Non-Fermi Liquid Behavior in a Weak Itinerant Ferromagnet MnSi

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Abstract

MnSi is a weak itinerant helimagnet with a relatively low order magnetic moment. Temperature dependance of resistivity shows that it enters non-Fermi liquid state above a critical pressure p_c which remains to be understood. The observed partial magnetic order above p_c indicates novel metallic state. Here, Fermi liquid and non-Fermi liquid theories are discussed with the main focus on the temperature dependance of resistivity. Experimental evidence for the non-Fermi liquid behavior of MnSi has been presented and the partial magnetic order has been discussed.

1 Introduction

There are two basic theories of magnetism-localized moment theory and itinerant electron theory. In localized moment theory, the valence electrons are attached to the atoms and cannot move about the crystal. The valence electrons contribute a magnetic moment which is localized at the atom. In the itinerant electron magnetic theory, electrons responsible for magnetic effects are ionized from the atoms and are able to move through the crystal. There are materials for which one or the other model is a rather good approximation [1]. There are models in terms of which these theories can be understood. Heisenberg model and Stoner model explain respectively localized and itinerant magnetic systems quite well. Yet there are some materials

with intermediate magnetic properties called near or weak ferromagnets in which the above mentioned theories become inadequate [2].
In 1957 Landau came up with a model for the metallic state combining the Pauli exclusion principle with the effects of screening of the columbic interaction named Fermi Liquid Theory (FLT) [3]. Among the many materials obeying FLT are the nearly and weakly ferromagnetic d-electron metals in which conduction bands derive from the substantial overlap of d-orbitals while the effects of spin-orbit coupling are weak [4]. There is a model consistent with the FLT which is developed for the ferromagnetic d-metals called Ferromagnetic Fermi Liquid theory (FFL). The general validity of the FFL, however, is in doubt. Non-fermi liquid behavior has been observed on the weakly magnetic d-electron compound MnSi [5].
In this paper, I present a brief description of the fermi liquid and non-fermi liquid theory and the experimental observation in MnSi indicating the non-fermi liquid behavior.

2 Fermi Liquid Theory

Landau developed the idea of quasiparticle excitation of interacting Fermi systems. This theory is known as Fermi Liquid Theory (FLT). Fermi liquids have spin $\frac{1}{2}$ excitations and obey Fermi statistics. Examples are ^3He, electrons in metals and heavy nuclei. Landau gave the phenomenological description of FLT and formal derivation was later done by Abrikosov and Khalantikov [6].
An electron in a metal collects around itself a screening cloud of other electrons, there by becoming a quasiparticle with some effective mass m^*. The number of quasi particles is equal to the number of free electrons N. The quasiparticles have momentum of p $=\hbar$k, spin projection $\frac{1}{2}$, and obey Pauli exclusion principle. In ground state, like the free electrons, the quasiparticles fill the fermi sea up to the Fermi momentum. There is one to one correspondence between the free particle and quasi particle regarding the quantities like Fermi momentum (eqn 1), Fermi velocity (eqn 2), energy of a single (quasi) particle (eqn 3) and density of state at the Fermi level (eqn 4), the quasi particle taking the effective mass (m^*) in place of mass of electron (m) in free electron model.

$$p_f = \hbar(3\pi^2 N)^{\frac{1}{3}} \tag{1}$$

$$v_f = \frac{p_f}{m^*} \tag{2}$$

$$\varepsilon(p) = \frac{p^2}{2m^*} \tag{3}$$

$$\frac{dn}{d\varepsilon} = \frac{3Nm^*}{p_f^2} \tag{4}$$

In FLT the interaction of quasiparticles is taken into account as a self consistent field of surrounding particle. The consequence is that energy of the system is not equal to the sum of energies of the N quasiparticles, but it is a functional of the distribution function. The energy of the quasiparticle is written as:

$$E = \varepsilon_o(p,\sigma) + \delta\varepsilon_{(p,\sigma)}^{meanfield} \tag{5}$$

where, $\varepsilon_o(p,\sigma)$ is the energy of the quasiparticle at T = 0 and $\delta\varepsilon_{(p,\sigma)}^{meanfield}$ is the mean field effect of the interaction with other quasi particles given by:

$$\delta\varepsilon_{(p,\sigma)}^{meanfield} = \frac{1}{2} S_{\sigma'} \int f(p,\sigma;p',\sigma')\delta n(p,\sigma) \frac{2dp_x dp_y dp_z}{(2\pi\hbar)^3} \tag{6}$$

The function $f(p,\sigma;p',\sigma')$ is related to the scattering amplitude of two quasi particles, and verifies time reversal symmetry i.e $f(p,\sigma;p',\sigma')$=$f(p',\sigma';p,\sigma)$; $\delta n(p,\sigma)$ = n-n_{Fermi} and accounts for small deviations of the density of states from the equilibrium value n_{Fermi}. The quasiparticles are associated with low energy excitations of the interacting system of electrons with a long life time near the Fermi energy, and hence it was created to explain the low temperature ($T < T_{Fermi}$). The total energy is given by:

$$E = E_o + \sum_{p,\sigma} \int \delta\varepsilon(p,\sigma)\delta n(p,\sigma) \tag{7}$$

which shows that total energy is not just the sum of energies of each quasi particle. The prediction for the temperature dependance of magnetic susceptibility χ, specific heat [6] and electric resistivity ρ [7] is given by:

$$\chi = \chi_o; \chi_o = \chi_o(m^*) \tag{8}$$

$$C = \gamma_o T; \gamma_o = \gamma_o(m^* \tag{9}$$

$$\rho = \rho_o + AT^2 \tag{10}$$

3 Non-Fermi Liquid System

In 1991 Seaman et al.[8] came up with measurement of specific heat, magnetic susceptibility and electrical resistivity on $Y_{1-x}U_xPd_3$ system that strongly disagreed with the Fermi-Liquid model of Landau. The Non-Fermi Liquid (NFL) behavior is characterized by weak power and logarithmic divergence in temperature dependance of the physical properties of these materials at low temperature which take the following form [9]:

$$\rho(T) \sim \rho_o[1 - a(\frac{T}{T_o})^n] \tag{11}$$

$$\frac{C(T)}{T} \sim -[\frac{bR}{T_o}]ln(\frac{b'T}{T_o})orT^{-1+\lambda} \tag{12}$$

$$\chi(T) \sim \chi_o[1 - c(\frac{T}{T_o})^{\frac{1}{2}}]or - ln(\frac{T}{T_o})orT^{-1+\lambda} \tag{13}$$

where, a can be positive or negative, $|a|$, b, b', and c are constants of the order of unity, n lines in the range 1≤n≤1.6 and $\lambda \leq 1$.
A number of models have been proposed to account for the NFL behavior observed in d-and f-electron systems. The underlying physics of this model lies in the single-impurity multichannel kondo model and quantum critical point theories [10].

4 Non-Fermi Liquid State in MnSi

MnSi is a d-transitional metal with a cubic crystallographic structure(a=4.588 $\mathring{A}$ [2]. Figure 1 shows the crystal structure of MnSi. There are 4 Mn ions and 4 Si ions in a unit cell. The position of Mn and Si ions in a unit cell are given by (u,u,u), ($\frac{1}{2}$+u,$\frac{1}{2}$-u),(-u, $\frac{1}{2}$+u, $\frac{1}{2}$-u) and ($\frac{1}{2}$-u, -u, $\frac{1}{2}$+u) where u_{Mn} and u_{Si} are 0.138 and 0.845. Although relatively simple, the cubic B20 crystal structure of MnSi is somewhat unusual in that it lacks space inversion symmetry. MnSi atoms are slightly rotated away from centrosymmetric positions, thus breaking the inversion symmetry [11]. The observed helical spin is attributed to the absence of space inversion symmetry. Due to the lack of inversion symmetry, in the spin-orbit coupling of MnSi there appears term $D(S_1 \times S_2).Q$ favoring the perpendicular spin orientation which stabilizes the helical spin density wave [11].
MnSi shows a magnetic transition at $T_c = 29.1$ K from a paramagnetic state to a helical magnetic structure. The spiral has a wavelength of 180 $\mathring{A}$ in the (111) direction. At zero temperature, there is a spontaneous magnetic

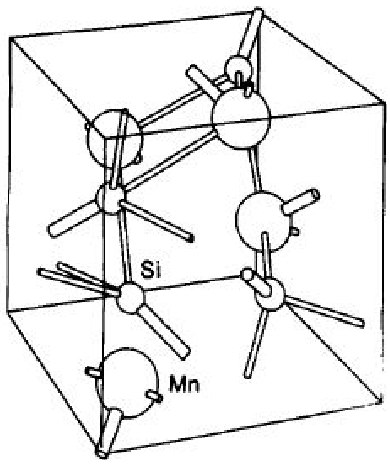

Figure 1: Crystal structure of Mnsi[11]

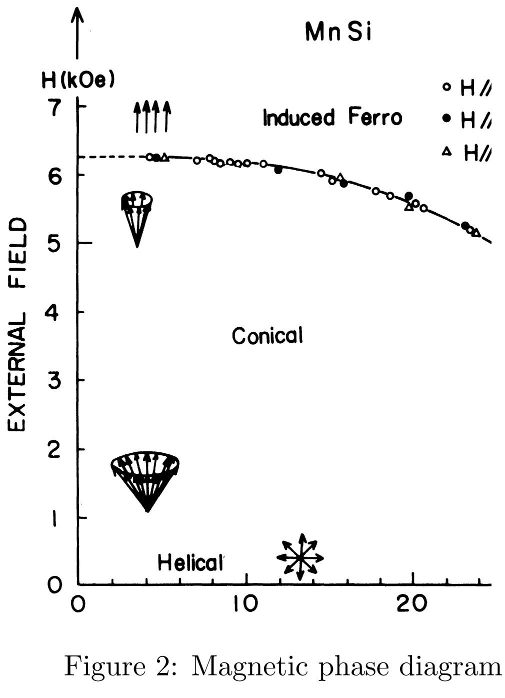

Figure 2: Magnetic phase diagram of MnSi[12]

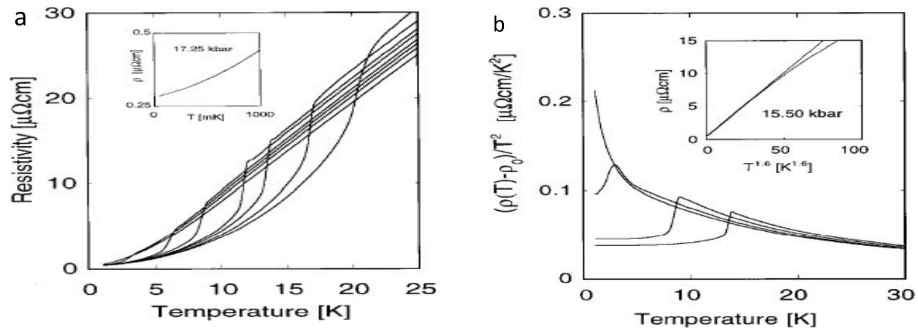

Figure 3: a) Resistivity Vs Temperature at different pressure b) Ratio of $\triangle\rho$ =ρ-ρ_o to T^2 at different pressure[14]

moment of 0.4 μ_B per Mn atom which is notably smaller than the effective paramagnetic moment of $\sim$ 1.4 μ_B obtained from a Curie-Weiss fit of susceptibility. In a field of 0.6T, the moments align in an induced ferromagnetic structure. All these factors suggest that Mn in the induced ferromagnetic state can be classified as a weak itinerant ferromagnet [13]. Figure 2 shows the pase diagram of MnSi determined by an ultrasonic method. A solid line in the figure represents the phase boundary where the helical component of the magnetic moment disappears while a broken line indicates boundary where the magnetic moment induced in the field direction decreases distinctly [12].

Experimental study of electrical resistivity of MnSi provides a cleanest example of non-Fermi liquid phase [5]. Figure 3a shows the variation of resistivity with temperature at different pressures (5.55, 8.35, 10.40, 11.40, 12.90, 13.55, 14.30, and 15.50 Kbar going down starting from the top curve at the far right). It is seen that the resistivity drops monotonically by approximately three orders of magnitude in all cases on cooling from 300K to 30 mK. For pressure below 14.6 Kbar, a shoulder appears in ρ Vs T, marking the onset of magnetic order. The peak position that is identified with transition temperature T_c is decreasing monotonically with high slope at p_c. In the magnetic phase below p_c has a quadratic (T^2) temperature dependance for $T \ll T_c$ which is the behavior expected for Fermi liquid in paramagnetic or weak polarized state. At p_c, the (T^2) regime collapses. It is seen that above p_c, the temperature variation of ρ is slower than quadratic. Figure 3b shows the variation of $\triangle\rho$ = ρ -ρ_o to T^2 with the temperature at the different pressures (10.40, 12.90, 14.30 and 15.50 Kbar) going up start-

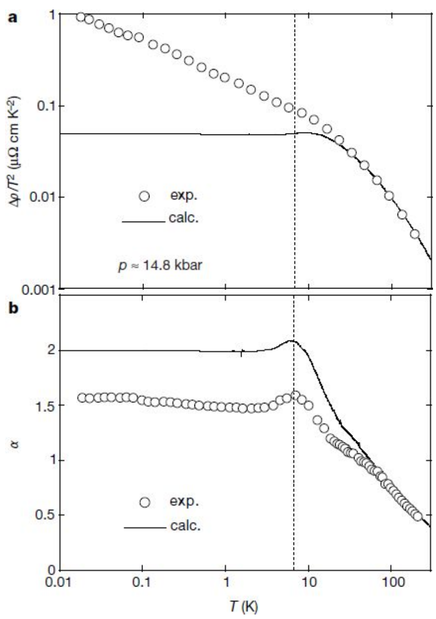

Figure 4: Comparision of the experimentally observed temperature dependence of the resistivity above p_c =14.6 Kbar with predictions of the model of a nearly ferromagnetic Fermi liquid as evaluated for MnSi[5]

ing from the bottom curve at the far left). It is seen that $\frac{\triangle\rho}{T^2}$ saturates at low T in the magnetic Fermi liquid state below p_c but grows with decreasing temperature without apparent limit in the paramagnetic state above p_c. The exponent defined by $\triangle\rho \propto T^{\alpha}$ is everywhere less than 2 and increases gradually from approximately 1.5 to 1.6 at the lowest temperature reached. Figure 4 shows a comparison of the prediction of the FFL model with the experiment. It shows that the prediction of FFL model are in agreement with the experiment at high T. But as temperature decreases, the expected quadratic T dependance deviates from the dependance in experimental observation [5]. There is currently no explanation for pressure dependance of the electrical resistivity in MnSi in the low temperature limit thus raising the question if it is the signature of a novel metallic state [15].

5 Partial Magnetic Order in the Non-Fermi Liquid State and Possibility of Non-Trivial Spin Structure

Spin fluctuation theory consistently explains quantitatively the observed T_c which, in turn, can be very well tracked up to p_c. This indicates that quantum critical spin fluctuation would some how explain the NFL resistivity. But failure of neutron scattering experiments to identify the nature of magnetic fluctuation gave a hint for the possibility of some kind of magnetic ordering [15]. On the other hand study of magnetic order as a function of pressure has revealed the persistence of magnetic moment at p_c [5]. Based on the intensity analysis of neutron scattering experiment, Pfleiderer et al. [15] have argued the ordering of the magnetic moment to be partial. According to them, the partial ordering might arise due to the two scenarios. First, helical structure may have broken into a multi-domain state in which the helix ends abruptly between domains. Second, the helix direction has unlocked from $< 111 >$ direction and no longer exhibits strict directional order. But there is neither theoretical explanation nor experimental observation for unlocking of the helical order. Thus the possible scenarios are: either there is some hidden forms of quantum criticality or the stability of new state with low-lying excitations. Again, according to Pfleiderer et al.[15] several complementary studies have established that the non-Fermi liquid resistivity emerges under pressure without quantum criticality. Furthermore, neutron Lamor diffraction, a novel polarized neutron scattering technique, has revealed that partial order on local scales is not related to the helical order, suggesting that it represents a novel state and thus arising a conceptual question about the kind of spin ordering expected other than a plain pinning of the helix or a multi-domain state [15]. There are a couple of proposed spin structure [16][17][18]. But neither of them give the accurate result. This suggests that there might be a non-trivial spin structure in MnSi [15].

6 Conclusion

MnSi is a weak itinerant ferromagnet. But it shows a $T^{\frac{3}{2}}$ behavior of resistivity which is not consistent with the current models of the itinerant electron ferromagnetism. Origin of this form of $\rho(T)$ may lie in the novel form of magnetic ordering indicating non-trivial spin structures. There is no theoretical account for the NFL resistivity and how it is related to the partial magnetic ordering.This has raised the need for more experimental evidences.

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