\dagger c_{k\downarrow} \right) T_3 \right)$$

Kondo (isospin-flipping) interaction à la Lipkin model

$c_{k\sigma}$: annihilation operator for nucleon in level k and isospin σ

T_+, T_-, T_3: isospin operator for D meson

Cf. π-exchange interaction: S.Y. and K.Sudoh, Phys. Rev. D80, 034008 (2009)

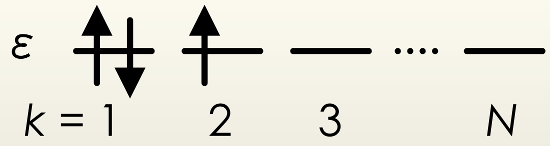
Purpose: the ground state energy?

3. Kondo effect in atomic nuclei

S.Y., Phys. Rev. C93, 065204 (2016)

“Exact solution”

$\boxed{\text{Simple case: } \varepsilon_k = \varepsilon}$



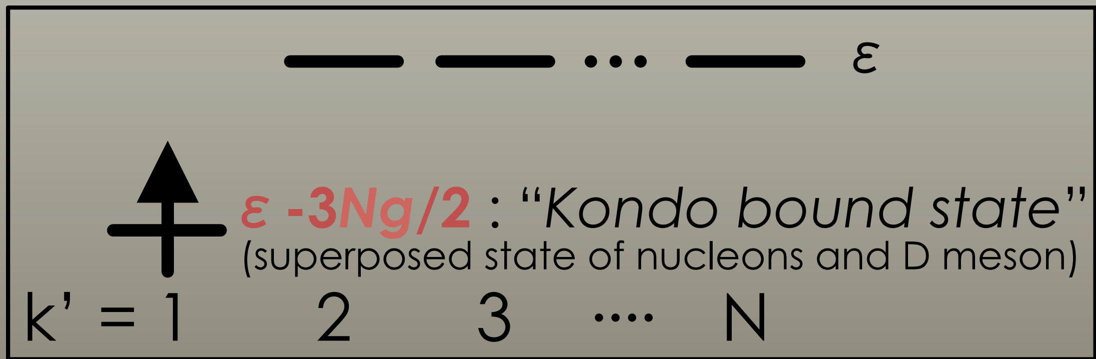
Case of nucleon #=1

$$H|\psi^{(1)}_{0,0}\rangle = E|\psi^{(1)}_{0,0}\rangle \qquad |\psi^{(1)}_{0,0}\rangle = \sum \Gamma_k \underline{\left(c_{k\uparrow}{}^{\dagger} |\downarrow\rangle_{\mathrm{imp}} - c_{k\downarrow}{}^{\dagger} |\uparrow\rangle_{\mathrm{imp}} \right)}$$ singlet w.f.

$$\{\Gamma_k\} = \{\Gamma_1, \ldots, \Gamma_N\}$$

$$\epsilon \Gamma_k - \frac{3}{2} g \sum \Gamma_n = E \Gamma_k$$ linear algebraic equation

$$E = \epsilon - \frac{3}{2} N g \ (\mathrm{n.d.f.} = 1), \ \ \epsilon \ (\mathrm{n.d.f.} = N-1)$$ solution !!



3. Kondo effect in atomic nuclei

S.Y., Phys. Rev. C93, 065204 (2016)

What's about more general cases?

Mean-field (+RPA) approach

How does it work?

Step 1. Introduce auxiliary fermion fields f_σ (SU(2))

$$T_+ = f_\uparrow^\dagger f_\downarrow,$$
$$T_- = f_\downarrow^\dagger f_\uparrow,$$
$$T_3 = \frac{1}{2}(f_\uparrow^\dagger f_\uparrow - f_\downarrow^\dagger f_\downarrow).$$

$$\boxed{\sum_\sigma f_\sigma^\dagger f_\sigma = 1}$$

fermion # 0, 2

fermion # 1

physical space

auxiliary fermion # constraint

Step 2. Introduce Lagrange multiplier λ

$$H = \sum \epsilon_k c_{k\sigma}^\dagger c_{k\sigma} + g\left(\sum f_\sigma^\dagger f_{\sigma'} c_{k'\sigma'}^\dagger c_{k\sigma} - \frac{1}{2}\sum c_{k'\sigma}^\dagger c_{k\sigma}\right) + \underline{\lambda\left(\sum f_\sigma^\dagger f_\sigma - 1\right)}$$

Step 3. Apply mean-field (Δ) approx. $\boxed{\Delta = -g\sum\langle f_\sigma^\dagger c_{k\sigma}\rangle}$ **"gap"** singlet

$$H_{\mathrm{MF}} = \sum \epsilon_k c_{k\sigma}^\dagger c_{k\sigma} + \sum\left(\Delta^* f_\sigma^\dagger c_{k\sigma} + \Delta c_{k\sigma}^\dagger f_\sigma\right) + \lambda\sum f_\sigma^\dagger f_\sigma + \frac{|\Delta|^2}{g} - \lambda$$

Step 4. Variation by λ and Δ $\quad \frac{\partial}{\partial\lambda}\langle H_{\mathrm{MF}}\rangle = 0, \quad \frac{\partial}{\partial\Delta}\langle H_{\mathrm{MF}}\rangle = 0$

3. Kondo effect in atomic nuclei

S.Y., Phys. Rev. C93, 065204 (2016)

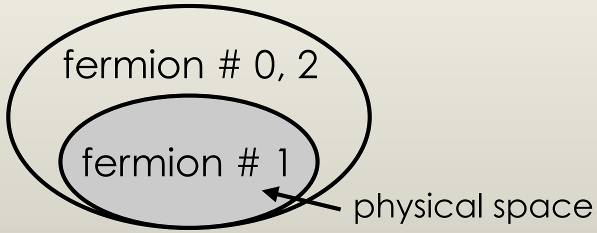
What's about more general cases?

Mean-field (+RPA) approach

Step 1. Introduce auxiliary fermion fields f_σ (SU(2))

$$T_+ = f_\uparrow^\dagger f_\downarrow,$$
$$T_- = f_\downarrow^\dagger f_\uparrow,$$
$$T_3 = \frac{1}{2}(f_\uparrow^\dagger f_\uparrow - f_\downarrow^\dagger f_\downarrow).$$

$$\boxed{\sum f_\sigma^\dagger f_\sigma = 1}$$



auxiliary fermion # constraint

Step 2. Introduce Lagrange multiplier λ

$$H = \sum \epsilon_k c_{k\sigma}^\dagger c_{k\sigma} + g\left(\sum f_\sigma^\dagger f_{\sigma'} c_{k'\sigma'}^\dagger c_{k\sigma} - \frac{1}{2}\sum c_{k'\sigma}^\dagger c_{k\sigma}\right) + \underline{\lambda\left(\sum f_\sigma^\dagger f_\sigma - 1\right)}$$

Step 3. Apply mean-field (Δ) approx.

$$\boxed{\Delta = -g\sum \langle f_\sigma^\dagger c_{k\sigma}\rangle}$$

"gap"

singlet

$$H_{\mathrm{MF}} = \sum \epsilon_k c_{k\sigma}^\dagger c_{k\sigma} + \sum\left(\Delta^* f_\sigma^\dagger c_{k\sigma} + \Delta c_{k\sigma}^\dagger f_\sigma\right) + \lambda\sum f_\sigma^\dagger f_\sigma + \frac{|\Delta|^2}{g} - \lambda$$

Step 4. Variation by λ and Δ

$$\frac{\partial}{\partial\lambda}\langle H_{\mathrm{MF}}\rangle = 0, \quad \frac{\partial}{\partial\Delta}\langle H_{\mathrm{MF}}\rangle = 0$$

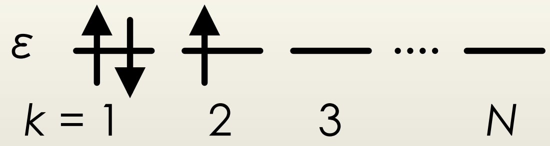
3. Kondo effect in atomic nuclei

S.Y., Phys. Rev. C93, 065204 (2016)

What's about more general cases?

Mean-field (+RPA) approach

Simple case: $\varepsilon_k = \varepsilon$



Step 3

$$H_{\mathrm{MF}} = \psi^\dagger \mathcal{H}_{cf} \psi + \frac{|\Delta|^2}{g} - \lambda$$

Matrix

Attraction by
N-D mixing (Δ)
↓
New ground state

$$
\mathcal{H}_{cf} = \begin{array}{cc}
 & \begin{array}{cccc|cccc} N_\uparrow & N_\uparrow & & D_\uparrow & N_\downarrow & N_\downarrow & & D_\downarrow \end{array} \\
\begin{array}{c} N_\uparrow \\ N_\uparrow \\ \\ D_\uparrow \\ N_\downarrow \\ N_\downarrow \\ \\ D_\downarrow \end{array} &
\left(\begin{array}{cccc|cccc}
\epsilon & 0 & \cdots & \Delta^* & 0 & 0 & \cdots & 0 \\
0 & \epsilon & \cdots & \Delta^* & 0 & 0 & \cdots & 0 \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\
\Delta & \Delta & \cdots & \lambda & 0 & 0 & \cdots & 0 \\
\hline
0 & 0 & \cdots & 0 & \epsilon & 0 & \cdots & \Delta^* \\
0 & 0 & \cdots & 0 & 0 & \epsilon & \cdots & \Delta^* \\
\vdots & \vdots & \ddots & \vdots & \vdots & \vdots & \ddots & \vdots \\
0 & 0 & \cdots & 0 & \Delta & \Delta & \cdots & \lambda
\end{array}\right)
\end{array}
$$

Basis

$$
\psi = \left(\begin{array}{c} c_{1\uparrow} \\ \vdots \\ c_{N\uparrow} \\ f_\uparrow \\ \hline c_{1\downarrow} \\ \vdots \\ c_{N\downarrow} \\ f_\downarrow \end{array}\right)
$$

Diagonalization

(next page)

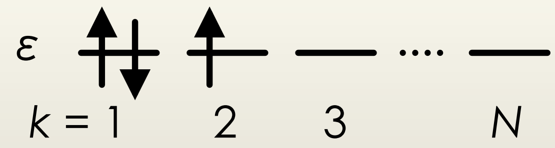
3. Kondo effect in atomic nuclei

S.Y., Phys. Rev. C93, 065204 (2016)

What's about more general cases?

Mean-field (+RPA) approach

Simple case: $\varepsilon_k = \varepsilon$



Step 3

$$H_{\mathrm{MF}} = \phi^\dagger \mathcal{H}_{cf}^{\mathrm{diag}} \phi + \frac{|\Delta|^2}{g} - \lambda$$

$$= \sum E_k {d_{k\sigma}}^\dagger d_{k\sigma} + \frac{|\Delta|^2}{g} - \lambda$$

$$D = \sqrt{(\epsilon - \lambda)^2 + 4N|\Delta|^2}$$

Diagonalized matrix

$$\mathcal{H}_{cf}^{\mathrm{diag}} = \mathrm{diag}\left(\epsilon, \dots, \epsilon, \underbrace{\frac{1}{2}(\epsilon + \lambda - D)}_{\text{lowest energy } (\uparrow)}, \frac{1}{2}(\epsilon + \lambda + D), \epsilon, \dots, \epsilon, \underbrace{\frac{1}{2}(\epsilon + \lambda - D)}_{\text{lowest energy } (\downarrow)}, \frac{1}{2}(\epsilon + \lambda + D)\right)$$

New basis

$$\phi = \begin{pmatrix} d_{1\uparrow} \\ \vdots \\ d_{N\uparrow} \\ d_{N+1\uparrow} \\ \hline d_{1\downarrow} \\ \vdots \\ d_{N\downarrow} \\ d_{N+1\downarrow} \end{pmatrix}$$

$$\begin{aligned}
d_{1\sigma} &= \frac{1}{\sqrt{2}}(c_{1\sigma} - c_{2\sigma}) \\
d_{2\sigma} &= \frac{1}{\sqrt{2}}(c_{1\sigma} - c_{3\sigma}) \\
&\vdots \\
d_{N-1\sigma} &= \frac{1}{\sqrt{2}}(c_{1\sigma} - c_{N\sigma}) \\
d_{N\sigma} &= \boxed{\frac{1}{\sqrt{2N}}\sqrt{1 - \frac{\epsilon - \lambda}{D}}(c_{1\sigma} + \ldots + c_{N\sigma}) - \frac{1}{\sqrt{2}}\sqrt{1 + \frac{\epsilon - \lambda}{D}} f_\sigma} \\
d_{N+1\sigma} &= \frac{1}{\sqrt{2N}}\sqrt{1 + \frac{\epsilon - \lambda}{D}}(c_{1\sigma} + \ldots + c_{N\sigma}) + \frac{1}{\sqrt{2}}\sqrt{1 - \frac{\epsilon - \lambda}{D}} f_\sigma
\end{aligned}$$

Linear combination of (coherent) nucleon and D meson

$$\boxed{|\psi_0\rangle = {d_{N\uparrow}}^\dagger {d_{N\downarrow}}^\dagger |0\rangle}$$

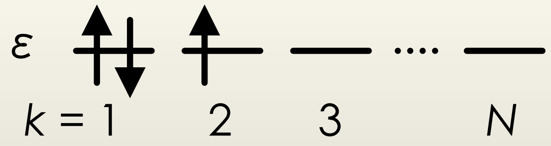
3. Kondo effect in atomic nuclei

S.Y., Phys. Rev. C93, 065204 (2016)

What's about more general cases?

Mean-field (+RPA) approach

Simple case: $\varepsilon_k = \varepsilon$



Step 3

$$H_{\rm MF} = \phi^\dagger \mathcal{H}^{\rm diag}_{cf} \phi + \frac{|\Delta|^2}{g} - \lambda$$

$$= \sum E_k {d_{k\sigma}}^\dagger d_{k\sigma} + \frac{|\Delta|^2}{g} - \lambda$$

Diagonalized matrix

$$D = \sqrt{(\epsilon - \lambda)^2 + 4N|\Delta|^2}$$

$$\mathcal{H}^{\rm diag}_{cf} = \mathrm{diag}\left(\epsilon, \ldots, \epsilon, \frac{1}{2}(\epsilon + \lambda - D), \frac{1}{2}(\epsilon + \lambda + D), \epsilon, \ldots, \epsilon, \frac{1}{2}(\epsilon + \lambda - D), \frac{1}{2}(\epsilon + \lambda + D)\right)$$

lowest energy (↑) lowest energy (↓)

Step 4

$$E_{\rm MF}(\lambda, \Delta) = \langle \psi_0 | H_{\rm MF} | \psi_0 \rangle \qquad |\psi_0\rangle = {d_{N\uparrow}}^\dagger {d_{N\downarrow}}^\dagger |0\rangle$$

$$= 2E_N + \frac{|\Delta|^2}{g} - \lambda$$

Variation by $\frac{\partial}{\partial \lambda} E_{\rm MF} = 0, \quad \frac{\partial}{\partial \Delta} E_{\rm MF} = 0$

$$\lambda = \epsilon, \quad \Delta = \sqrt{N g}$$

$$\boxed{E_{\rm MF}(\epsilon, \sqrt{N g}) = \epsilon - N g}$$

"Kondo bound state"

Binding energy (MF): *Ng*

different form exact solution 3*Ng*/2?

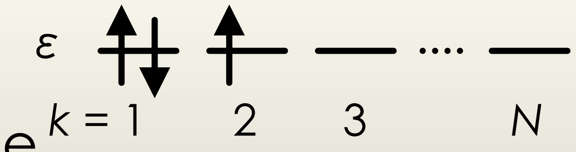
3. Kondo effect in atomic nuclei

S.Y., Phys. Rev. C93, 065204 (2016)

What's about more general cases?

Mean-field (+RPA) approach

Simple case: $\varepsilon_k = \varepsilon$



① Mean-value of auxiliary fermion number is one.

$$\langle \psi_0 | \sum f_\sigma{}^\dagger f_\sigma | \psi_0 \rangle = 1$$

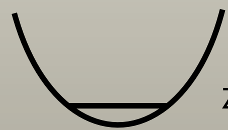
② Fluctuation effect (random-phase approximation; RPA)

$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X \\ Y \end{pmatrix} = \Omega_\nu \begin{pmatrix} X \\ Y \end{pmatrix}$$

$$A_{\mu\nu\rho\sigma} = \langle \psi_0 | \left[a_{0\nu}{}^\dagger a_{1\mu}, \left[H, a_{1\rho}{}^\dagger a_{0\sigma} \right] \right] | \psi_0 \rangle$$

$$-B_{\mu\nu\rho\sigma} = \langle \psi_0 | \left[a_{0\nu}{}^\dagger a_{1\mu}, \left[H, a_{0\sigma}{}^\dagger a_{1\rho} \right] \right] | \psi_0 \rangle$$

$$\{\Omega_\nu\} = \{\Omega_{\pm 1}, \Omega_{\pm 2}, \Omega_{\pm 3}, \Omega_0\}$$
$$= \left\{ \pm\sqrt{2}Ng, \pm\sqrt{2}Ng, \pm\sqrt{2}Ng, 0 \right\}$$



zero-point energy in H.O. potential

$$\Delta E_{\mathrm{RPA}} = \frac{1}{2} \sum_{\nu > 0} \Omega_\nu - \frac{1}{2} \mathrm{Tr} A$$
$$= \frac{1}{2}(3\sqrt{2} - 5)Ng$$
$$\simeq -0.378Ng,$$

Binding energy (MF+RPA): 1.378*Ng*

close to exact solution 3*Ng*/2=1.5*Ng*!!

$$\begin{aligned} E_{\mathrm{MF+shift+RPA}} &= E_{\mathrm{MF+shift}} + \Delta E_{\mathrm{RPA}} \\ &= \epsilon - \frac{1}{2}(7 - 3\sqrt{2})Ng \\ &\simeq \epsilon - \underline{1.378Ng}. \end{aligned}$$

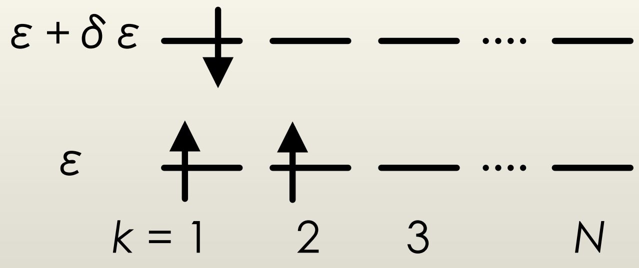
3. Kondo effect in atomic nuclei

S.Y., Phys. Rev. C93, 065204 (2016)

What's about more general cases?

Mean-field (+RPA) approach

$\boxed{\text{Simple case: } \varepsilon_k = \varepsilon}$



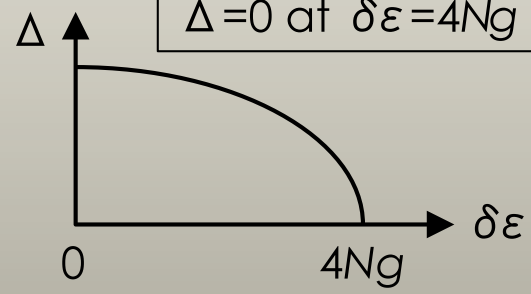
③ Violation of isospin symmetry (application)

$$H_0 \to H_0 = \sum \epsilon_{k\sigma} c_{k\sigma}{}^{\dagger} c_{k\sigma}$$

$\boxed{\varepsilon_{\uparrow} = \varepsilon,\ \varepsilon_{\downarrow} = \varepsilon + \delta\varepsilon}$

$$\lambda = \epsilon + \frac{1}{2}\delta\epsilon, \quad \Delta = \sqrt{N}g\sqrt{1 - \frac{(\delta\epsilon)^2}{16N^2g^2}}$$

$\boxed{\Delta = 0 \text{ at } \delta\varepsilon = 4Ng}$



→ isospin breaking

$$\tilde{E}_{\mathrm{MF}}\left(\epsilon + \frac{1}{2}\delta\epsilon, \sqrt{N}g\sqrt{1 - \frac{(\delta\epsilon)^2}{16N^2g^2}}\right)$$

$$= \epsilon - Ng + \frac{1}{2}\delta\epsilon - \frac{(\delta\epsilon)^2}{16Ng}.$$

$\boxed{E_{MF} = \varepsilon \text{ at } \delta\varepsilon = 4Ng}$

4. Conclusion

① We study the Kondo effect of $\bar{D}s/\bar{D}s^*$ meson in nuclear matter.

② We apply the renormalization group equation and find fixed point at the Kondo scale.

③ The Kondo scale is relevant to the width of the Kondo resonance as mixing of $\bar{D}s/\bar{D}s^*$ meson and nucleon in the ground state.

Future works:

1. Application to *realistic* $\bar{D}s/\bar{D}s^*$ meson-nucleon interaction.
2. Application to other heavy hadrons.
3. Observables and reactions for experiments.
4. etc.

Conclusion

① We study the Kondo effect of $\bar{D}s/\bar{D}s^*$ meson

Heavy meson in nuclear matter

x HQS interaction (non-Abelian)

= “Kondo resonance/bound” state

Kondo resonance as mixing of $\bar{D}s/\bar{D}s^*$ meson and nucleon in the ground state.

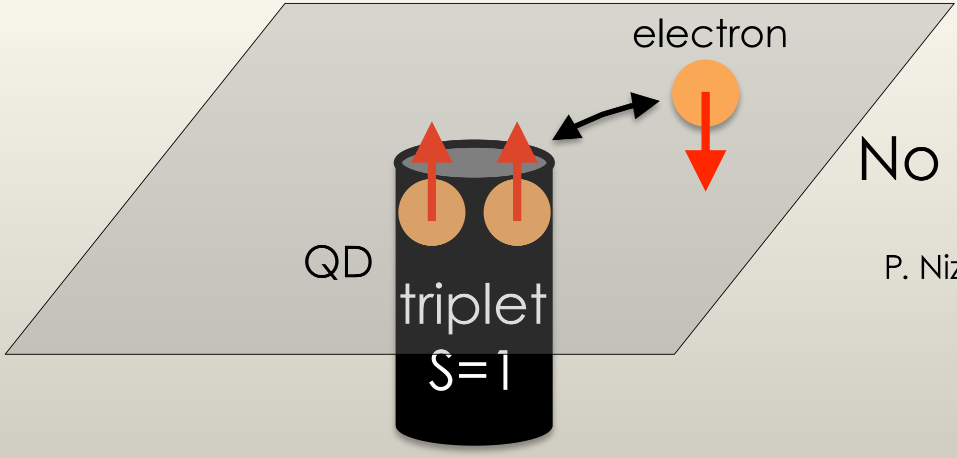
Future works:

1. Application to *realistic* $\bar{D}s/\bar{D}s^*$ meson-nucleon interaction.
2. Application to other heavy hadrons.
3. Observables and reactions for experiments.
4. etc.

2. Kondo effect for D_s^- and D_s^{*-} meson

S.Y., K. Sudoh, arXiv:1607.07948 [hep-ph]

Quantum Dots (QDs)



Impurity spin S≥1
↓
No Kondo effect in n(≥2) loops
("underscreening")

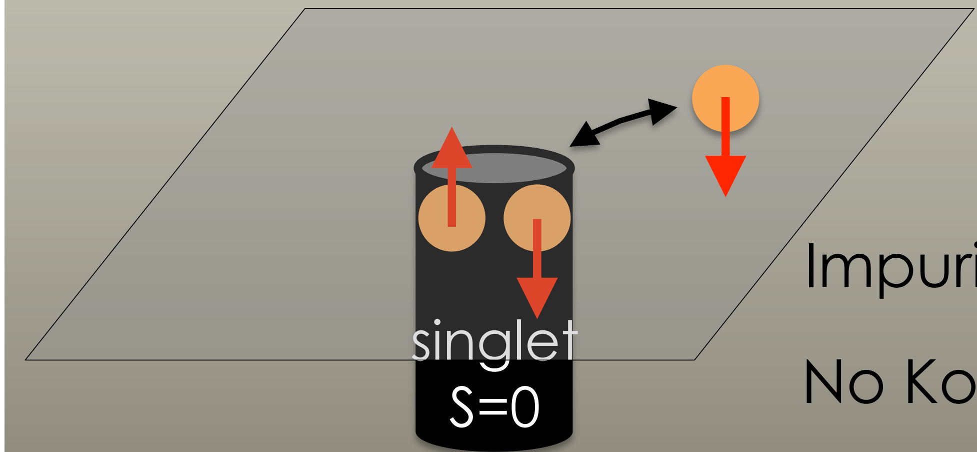
P. Nizières and A. Blandin, J. Phys. (Paris) 41, 193 (1980)

\+ quantum mechanical superposition

Mixing of triplet and singlet QDs makes the Kondo effect.

M. Pustilnik and L. I. Glazman, Phys. Rev. Lett. 85, 2993 (2000)
M. Eto and Y. V. Nazarov, Phys. Rev. Lett. 85, 1306 (2000)
M. Eto and Y. V. Nazarov, Phys. Rev. B 64, 085322 (2001)
W. Izumida, O. Sakai and S. Tarucha, Phys. Rev. Lett. 87, 216803 (2001)

Similar to $\bar{D}s$-$\bar{D}s^*$ Kondo effect !
Mixing by heavy quark symmetry



Impurity spin S=0
↓
No Kondo effect