Kondo effect in dense matter

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The Kondo effect is a phenomenon that indicates the enhancement of the electric resistance at low temperature in metal including impurity atoms with finite spins. This is caused by combination of three conditions: (i) existence of degenerate state (e.g. Fermi surface), (ii) quantum effect by loop integral and (ii) non-Abelian interaction between the itinerant light fermions (electrons) and the heavy impurity particle (atom). Interestingly, it has been pointed out that the Kondo effect can occur in nuclear matter as well as in quark matter, when heavy (charm and bottom) hadrons or quarks exist as impurity particles in the medium. The non-Abelian interaction is provided not only by spin-exchange interaction with $SU(2)_{spin}$ symmetry but also by isospin-exchange interaction with $SU(2)_{isospin}$ symmetry and by color-exchange interaction with $SU(3)_{color}$ symmetry. The Kondo effect in those systems is important because it can change the properties of the medium. The Kondo effect should be investigated in future experiments at accelerator facilities.

KEYWORDS: Kondo effect, heavy quark effective theory

1. Introduction

The Kondo effect is a famous phenomenon that the electric resistance becomes logarithmically enhanced at low temperature in metal where atoms with finite spin are included as impurity particles. The existence of the logarithmic enhancement on temperature in the electric resistance $\sim \ln T$ was already known in early twenty century, but it was against our intuitive picture. As it is well known, the electron-phonon scattering gives T^5 behavior and the electron-electron scattering gives T^2 behavior, and the scattering of electron off impurity atom (without spin) gives a constant value. Hence, none of them could explain the logarithmic enhancement, until Kondo gave the first explanation about the mechanism in his seminal paper in 1964 [1]. He analyzed the scattering matrix up to the 2nd order perturbation beyond the 1st order (Born) approximation, and found that the delicate combination of three conditions induced the logarithmic enhancement in the scattering amplitude. Those conditions are: (i) existence of degenerate state (e.g. Fermi surface), (ii) quantum effect by loop integral and (ii) non-Abelian interaction between the itinerant light fermions (electrons) and the heavy impurity particle (atom). In fact, it was demonstrated that the 2nd order diagram is logarithmically more enhanced than the 1st order diagram by quantum fluctuation with paris of particles and holes near Fermi surface. This enhancement becomes much stronger at low temperature. It makes several physical observables (thermodynamic quantities, transport coefficients, etc.) enhanced or suppressed. At the same time, we need to regard that the perturbative approach should be broken at low temperature, and that it should lead to the study of the non-perturbative physics in this system.

To demonstrate the Kondo effect, we consider the Fermi gas composed of light fermion (ψ) has a impurity heavy particle (Ψ). Their interaction is described by a simple contact interaction Hamiltonian

$$\mathcal{H}_{\mathrm{int}} = G \sum_{c=1}^{n^2-1} \sum_{k,l,i,j=1}^{n} \psi_k^\dagger (t^c)_{kl} \psi_l \Psi_i^\dagger (t^c)_{ij} \Psi_j, \tag{1}$$