Chapter 1

Introduction

1.1 The History of Kondo Effect: Dilute Magnetic Alloys

It is well known that the resistivity of a metal decreases monotonically as temperature decreases due to the electron-phonon scattering rate: at high temperatures, the eletron-phonon scattering rate, and hence the resistivity, decreases linear with T, while at low temperatures (well below the Debye temperature), they decrease as T^5. At sufficient low temperatures, the electron-phonon scattering is negligible and the resistivity saturates to a finite value due to the temperature independent rate of electrons scattering with the impurities and defects in the metal. In the 1930s, de Haas *et al.* [4] measured the electrical resistance of Au bulk samples, and found something surprising: the resistance decreases as temperature decreases as mentioned above, but as $T \approx 4$ K, the resistance reached its minimum and if the temperature decreases further, the resistance increases. The reason for the minimum was not known at that time.

In 1964, Sarachik *et al.* [5] measured the resistance of Mo-Nb and Mo-Re alloys with and without 1% Fe, and demonstrated the resistance minimum was related to the existence of localized magnetic moments. The experimental facts inspired Kondo [6] to consider the $s-d$ exchange interaction model in his theoretical work [7] to explain the resistance minimum. He treated the $s-d$ exchange interaction as perturbation, calculated to second order Born's approximation, and then obtained the scattering rate between free electrons and localized magnetic moments, and hence the resistivity, had $a-b$ log$T$ dependence. He succeeded in explaining the log$T$ dependence and the minimum of the resistivity for metals containing localized magnetic impurities. The effect arises from the free electron-localized moment interaction is called Kondo effect.

Although Kondo resolved the puzzle, he brought a new problem: the resistivity according to Kondo's calculation would diverge as $T \to 0$ due to the logarithmic term. This was unphysical and it means that Kondo's perturbation calculation lost its validity at low temperatures, and a more comprehensive theory was needed to explain the low temperature behavior. The search for such a theory became known as the "Kondo problem". Y. Nagaoka [8] and K. Yosida [9] pointed out that at the low temperature limit, a singlet bound state would form, and the resistivity obeyed a $c-dT^2$ dependence at low temperatures. The temperature regime, within which the $a-b$ log$T$ dependence revealed, was called the weak coupling regime, while the temperature regime, within which the $c-d\ T^2$ revealed, was called the strong coupling. The crossover from the weak to the strong coupling regime was observed in M. D. Daybell's experimental work [10], in which the resistivity of CuFe alloys was measured. The resistivity of CuFe had log$T$ increasing as temperature decreased for 5 K $\lesssim T \lesssim$ 10 K, departed from the log$T$ dependence as $T \lesssim$ 5 K, and had $c-dT^2$ at low temperatures. The Kondo problem was finally answered in 1975 by Wilson, who devised the numerical renormalization group (NRG) methods to calculate the ground state and low temperature thermodynamic properties behavior for the $S = 1/2$ $s - d$ model. His calculation indicated that below a characteristic temperature, namely Kondo temperature T_K, the local magnetic moment was screened by the spin of the surrounding free electrons, to form a singlet state, and was interpreted in terms of a form of Landau Fermi liquid theory by Nozières [11, 12]. After nearly two decades after Wilson's developing the NRG method, an extending of the method was used by Costi *et al.* to accurately calculated the transport properties such as resistivity over a broad range of temperatures [13].

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1.2 Kondo Effect in Tunnel Junctions

Although the Kondo effect was initially discovered in dilute magnetic alloys, it had also been observed in tunnel junctions which contain magnetic impurities embedded in the insulating barrier and sandwiched by two metal [14, 15, 16, 17]. The existence of the localized magnetic moments will cause an enhanced electron tunneling rate which is due to the interaction between the free electrons in the two metal leads and the localized magnetic moments. The enhanced electron tunneling rate will result in an enhanced differential conductance $G \equiv dI/dV$ while in bulk samples, the existence of the localized magnetic moments will cause an enhanced scattering rate and hence the enhanced resistance. Therefore, the study of the temperature dependence of the zero-bias conductance in tunnel junctions which contain localized magnetic moments in their barrier is equivalent to the study of the resistance as a function of temperature in the dilute magnetic alloys. Moreover, except the temperature dependent zero-bias conductance, the conductance at finite bias V can also be studied in the junction geometry. Therefore, the tunneling rate as a function of energy can be studied in both the equilibrium ($eV \lesssim k_B T_K$) and the non-equilibrium ($eV \gtrsim k_B T_K$) regime [18, 19]. To study Kondo effect, the $G(V,T)$ spectrum in a tunnel junction with localized magnetic moments in the barrier contains more information than the resistance in a dilute magnetic alloy.

Recently, Kondo effect was also appeared in a semiconductor quantum dot, which couples to two leads [20, 21]. Due to the small size of the dot, the on site Coulomb interaction U was large. Through varying the gate voltage, the energy of the levels in the dot could be tuned. An energy level ϵ_0 could be tuned to be well below the Fermi energy of the two coupling leads while the next higher level $\epsilon_0 + U$ lay above the Fermi energy. At low temperatures, the levels whose energy $\leq \epsilon_0$ were filled by electrons while the levels whose energy $\geq \epsilon_0 + U$ were empty. If the number of electrons (= the number of levels whose energy $\leq \epsilon_0$) were odd (this could be achieved by tuning the gate voltage), the net spin of the dot was 1/2 and the dot could be viewed as a spin 1/2 magnetic impurity. The net spin in the dot would interact with the spin of the free electrons in the leads while they tunneled through the dot and caused the results similar to the tunnel junction case which contains magnetic moments in the barrier.

1.3 Why We Study Kondo Effect through the Al/AlO$_x$/Sc Tunnel Junctions?

The $S = 1/2$ case is the simplest model to study Kondo effect, and many theoretical works were carried out based on this model. Although the $S = 1/2$ case had been studied in the quantum dot experiment, it is not studied in the planar tunnel junction geometry so far. Therefore, experiment on the tunnel junctions with $S = 1/2$ impurities localized in the barrier and comparing the results to the corresponding theoretical works are interesting and meaningful. The spin angular momentum of a single Sc atom, whose electron configuration is [Ar]$4s^2 3d^1$, is 1/2. In the tunnel junctions fabrication, some Sc atoms will diffuse into the insulating barrier to form localized moments with $S = 1/2$. The tunnel junction geometry, which allows one to obtain more information than the bulk sample does, and the $S = 1/2$ case, are the reasons why we study the Kondo effect through the Al/AlO$_x$/Sc tunnel junctions.