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Kondo cloud of single heavy quark in cold and dense matter

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ABSTRACT

The Kondo effect is a universal phenomena observed in a variety of fermion systems containing a heavy impurity particle whose interaction is governed by the non-Abelian interaction. At extremely high density, I study the Kondo effect by color exchange in quark matter containing a single heavy (charm or bottom) quark as an impurity particle. To obtain the ground state with the Kondo effect, I introduce the condensate mixing the light quark and the heavy quark (Kondo cloud) in the mean-field approximation. I estimate the energy gain by formation of the Kondo cloud, and present that the Kondo cloud exhibits the resonant structure. I also evaluate the scattering cross section for the light quark and the heavy quark, and discuss its effect to the finite size quark matter.

1. Introduction

Heavy (charm or bottom) quarks, whose dynamics is governed by Quantum Chromodynamics (QCD), are useful tools to investigate the properties of nuclear and quark matter. It is considered that the dynamics of the heavy quarks are hardly affected by light quarks, and the heavy-quark symmetry for heavy flavor and spin makes the dynamics simple; therefore they enable us to carry out a systematic analysis of the structures and reaction processes [1,2]. However, the situation may not be so simple when heavy quarks exist in medium at low temperature and high density. In condensed matter physics, it is known that the medium properties can be changed significantly once the system is contaminated with impurities. For instance, the Kondo effect occurs when a small number of impurity particles are injected into the system, and it changes the thermodynamic and transport properties [3–5]. In this paper, I study the Kondo effect in quark matter at low temperature and high density, which is called the QCD Kondo effect [6–8]. The research on the QCD Kondo effect has had positive spin-offs so far: the Kondo effect in strong magnetic field [9] and in the color superconductivity [10], the Fermi/non-Fermi liquid properties in multi-channel Kondo effect [11], and non-trivial topological properties of heavy quark spin in ground state [12]. Also, it has been argued that one can analyze the information about high density matter, given the fact that heavy quarks can be produced in interior cores of neutron stars [8] or in heavy ion collisions at low energy in accelerator facilities such as GSI-FAIR [13] and J-PARC.

In the 1960s, J. Kondo established the theoretical foundations for the effect in order to explain why the electric resistance of a metal containing a small amount of magnetic (spin) impurities behaved with a logarithmical enhancement at low temperatures. His research indicated that the spin-exchange (non-Abelian) interaction between the conducting electron and the spin impurities led to the situation where the coupling constant got stronger and the Landau pole appeared [14]. The emergence of the pole was closely related to not only the non-Abelian interaction but also the Fermi surface (degenerate states) and the loop effect (virtual creation of particle-hole pairs). So far, many theoretical methods to study the Kondo effect have been developed [3–5], and nowadays it is thought that the Kondo effect provides a direct insight into strong coupling mechanisms in condensed matter systems [15–21].

The Kondo effect can appear in the nuclear/quark matter containing heavy impurity particles (i.e. heavy hadrons/quarks); their energy scales are not comparable to that of the Kondo effect which involves the system of electrons. Several types of non-Abelian interactions are used for the strong interaction: the spin exchange with SU(2) symmetry and the isospin exchange with SU(2) symmetry in nuclear matter [6,22,23] [24]; color exchange with SU(3) symmetry in quark matter [6,7,9,8,10,11]. The Fermi surface and the loop effect naturally appear in nuclear/quark matter at low temperatures; these conditions seem to be favorable for the QCD Kondo effect to occur.

The enhancement of the interaction by the Kondo effect will cause changes in thermodynamic properties and transport properties in nuclear/quark matter. Thus, the Kondo effect provides us with a tool to study (i) heavy-hadron–nucleon (heavy-quark–light-quark) interaction, (ii) modification of impurity properties by

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medium and (iii) change of nuclear/quark matter by impurity effect (cf. Ref. [25]).

So far, the QCD Kondo effect has been studied within the framework of perturbation, but the approach becomes invalid at low energy scales (the Kondo scale) [6,7,9]. Likewise the Landau pole appears in the scattering amplitude on Fermi surface at low temperatures, as the origin of Fermi instability which is known in superconductivity. Below the Kondo scale, all the physical quantities have their poles, and so meaningful results cannot be obtained (see Refs. [3–5]). Thus, the non-perturbative approach should be used to investigate their low-energy behaviors in terms of the QCD Kondo effect.

Recent studies dealt with this issue by using a non-perturbative approach and the mean-field approximation [8,10] [26]. The mean-field approach is simple, but it gives us a general understanding of the Kondo effect, as it does in condensed matter physics [27–33] [34]. The use of the mean-field approach can be justified, because it gives the results consistent with the exact solutions in ground state in large N for SU(N) symmetry in non-Abelian interaction term [30]. In Refs. [8,10], an infinitely extended matter state of heavy quarks was considered under the assumption that the number of the heavy quarks was infinite. But those studies did not cover the situation where a single heavy quark could exist in quark matter which may be realized in heavy ion collisions at low energy. In the present paper, I consider the system where there is a single heavy quark in quark matter, and use the mean-field approach to study its ground state. I call an attention that the big difference between the previous studies and the present one is that in the latter, the existence of the heavy quark breaks the translational symmetry of the system, because the single heavy quark behaves like a point defect in quark matter.

In the mean-field approach, I define the Kondo cloud by the condensate of a light quark with a heavy quark, i.e. the light-hole–heavy -quark condensate and the light-quark–heavy-antiquark condensate in the color singlet channel [8]. The formation of the condensate makes the system stable. The previous study [8], involving color current interaction between the two quarks, showed that the Kondo effect occurs on quark matter at low temperatures and high densities under the assumption that heavy quarks were uniformly distributed in space. In the present paper, considering a single heavy quark in quark matter, I demonstrate that the Kondo cloud emerges as the resonant state.

The paper consists of six sections. In section 2, I introduce the color current interaction for a light quark and a heavy quark. Section 3 gives a brief description of the perturbation approach to a scattering of a light quark and a heavy quark, and shows that the approach becomes invalid at low energy scales. In section 4, I use the mean-field approach to investigate the Kondo cloud for a single heavy quark. Section 5 presents the numerical results of the cross section of the scattering of the light quark and the heavy quark in the Kondo cloud, and discuss the effects on transport property of quark matter under the influence of the Kondo cloud. The final section is devoted to the conclusion.

2. Color current interaction

The interaction between the light quark (ψ) and the heavy quark (Ψ) is supplied by the gluon-exchange in QCD. To simplify the discussion, I use the contact interaction with zero range instead of the gluon-exchange interaction with finite range [35–38]. The essence of the discussion does not change for the QCD Kondo effect, as long as color (non-Abelian) exchange is maintained in the interaction [7]. For the simple setting, I regard the light quark mass zero, and regard the heavy quark mass infinity large. As for the heavy quark, following the heavy-quark symmetry [1,2], I consider the v-frame in which the heavy quark is at rest, and separate the heavy quark momentum as $p^\mu = m_Q v^\mu + k^\mu$ for the heavy quark mass m_Q, where $m_Q v^\mu$ is the on-mass-shell part (v^μ the four-velocity with $v^\mu v_\mu = 1$) and the off-mass-shell part k^μ whose scale is much smaller than m_Q. Correspondingly, I define the heavy quark effective field $\Psi_v = \frac{1+\slashed{v}}{2} e^{i m_Q v\cdot x}\Psi$ by factorizing out the on-mass-shell part and leaving only the off-mass-shell part in the original field Ψ [1,2]. Notice $\bar{\Psi}_v \Psi_v = \Psi_v^\dagger \Psi_v$.

Based on the above setup, I give the Lagrangian

$$\mathcal{L} = \bar{\psi}(i\slashed{\partial} + \mu\gamma^0)\psi + \bar{\Psi}_v v\cdot i\partial \Psi_v - G_c \sum_{a=1}^{N_c^2-1} \bar{\psi}\gamma^\mu T^a \psi\, \bar{\Psi}_v \gamma_\mu T^a \Psi_v, \quad (1)$$

with $\psi = (\psi_1, \ldots, \psi_{N_f})^t$ for the light flavor number N_f. I will set $N_f = 2$ in numerical calculation. In the right hand side, the first and second terms represent the kinetic terms for light and heavy quarks, respectively, with μ the chemical potential for light quarks. The third term is the interaction term with the coupling constant $G_c > 0$. $T^a = \lambda^a/2$ ($a = 1, \ldots, N_c^2 - 1$; $N_c = 3$) are generators of color SU(N_c) group with λ^a the Gell-Mann matrices. This color exchange interaction mimics the one-gluon exchange interaction. It was shown that the one-gluon exchange interaction between a light quark and a heavy quark is screened by the Debye mass in finite-density medium, and that it leads to the short-range interaction [7]. In the followings, I set $v^\mu = (1, \mathbf{0})$ as a static frame.

3. Perturbative treatment of scattering

Based on Eq. (1), let us investigate how the interaction strength can be changed by medium effect in quark matter. When a heavy quark exists as an impurity particle, it can be dressed by virtual pairs of light quark and hole near the Fermi surface. Due to those pairs, the interaction strength G_c in Eq. (1) can be modified from the value in vacuum. I use the renormalization group method to estimate the value of the G_c in medium. Such analysis is known as the so called "poor man's scaling" as an early application of renormalization group to the Kondo effect [39]. This method was also applied to the QCD Kondo effect with one-gluon exchange interaction [7]. The following derivation essentially obeys the description in Ref. [7].

I consider the scattering process of a light quark q and a heavy quark Q, $q_l(p) + Q_j \to q_k(p') + Q_i$, where p and p' are incoming and out-going four-momenta, and the subscripts $i, j, k, l = 1, \ldots, N_c$ stand for the color indices. I consider that the interaction strength G_c depends on the energy scale below or above the Fermi surface, and hence it is denoted by $G_c(\Lambda)$ for given energy scale Λ, which is measured from the Fermi surface. The renormalization group equation leads to the relationship between $G_c(\Lambda - \mathrm{d}\Lambda)$ for lower scale $\Lambda - \mathrm{d}\Lambda$ and $G_c(\Lambda)$ for higher scale Λ, where $\mathrm{d}\Lambda > 0$ is an infinitely small quantity. The difference between $G_c(\Lambda - \mathrm{d}\Lambda)$ and $G_c(\Lambda)$ is given by the loop diagram with momentum integration in the small shell region between $\Lambda - \mathrm{d}\Lambda$ and Λ.

When I set $v^\mu = (1, \mathbf{0})$ in Eq. (1), I obtain the scattering amplitude at tree level,

$$\mathcal{M}^{(1)}_\Lambda = -iG_c(\Lambda)\gamma^0 T_{kl,ij}, \quad (2)$$

at certain energy scale Λ, where I define $T_{kl,ij} = \sum_{a=1}^{N_c} (T^a)_{kl}(T^a)_{ij}$ following the notation in Ref. [7]. I can similarly introduce the scattering amplitude

$$\mathcal{M}^{(1)}_{\Lambda-\mathrm{d}\Lambda} = -iG_c(\Lambda - \mathrm{d}\Lambda)\gamma^0 T_{kl,ij}, \quad (3)$$