QCD Kondo effect in quark matter with heavy flavor impurities

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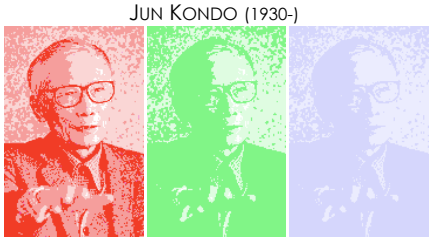
Conclusion: *Appearance of heavy quark impurities in a light quark matter gives rise to a drastic change of transport properties due to the QCD Kondo effect.*

[1] S. Yasui, K. Sudoh, Phys. Rev. C88, 015201 (2013).
[2] K. Hattori, K. Itakura, S. Ozaki, S. Yasui, Phys. Rev. D92, 065003 (2015).

1. Introduction to "Kondo effect"

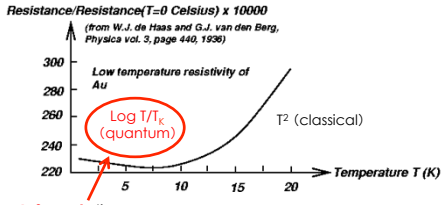
Jun Kondo (1930-)



Progress of Theoretical Physics, Vol. 32, No. 1, July 1964

Resistance Minimum in Dilute Magnetic Alloys

Jun Kondo

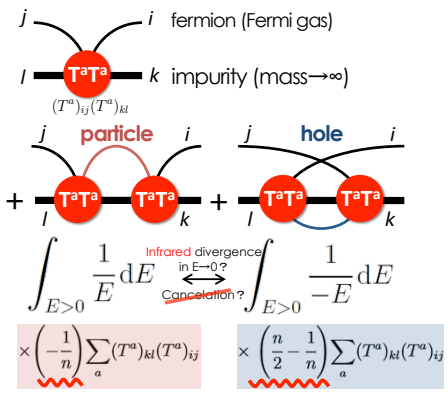


Infrared divergence (T_K:Kondo temperature (scale))

Key words for Kondo effect

- ⓪ **Heavy impurity** (mass → ∞)
- ① **Fermi surface** (particle-hole symmetry)
- ② **Loop effect**
- ③ **Non-Abelian int.** (SU(*n*) symmetry)

Analysis in perturbation



Breakdown of perturbation at infrared energy scale

Kondo effect

⓪ Heavy impurity ① Fermi surface
② Loop effect ③ Non-Abelian int.

Resummation (Abrikosov (1965)), Scaling (Anderson (1970)), Renormalization group (Wilson (1975)), ...

2. Kondo effect in quark matter

"Kondo effect" in strong interaction

Nambu-Jona-Lasinio-type interaction; SY, Sudoh, Phys. Rev. C88, 015201 (2013)

Medium	Nuclear Matter	Quark Matter
Impurity (mass→∞)	$\bar{D}$ meson ($\bar{c}q$)	Charm Quark
Non-Abelian	$T^a \in SU(2)_{isospin}$	$T^a \in SU(3)_{color}$

(Cf. Heavy quark "spin" does not flip in heavy quark mass limit, hence it is irrelevant to the Kondo effect)

What's the effect of gluon-exchange??

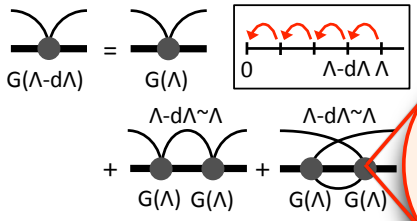
"Dynamical screening" in color magnetic gluon

Cf. Colos superconductivity: Son, Phys. Rev. D59, 094019 (1999), Hsu, Schwetz, Nucl. Phys. B572, 211 (2000)

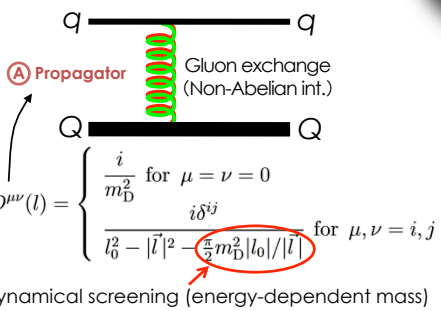
Our Strategy

Renormalization group (RG) equation

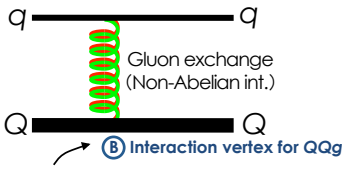
1. Scattering amplitude at energy scale Λ



2. Properties of gluon-exchange



Dynamical screening (energy-dependent mass)
Cf. Baym et al. (1990)



Effective Lagrangian for heavy quark

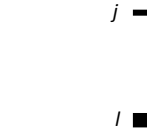
$$\mathcal{L}_{\rm HQET} = \bar{Q}_v iv\cdot D Q_v + \mathcal{O}(1/m_Q)$$

$D_\mu = \partial_\mu + igA_\mu^A T^A$

Color dependence only (T^A).
No spin-dependence.

Cf. Manohar, Wise "Heavy Quark Physics" (2000)

3. Renormalization group (RG) equation



$$(A(\Lambda)v^0\gamma^0 + B(\Lambda)\vec{v}\cdot\vec{\gamma}) \otimes \frac{1+\not{v}}{2}\sum_a (T^a)_{kl}(T^a)_{ij}$$

$$-C\frac{dA}{dx} = \frac{1}{2}\frac{k_F^2}{(2\pi)^2}\left\{\left(1-\frac{1}{n^2}\right)4\frac{\cos\alpha}{x^2}v + C\left\{\frac{n}{x}+\frac{1}{nx^2}\left((n^2-4)-2nx\right)\cos\alpha v\right\}\right\}A^2 + \mathcal{O}(v^2) \qquad x=\Lambda/k_F$$

$$-C\frac{dB}{dx} = \frac{1}{2}\frac{k_F^2}{(2\pi)^2}\left[\left(1-\frac{1}{n^2}\right)\left(-\frac{4}{3x^2}A^2\right) + C\left\{\frac{1}{3x^2}\left(\frac{4}{n}-n(1-x)\right)A^2 + \frac{2n}{x}AB\right\}\right] + g^2\frac{C}{6k_F^2}\frac{1}{x} + \mathcal{O}(v^1)$$

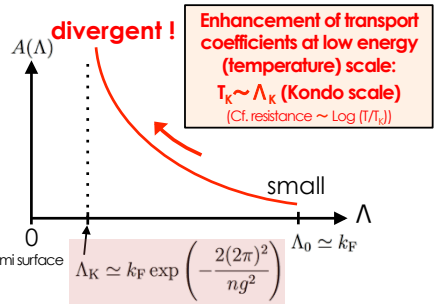
Dynamical screening by magnetic gluon

Gluon exchange (Non-Abelian int.)

Solution

$$A(x) = \frac{A(x_0)}{1+A(x_0)\frac{1}{2}\frac{k_F^2}{(2\pi)^2}n\log\frac{x}{x_0}}\mathcal{O}(v^0) + \frac{A(x_0)^2}{\left(1+A(x_0)\frac{1}{2}\frac{k_F^2}{(2\pi)^2}n\log\frac{x}{x_0}\right)^2}\mathcal{O}(v^1) \times\frac{1}{2}\frac{k_F^2}{(2\pi)^2}\left\{\left(\frac{4}{C}\left(1-\frac{1}{n^2}\right)+\frac{n^2-4}{n}\right)\left(\frac{1}{x}-\frac{1}{x_0}\right)+2\log\frac{x}{x_0}\right\}(\cos\alpha)v + \mathcal{O}(v^2) \qquad x=\Lambda/k_F$$

$$B(x) = \frac{1}{2Cnx_0x\left(1+A(x_0)\frac{1}{2}\frac{k_F^2}{(2\pi)^2}n\log\frac{x}{x_0}\right)^2} \times\left[\frac{1}{2}\frac{k_F^2}{(2\pi)^2}\left(4(n^2-1)+Cn(n^2-4)\right)(x-x_0)A(x_0)\right.$$



Enhancement of transport coefficients at low energy (temperature) scale: $T_K \sim \Lambda_K$ (Kondo scale)
(Cf. resistance ~ Log (T/T_K))

Kondo scale!!

(low energy scale for infrared divergence)