Pressure Effects on the Superconducting Transition Temperature of Ferromagnetic Superconductors

Rikio Konno and Nobukuni Hatayama

***Abstract*— The pressure effects on the superconducting transition temperature of ferromagnetic superconductors are investigated numerically. The authors obtained the analytical expression of the pressure coefficients of the superconducting transition temperature with the superconducting gap with line nodes and with the superconducting gap similar to the thin film of A2 phase in liquid ^{3}He [1], [2] based on the free energy derived from the microscopic Hamiltonian[3], [4]. It is assumed that the Curie temperature is much higher than the superconducting transition temperatures. There has been no numerical investigation of pressure effects on the superconducting transition temperatures of ferromagnetic superconductors based on the microscopic model although Huang et al. investigate the pressure effects on the superconductors [5].**

***Index Terms*—Magnetization, Temperature dependence, Superconducting transition temperature.**

I. INTRODUCTION

Many researchers have paid attention to ferromagnetic susperconductors [6], [7] since ferromagnetic superconductors UGe_2 [8], UCoGe [9], and URhGe [10], [11] were discovered.

The antecedent work about ferromagnetism and superconductivity is mentioned. For example, Tateiwa et al. studied magnetic properties under pressure in UGe_2 [12]. Pfleiderer et al. investigated pressure induced crossover of the magnetic transition in MnSi [13]. Recently, Shopova and Uzunov [14] looked into the pressure dependence of the superconducting transition temperature and that of the Curie temperature in the ferromagnetic superconductors based on the Landau expansion of the free energy. Huang et al. reported the pressure coefficient of the superconducting transition temperature in $FeSe_{1-x}Te_x$ experimentally [5]. Aso et al. estimated the pressure dependence of the Stoner gap based on the Stoner model from the neutron intensities [15].

We obtained the analytical expression [1], [2] of the pressure coefficient of the superconducting transition temperatures and that of Curie temperature by the mean field approximation based on the Hamiltonian derived by Linder et al. [3], [4]. The thermodynamic Gruneisen's relation will be satisfied in this study automatically.

Although the analytical expression [1], [2] of the pressure coefficient of the superconducting transition temperature was obtained, it has not been understood well. Therefore, the pressure coefficient of the superconducting transition temperatures of ferromagnetic superconductors is investigated numerically.

The Curie temperature T_C is much higher than the superconducting transition Temperature T_{SC}. T_C is much lower than the Fermi temperature T_F. The magnetization is constant. This assumption is valid in UGe_2.

This paper is organized as follows. In the next section, the pressure coefficient of the superconducting transition temperatures with the superconducting gap with the line node and with the superconducting gap similar to the thin film of the A2 phase in liquid ^{3}He will be provided. In section 3, the numerical results will be shown. In section 4, the results will be summarized.

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II. THE PRESSURE COEFFCIENTS OF THE SUPERCONDUCTING TRANSITION TEMPERATURE

A. *The Case of the Superconducting Gap with the Line Node*

First, in this subsection, the pressure coefficient of the superconducting transition temperature with the line node superconducting gap is derived. Harada et al. displayed that the superconducting gap of the up-spin conduction band with line node is in UGe$_2$ experimentally [16]. The superconducting transition temperature T_{SC} with the line node superconducting gap is obtained as follows [1], [4]:

$$T_{SC} = 1.134 E_0 \exp(-2/c\sqrt{1+\tilde{M}(\tilde{T}_{SC})}) \,, \tag{1}$$

where E_0 is the cutoff energy. c is the weak coupling constant. $\tilde{M}$ is the reduced magnetization where $\tilde{T}_{SC} = T_{SC}/T_F$ and T_F is the Fermi temperature.

From (1), we obtain the pressure coefficient of the superconducting transition temperature

$$\frac{\partial T_{SC}}{\partial P} = T_{SC}\Big(\frac{\partial}{\partial P}(\ln 1.134 E_{\mathbf{0}}) + \frac{2}{c^2\sqrt{1+\tilde{M}(\tilde{T}_{SC})}}\frac{\partial c}{\partial P} + \frac{1}{c(1+\tilde{M}(\tilde{T}_{SC}))^{3/2}}\frac{\partial \tilde{M}(\tilde{T}_{SC})}{\partial P}\Big). \tag{2}$$

From (3), the increase of the cutoff energy E_0 leads to the increase of the pressure coefficient of the superconducting transition temperature because the superconducting transition temperature is proportional to the cutoff energy E_0. When the weak coupling constant and the magnetization increases, the pressure coefficient of the superconducting transition temperature increases because the superconducting transition temperature and the magnetization increase exponentially. The pressure coefficient of the superconducting transition temperature depends on the pressure coefficient of the weak coupling constant and that of the magnetization linearly. We will consider the case of the superconducting gap similar to the thin film of the A2 phase in liquid ^{3}He in the next subsection.

B. *The Case of the Superconducting Gap Similar to the Thin Film of A2 Phase in Lliquid ^{3}He*

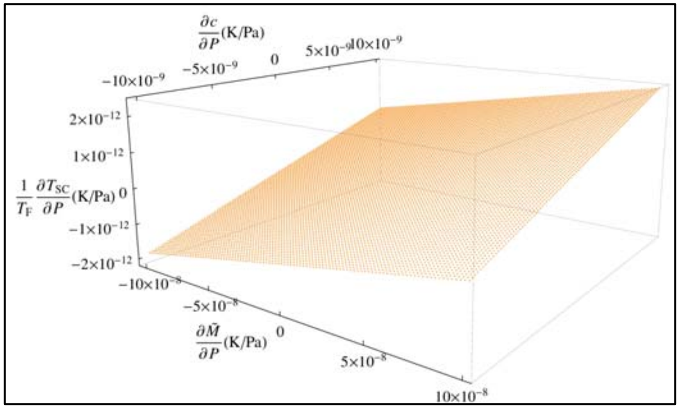
In this subsection, the pressure coefficient of the superconducting transition temperature in the superconducting gap of ^{3}He thin film is derived. The superconducting transition temperature in this case is obtained as follows [2], [3]:

$$T_{SC\sigma} = 1.13 E_0 \exp(-1/c\sqrt{1+\sigma\tilde{M}(\tilde{T}_{SC\sigma})}) \,. \tag{3}$$

From (3), we obtain the pressure coefficient of the superconducting transition temperature of the spin σ band

$$\frac{\partial T_{SC\sigma}}{\partial P} = T_{SC\sigma}\Big(\frac{\partial}{\partial P}(\ln 1.13 E_{\mathbf{0}}) + \frac{1}{c^2\sqrt{1+\sigma\tilde{M}(\tilde{T}_{SC})}}\frac{\partial c}{\partial P} + \frac{1}{2c(1+\sigma\tilde{M}(\tilde{T}_{SC}))^{3/2}}\frac{\partial(\sigma\tilde{M}(\tilde{T}_{SC}))}{\partial P}\Big). \tag{4}$$

From (4), the increase of the pressure coefficient of magnetization leads to the decrease of the pressure coefficient of the superconducting transition temperature of the down-spin band because the coefficient of the magnetization is negative. The pressure coefficient of the superconducting transition temperature has the linear behavior of the pressure coefficient of the weak coupling constant and that of the pressure coefficient of the magnetization in the similar ways of the case in the previous subsection.



The pressure coefficient of the cutoff energy E_0, that of the weak coupling constant, and that of the magnetization will be estimated if the pressure coefficients of the superconducting transition temperature are observed. In the next section the numerical results will be provided.

III. THE NUMERICAL RESULTS

A. *The Case of the Superconducting Gap with the Line Node*

In this subsection, the numerical results are obtained from (2). Fig.1 shows the pressure coefficient of the superconducting

Figure 1. The pressure coefficient of the superconducting transition temperature of the ferromagnetic superconductors with the line node superconducting gap $\partial(\ln 1.134E_0)/\partial P = 10^{-7}$ 1/Pa and $T_{SC}/T_F = 3.0\times10^{-6}$.

transition temperature with $\partial(\ln 1.134E_0)/\partial P = 10^{-7}$ and $T_{SC}/T_F = 3.0\times10^{-6}$. Fig.2 shows the pressure coefficient of the superconducting transition temperature with $\partial(\ln 1.134E_0)/\partial P = 10^{-8}$ and $T_{SC}/T_F = 3.0\times10^{-6}$. From Fig. 1 and Fig. 2, $\partial\tilde{M}(\tilde{T}_{SC})/\partial P$ increases in increase of the pressure coefficient of the superconducting transition temperature. $\partial c/\partial P$ increases in increases of the pressure coefficient of the superconducting transition temperature. There are no local maximums.

We compare the results with the experimental data of Tateiwa et al. [12]. From Tateiwa et al. [12], $\partial T_{SC}/\partial P$ is nearly equal to 10^{-8} K/Pa. If T_F =10000K, we estimate $\partial\tilde{M}(\tilde{T}_{SC})/\partial P \approx 10^{-9}$ 1/Pa and $\partial c/\partial P \approx 10^{-9}$ 1/Pa. These results are qualitatively consistent with the experimental data.

Figure 2. The pressure coefficient of the superconducting transition temperature of the ferromagnetic superconductors with the line node superconducting gap $\partial(\ln 1.134\,E_0)/\partial P = 10^{-8}$ 1/Pa and $T_{SC}/T_F = 3.0\times10^{-6}$.

B. The Case of the Superconducting Gap Similar to the Thin Film of A2 Phase in Liquid ^{3}He

Fig. 3 and Fig. 4 show the numerical results of $\partial T_{SC\uparrow}/\partial P$ and $\partial T_{SC\downarrow}/\partial P$ when $\partial(\ln 1.13E_0)/\partial P = 5\times10^{-6}, 5\times10^{-7}$, $T_{SC\uparrow}/T_F = 1.84\times10^{-4}$, $T_{SC\downarrow}/T_F = 1.14\times10^{-5}$, $\tilde{M}(\tilde{T}_{SC\uparrow}) = 0.475$, respectively. $\partial T_{SC\uparrow}/\partial P$ increases in the increase of the pressure coefficient of the magnetization and that of the weak coupling constant. On the other hand, $\partial T_{SC\downarrow}/\partial P$ decreases in the increase of the pressure coefficient of the magnetization and increases in the increase of the pressure coefficient of the weak coupling constant. In the both of the cases, there are no local maximums.

IV. SUMMARY

We have investigated the pressure coefficients of the superconducting transition temperatures with the line node superconducting gap and with that similar to the thin film of A2 phase in liquid ^{3}He. The pressure coefficients of the superconducting transition temperatures with the line node superconducting gap obtained are in qualitative agreement with

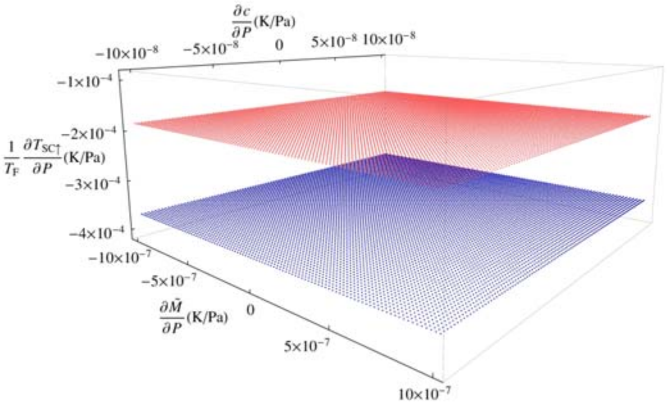
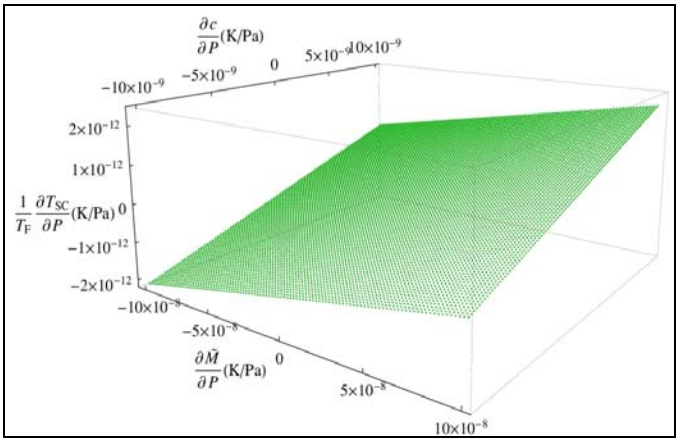


Figure 3. $\partial T_{SC\uparrow}/\partial P$ of the ferromagnetic superconductors with the superconducting gap similar to the thin film of A2 phase in ^3He, $\partial(\ln 1.134\ E_0)/\partial P = 5\times10^{-6}$ 1/Pa (the red points), $\partial(\ln 1.134\ E_0)/\partial P = 5\times10^{-7}$ 1/Pa (the blue points) and $T_{SC\uparrow}/T_F = 1.84\times10^{-4}$.



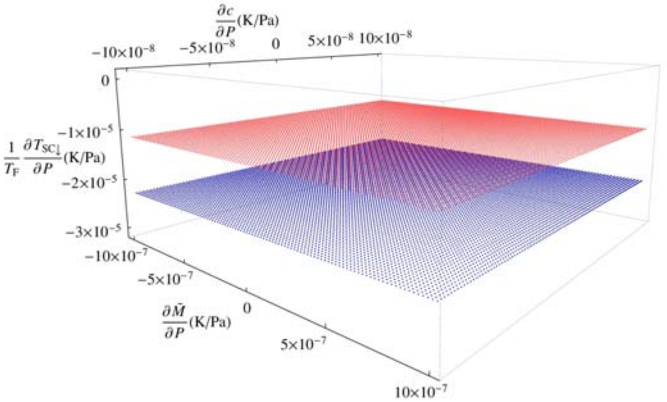


Figure 4. $\partial T_{SC\downarrow} / \partial P$ of the ferromagnetic superconductors with the superconducting gap similar to the thin film of A2 phase of ^3He , $\partial(ln1.134\ E_0) / \partial P = 5 \times 10^{-6}$ 1/Pa (the red points), $\partial(ln1.134\ E_0) / \partial P = 5 \times 10^{-7}$ 1/Pa (the blue points) and $T_{SC\downarrow} / T_F = 1.14 \times 10^{-5}$.

the experimental data [12]. From the numerical results, we will be able to estimate the pressure coefficient of the magnetization and that of the weak coupling constant from that of the superconducting transition temperatures.

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