Kondo effect in strong interaction

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Tokyo Institute of Technology

New Developments of Kondo Effect in Nuclear Physics@Keio Univ. 10 Dec. 2016

Content

Part 1. $\bar{D}_s$ meson in nuclear matter

Part 2. Charm quark in quark matter

Part 1. $\bar{D}_s$ meson in nuclear matter

Content of Part 1

1. Charm nucleus
2. $\bar{D}$ and $\bar{D}^*$ mesons in nuclear medium
3. Kondo effect of $\bar{D}_s$ and $\bar{D}_s^*$ mesons

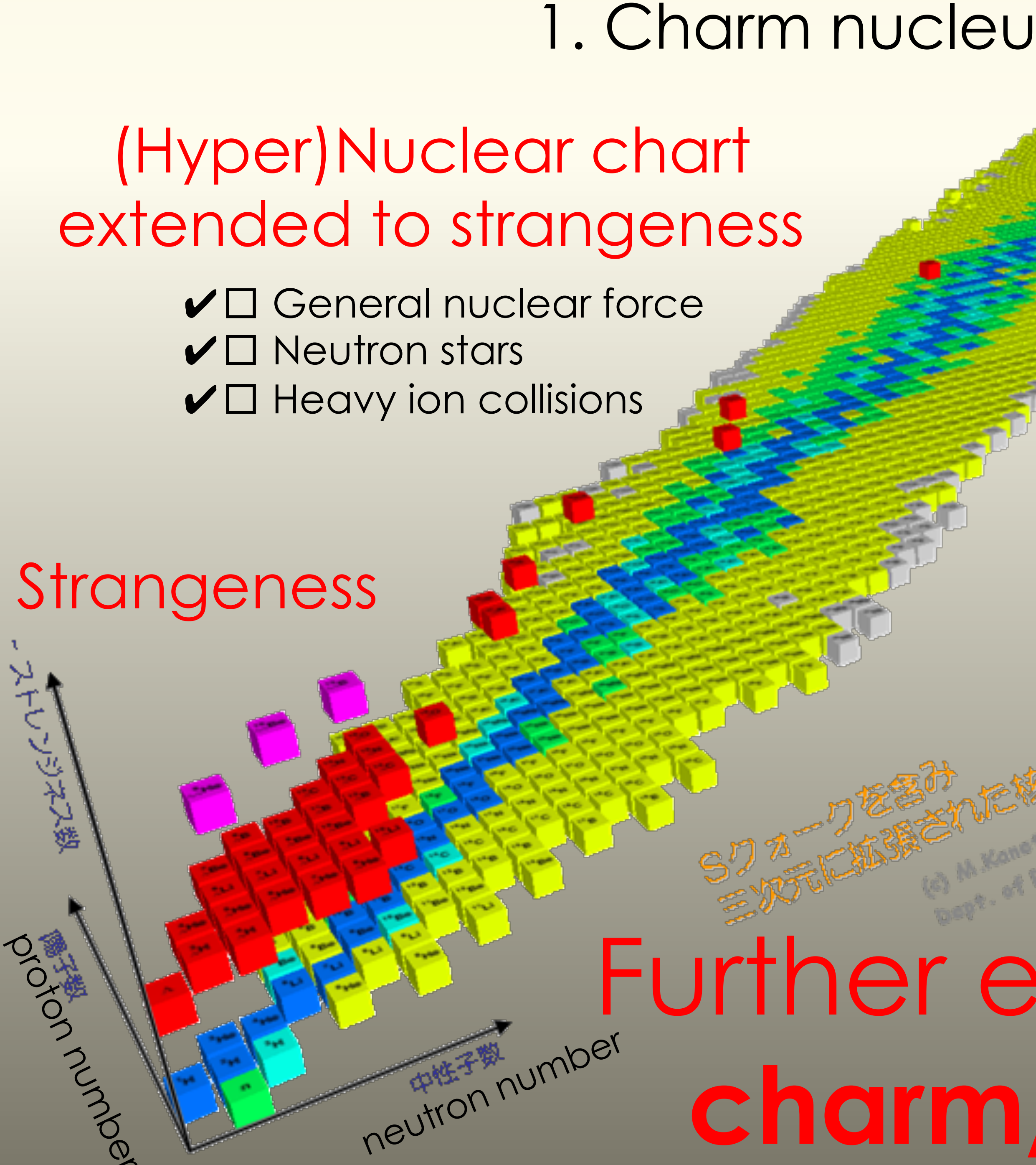
   S.Y., arXiv:1607.07948 [hep-ph]

1. Charm nucleus

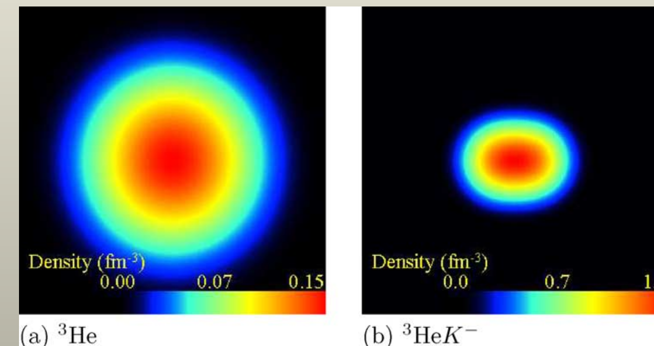
(Hyper)Nuclear chart extended to strangeness

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

Strangeness

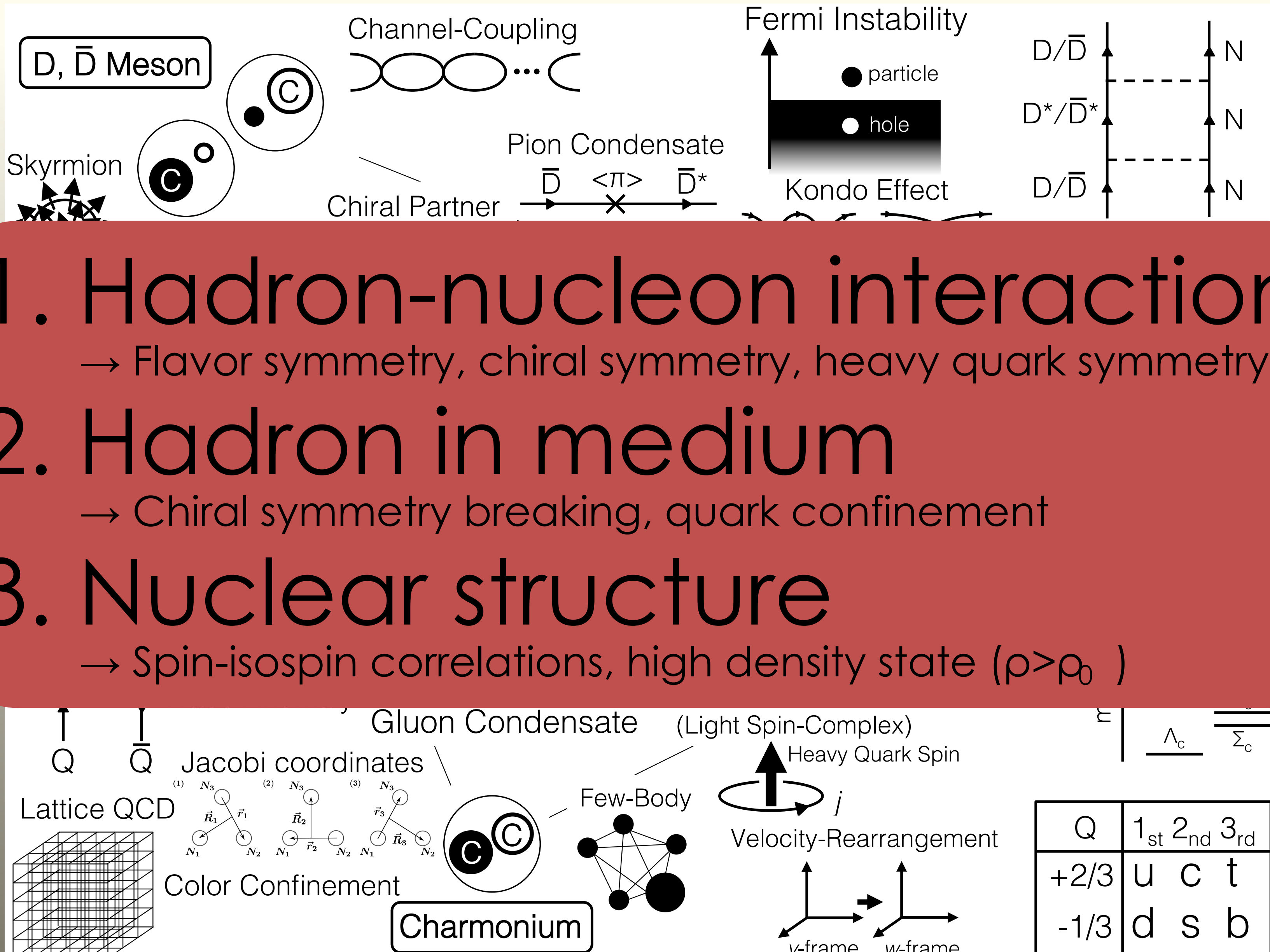


Anti-K mesic nuclei



Further extension to **charm/bottom?**

1. Charm nucleus



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

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

Heavy Hadrons in Nuclear Matter

Atsushi Hosaka[1,2], Tetsuo Hyodo[3], Kazutaka Sudoh[4], Yasuhiro Yamaguchi[3,5], and Shigehiro Yasui*[6]

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[2]J-PARC Branch, KEK Theory Center, Institute of Particle and Nuclear Studies, KEK, Tokai, Ibaraki, 319-1106, Japan
[3]Yukawa Institute for Theoretical Physics, Kyoto University, Kyoto, 606-8317, Japan
[4]Nishogakusha University, 6-16, Sanbancho, Chiyoda, Tokyo, 102-8336, Japan
[5]Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Genova, via Dodecaneso 33, 16146 Genova, Italy
[6]Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan

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

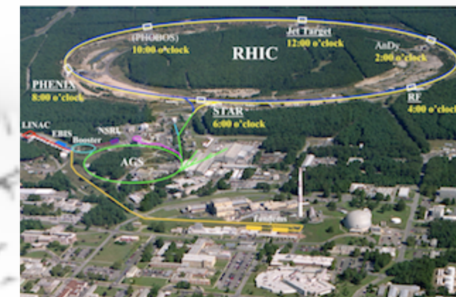
1. Charm nucleus

Experimental researches of dense matter/high energy physics

CERN-LHC

KEK Belle

BNL-RHIC



GSI-FAIR

J-PARC

ASTRO-H

What is new property of charm nuclei？

1. Charm nucleus

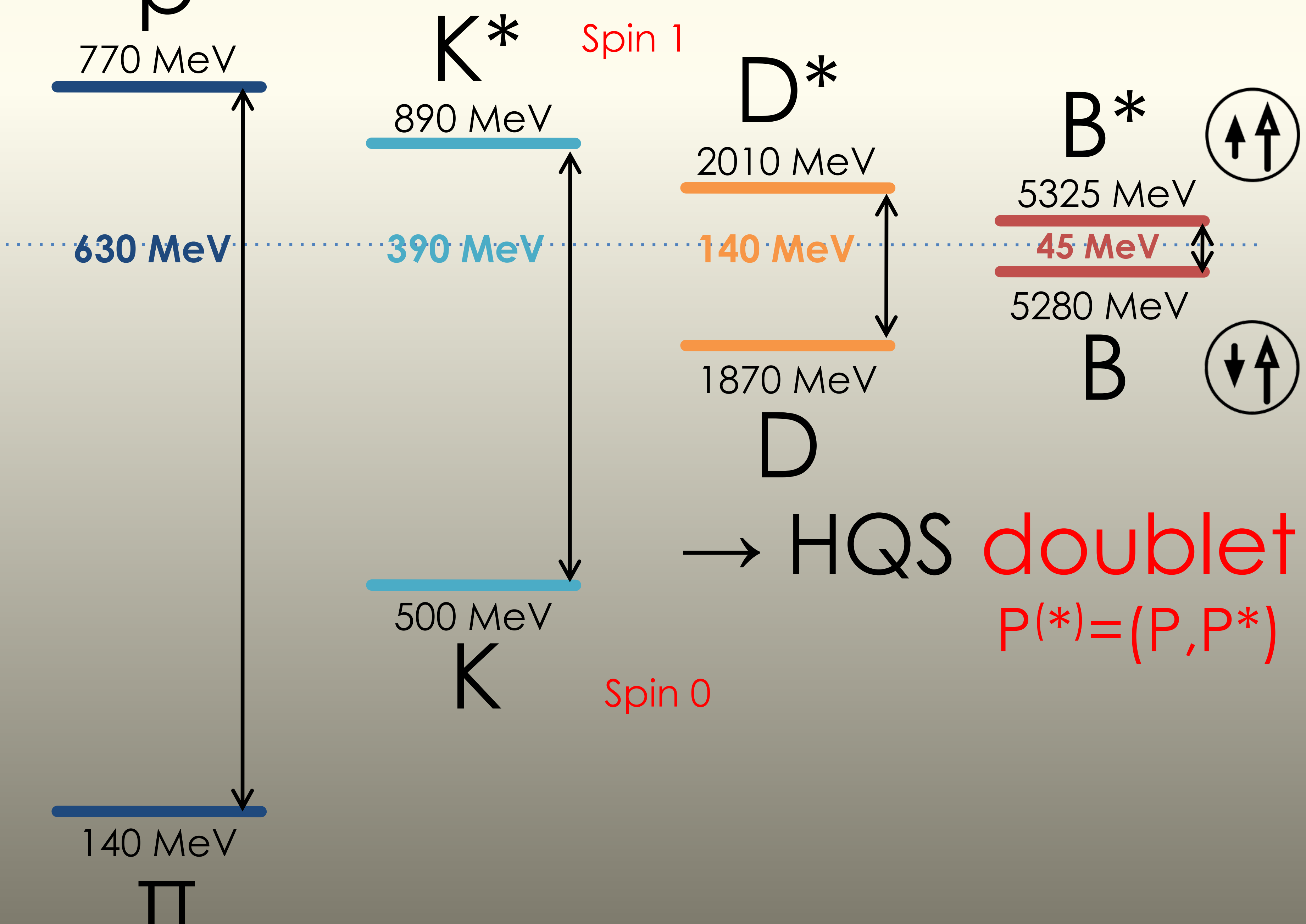
- Heavy mass of charm hadron

m_c=1.3 GeV and m_b=4.7 GeV

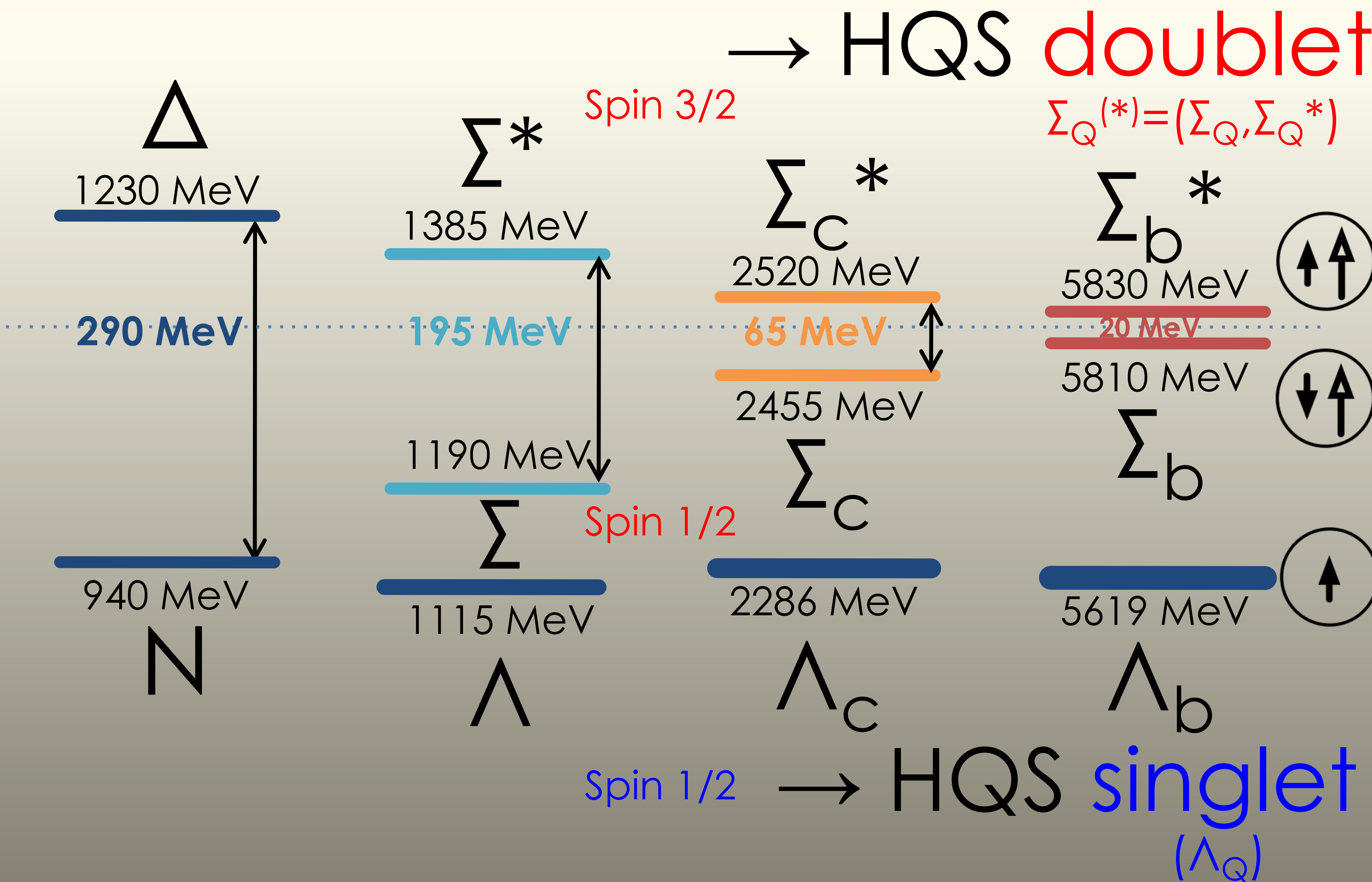
- <u>H</u>eavy <u>Q</u>uark <u>S</u>ymmetry (HQS)

Hadron spin = light quark spin x heavy quark spin

1. Charm nucleus



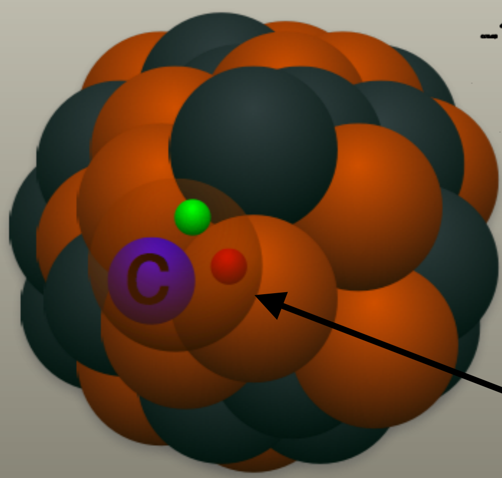
1. Charm nucleus

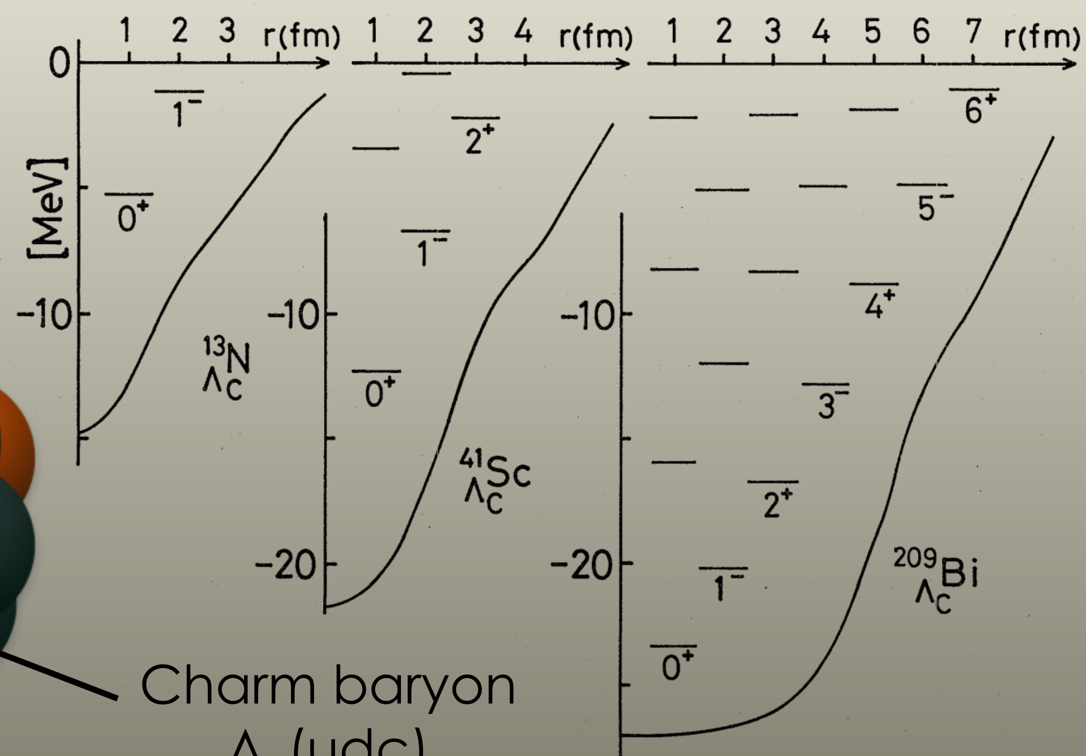


1. Charm nucleus

Example 1

Strangeness $\Lambda(uds)$ → Charm $\Lambda_c(udc)$





Charm baryon $\Lambda_c(udc)$

H.Bando, "Flavor Nuclei", PTP Suppl. 81, 197 (1985)

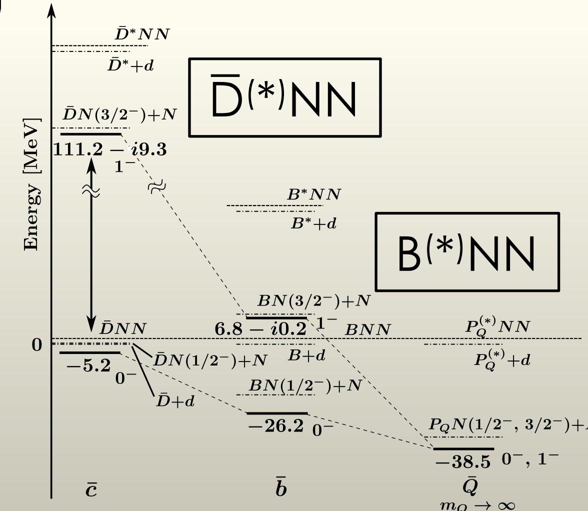
1. Charm nucleus

Example 2

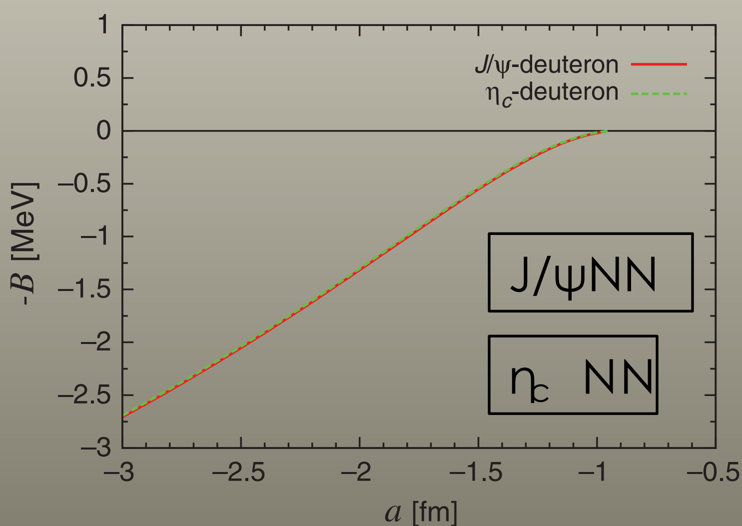
DNN

	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
$E_{\rm kin}$	338	352	438	335
$V(NN)$	0	−2	19	−5
$V(DN)$	−546	−575	−708	−540
$T_{\rm nuc}$	113	126	162	117
E_{NN}	113	124	181	113
P(odd)	75.0%	14.4%	7.4%	18.9%

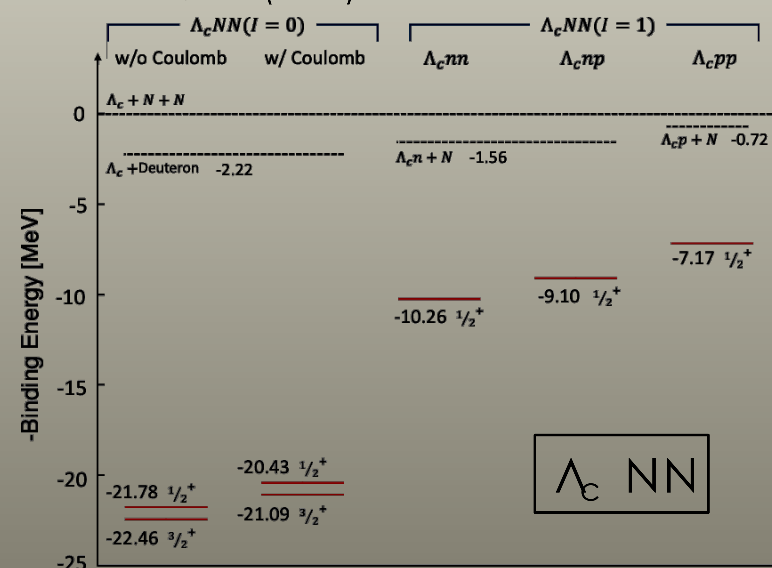
M. Bayer, C. W. Xiao, T. Hyodo, A. Dote, M. Oka, E. Oset, Phys. Rev. C86, 044004 (2012)



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

$\bar{D}$ meson

$\bar{Q}q$

2. $\bar{D}$ and $\bar{D}^*$ mesons in nuclear medium

2. $\bar{D}$ and $\bar{D}^*$ mesons in nuclear medium

$$Q\bar{q}$$

$$\textcolor{red}{\uparrow\downarrow}\ \uparrow$$

$P^{(*)} = P^*$ $\textcolor{red}{\uparrow}\uparrow$ or P $\textcolor{red}{\downarrow}\uparrow$

1^- same mass 0^-

$Q=b$ $\bar{B}^*$ / $\bar{D}^*$ $\bar{B}$ / $\bar{D}$

H.Georgi, Phys. Lett. B240, 447 (1990)
A.F.Falk, H.Georgi, B.Grinstein, Nucl. Phys. B343, 1 (1990)

2. $\bar{D}$ and $\bar{D}^*$ mesons in nuclear medium

$Q\bar{q}$

$$H_v(x) = \frac{1+\not{v}}{2}\left[P^{*}_{v\mu}(x)\gamma^{\mu} + i\gamma_5 P_v(x) \right]$$

1^- 0^-

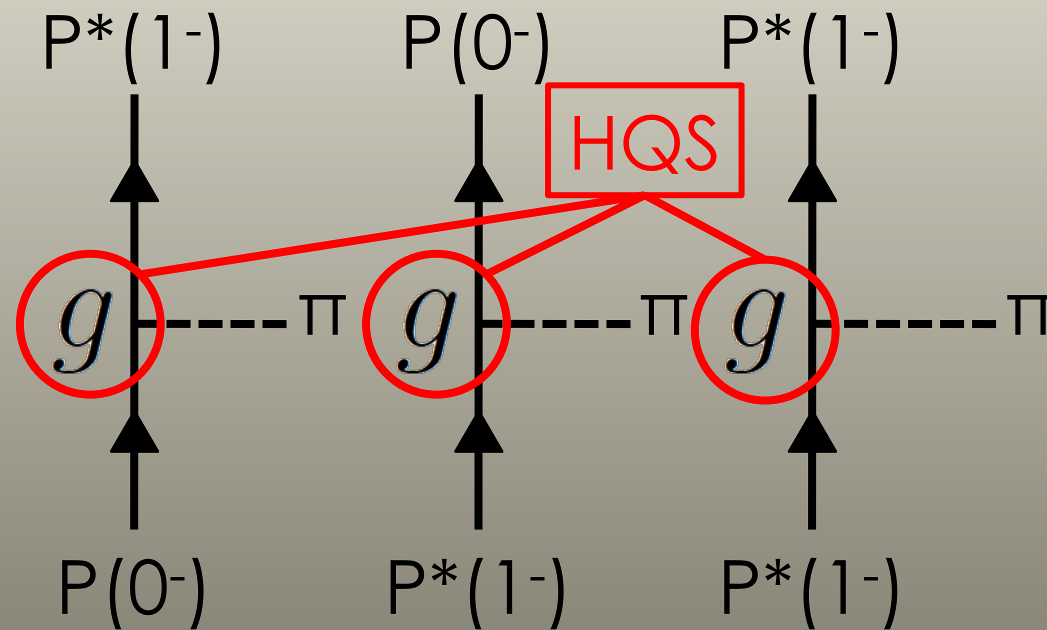
H.Georgi, Phys. Lett. B240, 447 (1990)
A.F.Falk, H.Georgi, B.Grinstein, Nucl. Phys. B343, 1 (1990)

2. $\bar{D}$ and $\bar{D}^*$ mesons in nuclear medium

Interaction of P(0⁻), P*(1⁻) meson and pion field with chiral symmetry + HQS

$$\mathcal{L}^{(0)}_{\rm HMET} = \underbrace{-{\rm Tr}\overline{H}_v v\cdot iDH_v}_{\text{kinetic term}} + \underbrace{g\,{\rm Tr}\overline{H}_v H_v \gamma_\mu\gamma_5 A^\mu}_{\text{interaction with pion}} + \mathcal{O}(1/M)$$

$$A_\mu = -\partial_\mu \pi$$

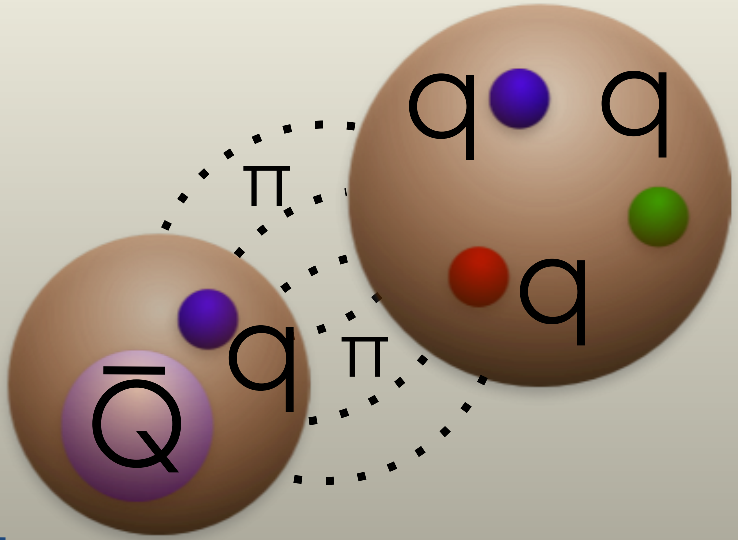


H.Georgi, Phys. Lett. B240, 447 (1990)
A.F.Falk, H.Georgi, B.Grinstein, Nucl. Phys. B343, 1 (1990)

2. $\bar{D}$ and $\bar{D}^*$ mesons in nuclear medium

S.Y., K.Sudoh, Phys. Rev. D80, 034008 (2009)
Y.Yamaguchi, S.Ohkoda, S.Y., A.Hosaka, Phys. Rev. D84, 014032 (2011)
Y.Yamaguchi, S.Ohkoda, S.Y., A.Hosaka, Phys. Rev. D85, 054003 (2013)
Y.Yamaguchi, S.Y., A.Hosaka, Nucl. Phys. A927, 110 (2014)

$$\bar{Q}q = \bar{P}^{(*)}$$



$\bar{D}^{(*)}$ meson   Nucleon

Hadronic molecule

① No *quark-antiquark* annihilation
(very simple system!)

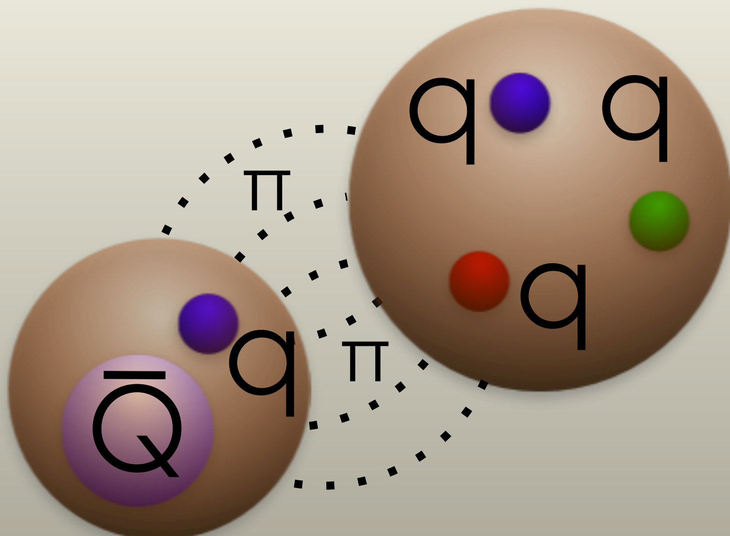
② Relation for interaction vertices:
$g_{PP^*\pi} = g_{P^*P^*\pi}$ (heavy quark symmetry)

What is the inter-hadron interaction ?

2. D̄ and D̄* mesons in nuclear medium

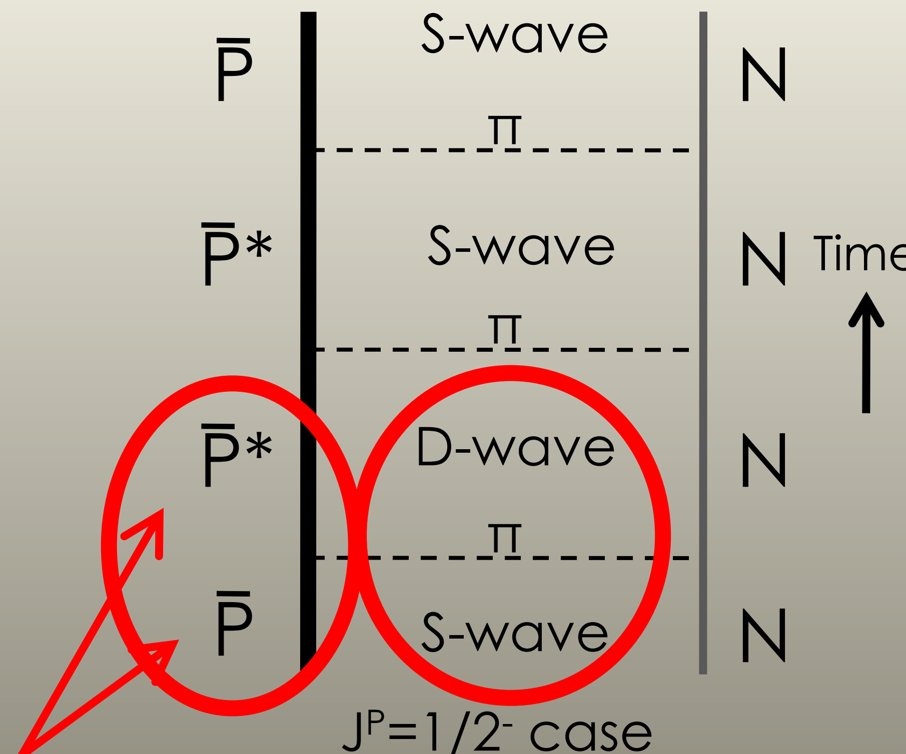
S.Y., K.Sudoh, Phys. Rev. D80, 034008 (2009)
Y.Yamaguchi, S.Ohkoda, S.Y., A.Hosaka, Phys. Rev. D84, 014032 (2011)
Y.Yamaguchi, S.Ohkoda, S.Y., A.Hosaka, Phys. Rev. D85, 054003 (2013)
Y.Yamaguchi, S.Y., A.Hosaka, Nucl. Phys. A927, 110 (2014)

$\bar{Q}q = \bar{P}^{(*)}$:



$\bar{D}^{(*)}$ meson   Nucleon

Hadronic molecule



$J^P = 1/2^-$ case

P̄(0⁻)-P̄*(1⁻) mixing and Tensor force are important !

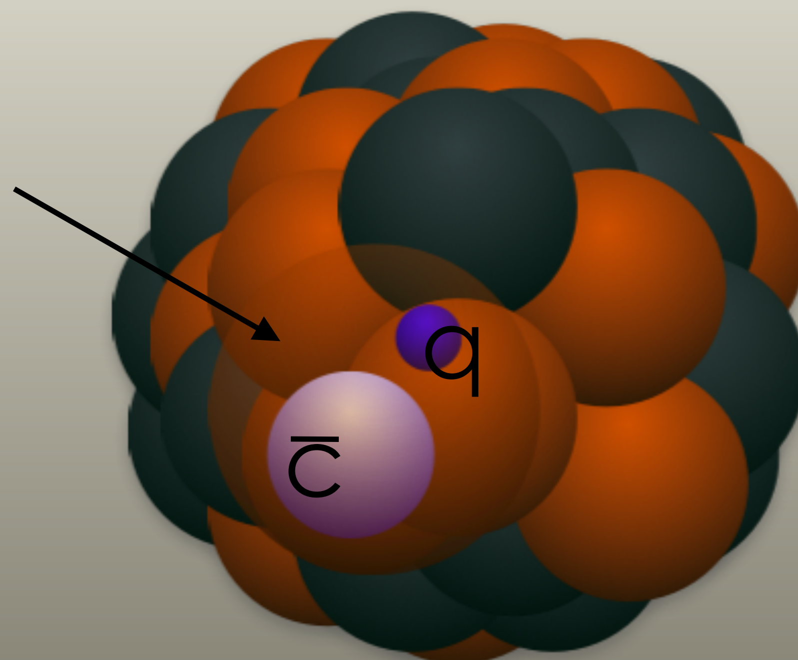
(mixing of S-wave and D-wave, like in deuteron)

Heavy-light meson

Kondo effect

"Heavy impurity" nuclear physics

$\bar{D}s$, $\bar{D}s^*$
($\bar{c}s$)



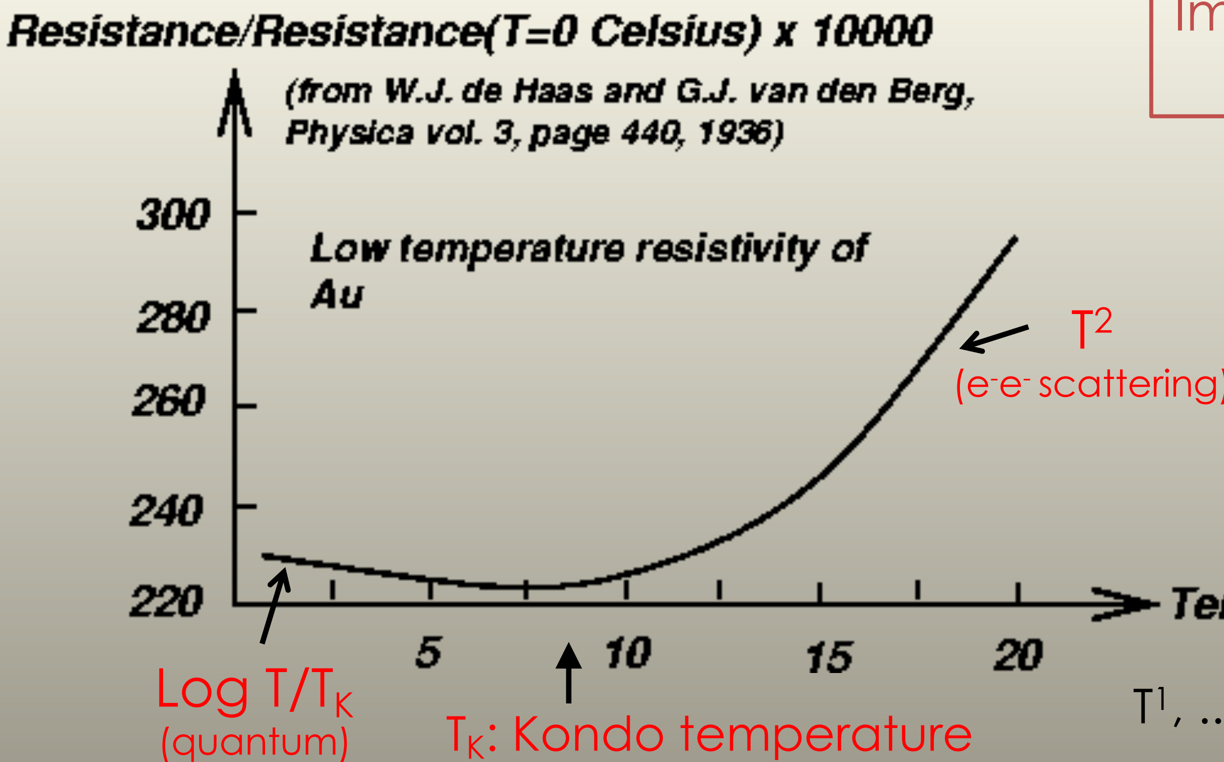
Nucleus

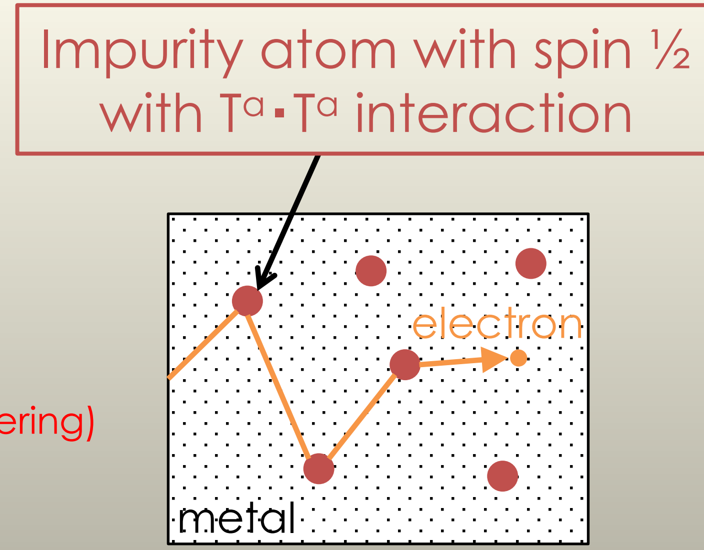
3. Kondo effect

What’s “Kondo effect”？

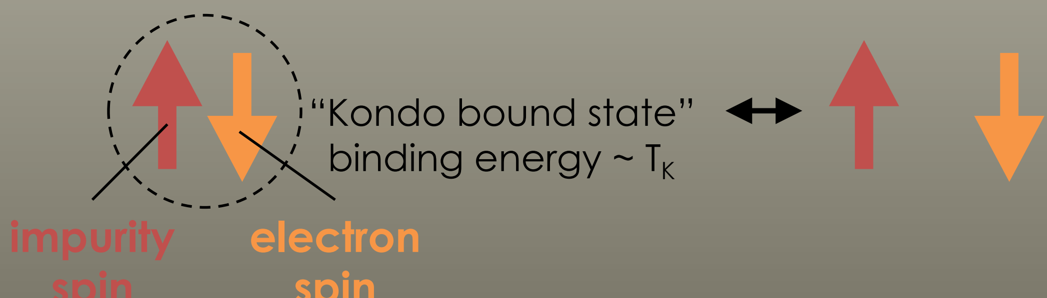
3. Kondo effect

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



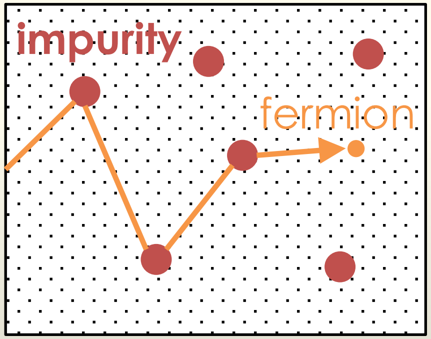


$T^1, \ldots, T^{n^2-1}$: generators of SU(n)
(n=2 for spin ½)



3. Kondo effect

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



Heavy impurity

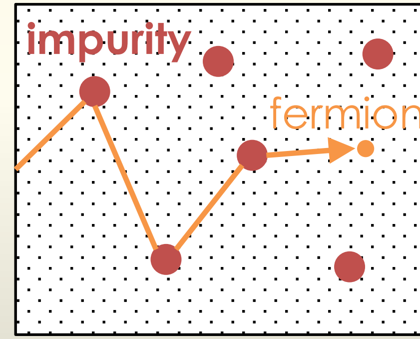
① Fermi surface
(degenerate state)

② Loop effect
(particle-hole creation)

③ Non-Abelian int.
(SU(n) symmetry)

3. Kondo effect

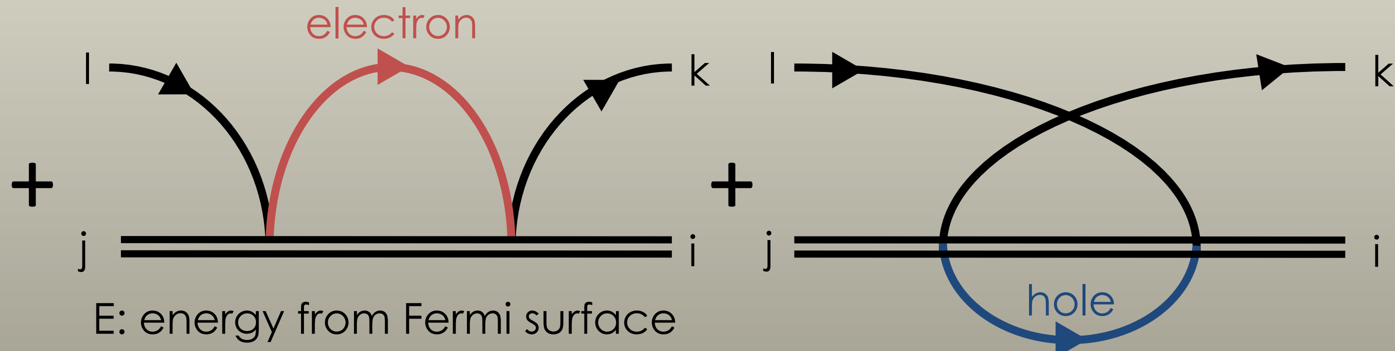
Original Work: J. Kondo (Prog. Theor. Phys. 32, 37 (1964))



Scattering amplitude at tree and **one-loop** levels

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

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



E: energy from Fermi surface

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

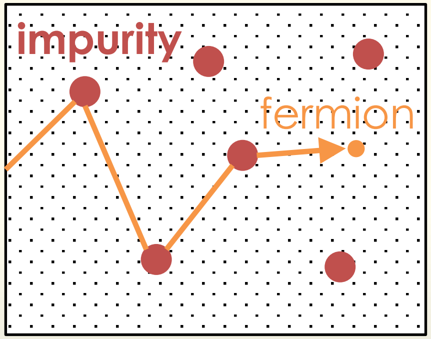
$$\times\left(\frac{n}{2}-\frac{1}{n}\right)\int_{E>0}\frac{1}{-E}\mathrm{d}E\sum_a (T^a)_{kl}(T^a)_{ij}$$

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

→ Logarithmic divergence in resistance of electron

3. Kondo effect

Application of Kondo effect to
Hadron/nuclear physics



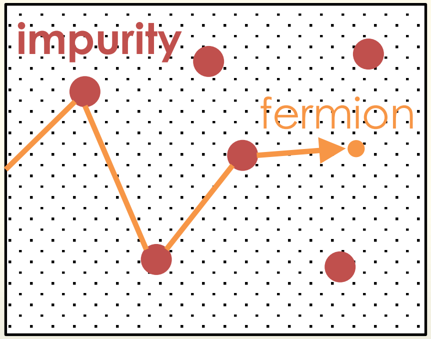
Fermi gas	electron gas	**nuclear matter** (p,n)	**quark matter** (u,d,s)
Heavy impurity	spin-atoms	**D/B mesons**	**c/b quarks**
Fermi surface (degenerate state)	✔☐	✔☐	✔☐
Loop effect (particle-hole creation)	electron-hole☐	**nucleon-hole☐**	**quark-hole☐**
Non-Abelian int. (SU(n) symmetry)	$SU(2)_{spin}$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

Hadronic/QCD Kondo effect (nuclear matter and quark matter)

1. NJL-type: S.Y., K.Sudoh, Phys. Rev. C88, 015201 (2013)
2. QCD: K. Hattori, K. Itakura, S. Ozaki, S.Y., Phys. Rev. D92, 065003 (2015)
3. "Magnetic catalysis": S. Ozaki, K. Itakura, Y. Kuramoto, arXiv:1509.06966 [hep-ph]
4. Kondo effect in 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]

3. Kondo effect

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)	$SU(2)_{spin}$	$\mathbf{SU(2)_{isospin}}$	$\mathbf{SU(3)_{color}}$

Hadronic/QCD Kondo effect (nuclear matter and quark matter)

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Why $\bar{D}s/\bar{D}s^*$ mesons？

3. Kondo effect

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

3. Kondo effect

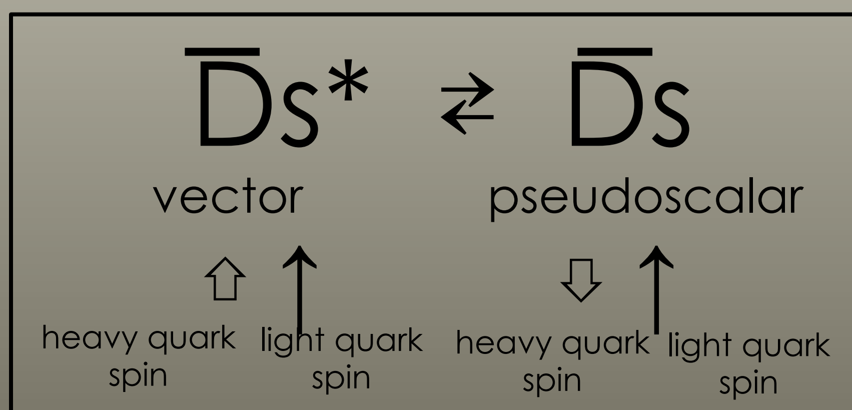
S.Y., arXiv:1607.07948 [hep-ph]

① Interaction of D̄s (D̄s*) meson and nucleon

$$\mathcal{L}_{\rm int} = \frac{1}{2}\sum_i c_i\, \bar{\psi}\Gamma_i\psi\, {\rm Tr}\bar{H}_{sv}\Gamma_i H_{sv}$$

$$\Gamma_1 = 1,\, \Gamma_2 = \gamma^\mu,\, \Gamma_3 = \sigma^{\mu\nu},\, \Gamma_4 = \gamma^\mu\gamma_5,\, \Gamma_5 = \gamma_5$$

$$H_{sv} = \left(\gamma^\mu P^*_{sv\mu} + i\gamma_5 P_{sv}\right)\frac{1+\not{v}}{2}$$ ← HQS



3. Kondo effect

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

① Interaction of D̄s (D̄s*) meson and nucleon

non-relativistic limit for nucleon

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

spin-nonexchange term

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

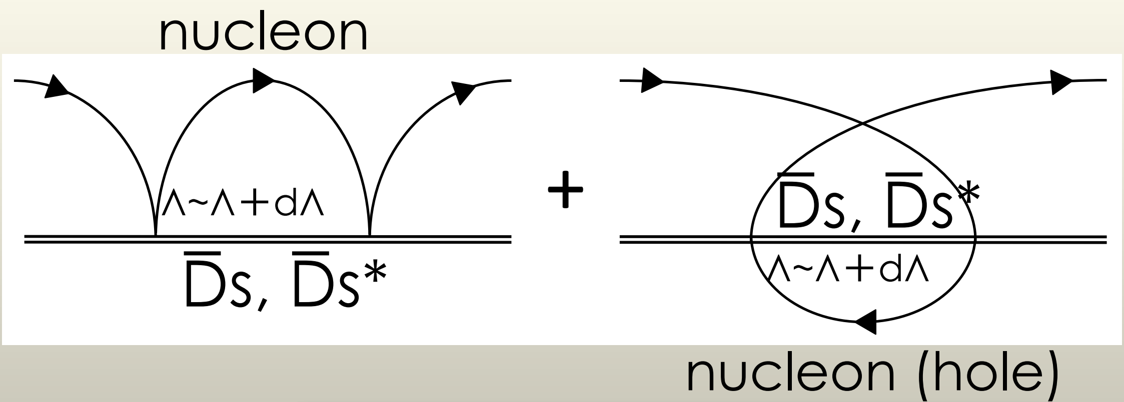
spin-exchange term

$$c_s = -(c_1 - c_2) \quad c_t = 2c_3 + c_4$$

3. Kondo effect

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

② Renormalization group equation



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

(Λ: loop momentum)

$$\frac{\mathrm{d}}{\mathrm{d}\ell} c_{s00}(\ell) = 0,$$

$$\frac{\mathrm{d}}{\mathrm{d}\ell} c_{s11}(\ell) = 0,$$

$$\frac{\mathrm{d}}{\mathrm{d}\ell} c_{t10}(\ell) = \frac{mk_{\mathrm{F}}}{2\pi^2} c_{t10}(\ell) c_{t11}(\ell),$$

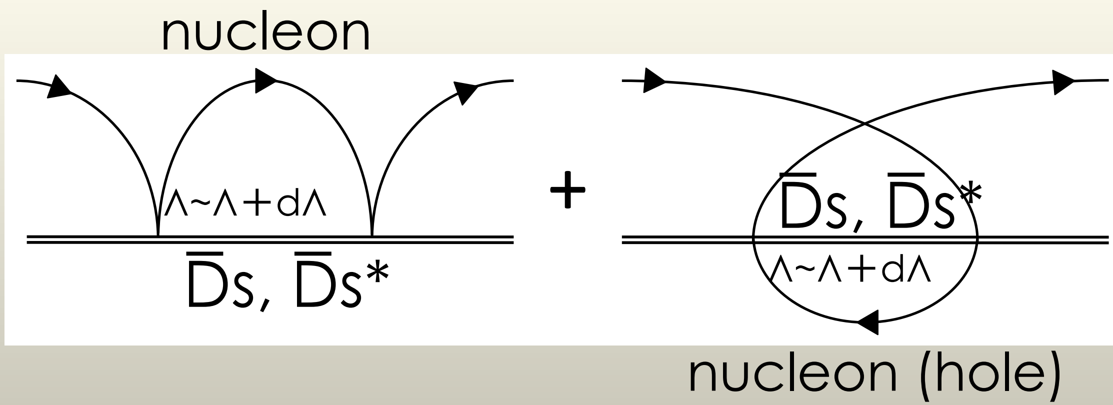
$$\frac{\mathrm{d}}{\mathrm{d}\ell} c_{t01}(\ell) = \frac{mk_{\mathrm{F}}}{2\pi^2} c_{t01}(\ell) c_{t11}(\ell),$$

$$\frac{\mathrm{d}}{\mathrm{d}\ell} c_{t11}(\ell) = \frac{mk_{\mathrm{F}}}{2\pi^2} c_{t11}(\ell)^2,$$

3. Kondo effect

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

② Renormalization group equation



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

(Λ: loop momentum)

$$c_{s00}(\ell) = c_{s11}(\ell) = c_s$$

spin-nonexchange term
(fixed point $c_s^* = c_s$)

$$c_{t11}(\ell) = c_{t10}(\ell) = c_{t01}(\ell) = \frac{c_t}{1 - \frac{m k_{\mathrm{F}}}{2\pi^2} c_t \ell}$$

spin-exchange term
(fixed point $c_t^* = \infty$ for $c_t > 0$)

Kondo scale
(infrared singularity)

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

3. Kondo effect

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

③ Mean-field approach

Cf. Eto and Nazarov, PRB64, 085322 (2001)

Kondo scale → non-perturbative treatment

Boson-fermion correspondence

$$\bar{D}_s^{(*)} \leftrightarrow \frac{1}{2}\psi_\sigma^i$$ *auxiliary* fermion (σ: light-spin, i:heavy-quark spin)

$$\mathcal{H}_{\text{int}} = \frac{c_t}{4}\sum_{i,k}\varphi^\dagger\sigma^k\varphi\,\psi^{i\dagger}\sigma^k\psi^i$$

$$\sum_{i,\sigma}\psi_\sigma^{i\dagger}\psi_\sigma^i = 1$$ constraint condition

Hamiltonian with auxiliary fermion

$$H_{\text{eff}} = \sum_{\boldsymbol{k},\sigma}\tilde{\varepsilon}_{\boldsymbol{k}}\varphi^\dagger_{\boldsymbol{k}\sigma}\varphi_{\boldsymbol{k}\sigma} - \frac{C_t}{4}\sum_{\boldsymbol{k}_1,\boldsymbol{k}_2,\sigma}\varphi^\dagger_{\boldsymbol{k}_1\sigma}\varphi_{\boldsymbol{k}_2\sigma} + 2\frac{C_t}{4}\sum_{i,\boldsymbol{k}_1,\boldsymbol{k}_2,\sigma_1,\sigma_2}\varphi^\dagger_{\boldsymbol{k}_1\sigma_1}\varphi_{\boldsymbol{k}_2\sigma_2}\psi^{i\dagger}_{\sigma_2}\psi^i_{\sigma_1} + v\left(\psi_\downarrow^{1\dagger} - \psi_\uparrow^{2\dagger}\right)\left(\psi_\downarrow^1 - \psi_\uparrow^2\right) + \lambda\left(\sum_{i,\sigma}\psi_\sigma^{i\dagger}\psi_\sigma^i - 1\right)$$

HQS breaking parameter v

"Gap" function as mean-field

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

mixing of auxiliary fermion and nucleon

Thermodynamic potential

$$\Omega(\lambda;\Delta^1,\Delta^2) = -\frac{1}{\beta}\int_{-D}^{D}\ln(1+e^{-\beta\omega})\bar{\rho}(\omega)\mathrm{d}\omega + \frac{|\Delta^1|^2+|\Delta^2|^2}{2(C_t/4)} - \lambda$$

$\bar{\rho}$ state-density of auxiliary fermion

3. Kondo effect

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

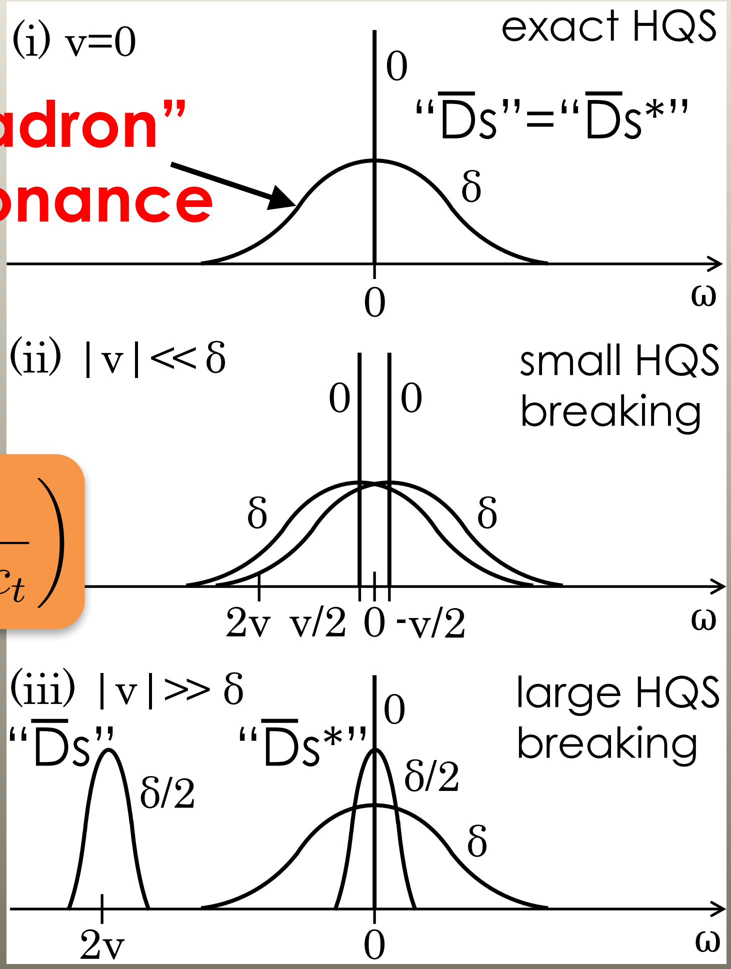
③ Mean-field approach

Cf. Eto and Nazarov, PRB64, 085322 (2001)

Kondo scale → non-perturbative treatment

Spectral function

"Heavy hadron"
Kondo resonance



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

Kondo scale
(infrared singularity)

"gap" δ: width of resonance

$$\delta = \frac{1}{2} D \exp\left(-\frac{2\pi^2}{mk_{\mathrm{F}}c_t}\right)$$

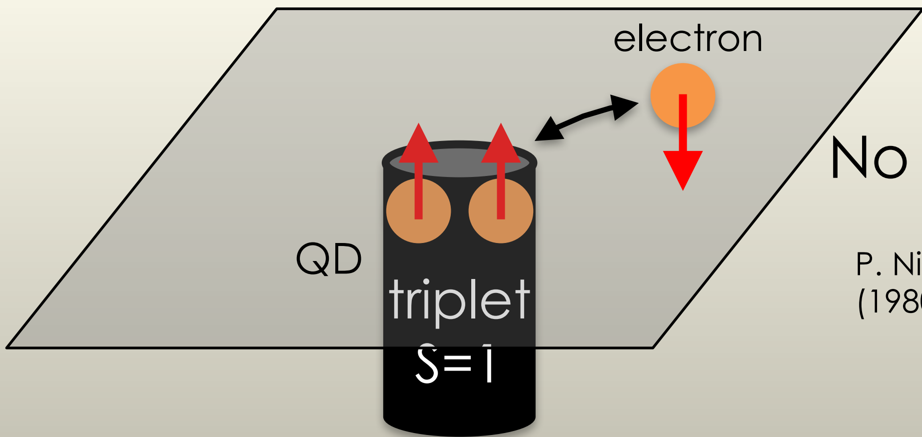
$$\delta \simeq \frac{1}{2} D \exp\left(-\frac{2\pi^2}{mk_{\mathrm{F}}c_t}\right)$$

$$\delta \simeq \frac{1}{2} \frac{D^{4/3}}{(-v)^{1/3}} \exp\left(-\frac{8\pi^2}{3mk_{\mathrm{F}}c_t}\right)$$

3. Kondo effect

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

Quantum Dots (QDs)



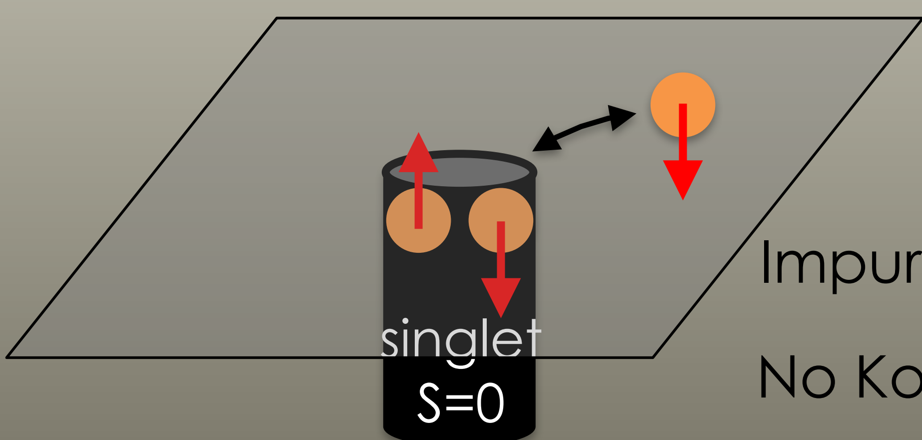
Impurity spin S≥1

↓

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