The pressure coefficient of the Curie temperature of ferromagnetic superconductors

R Konno and N Hatayama
Kinki University Technical College, 7-1 Kasugaoka, Nabari-shi, Mie 518-0459, Japan
E-mail: r-konno@ktc.ac.jp

Abstract. The pressure coefficient of the Curie temperature of ferromagnetic superconductors is studied numerically. In our previous study the pressure coefficient of the Curie temperature and that of the superconducting transition temperature were shown based on the Hamiltonian derived by Linder et al. within the mean field approximation about the electron-electron interaction analytically. There have been no numerical results of the pressure coefficient of the Curie temperature derived from the microscopic model. In this study the numerical results are reported. These results are qualitatively consistent with the experimental data in UGe$_2$.

1. Introduction
The ferromagnetic superconductors [1, 2] have attracted many researchers again since the ferromagnetic superconductors UGe$_2$ [3], UCoGe [4] and URhGe [5, 6] were discovered. Many experimentalists have actively investigated the Curie temperature and the superconducting transition temperature of these materials under pressure [7].

We mention the antecedent studies of pressure effects on magnetism and superconductivity chronologically. For example, Pfleiderer et al. studied critical behaviour at the magnetic transition as a function of hydrostatic pressure phenomenologically [8]. Matsumoto and Sigrist investigated the temperature-pressure phase diagram by using the Landau expansion of the free energy [9]. Aso et al. obtained the pressure dependence of the Stoner gap based on the Stoner model from the neutron intensities [10].

Recently, Shopova and Uzunov investigated the pressure dependence of the superconducting transition temperature and that of the Curie temperature of ferromagnetic superconductors phenomenologically [11]. Shopova and Uzunov used the Landau expansion of the free energy about the superconducting order parameters and the magnetisation. Huang et al. reported the pressure coefficient of the superconducting transition temperature in FeSe$_{1-x}$Te$_x$ experimentally [12]. These theoretical investigations are based on the Landau expansion of the free energy phenomenologically.

The purpose of this study is expressed. The pressure coefficient of the Curie temperature and that of the superconducting transition temperature derived from the single band model by Linder and Subo [13] were analysed in the context of the mean-field theory [14]. The analytical expression of the pressure coefficient of the Curie temperature and that of the superconducting transition temperature by taking into account the ferromagnetic order in the ferromagnetic superconductors were obtained [14] while the pressure coefficient of the superconducting transition temperature with no magnetic order were obtained [12]. The numerical results are
shown in this paper because the pressure coefficient of the Curie temperature based on the microscopic model has been unresolved numerically.

The remainder of this paper is organised as follows. In the next section, the pressure coefficient of the Curie temperature will be derived. In section 3, the numerical results will be obtained. Section 4 will be devoted to conclusions. After submitting this paper, Mineev [15] and Shimizu et al. [16] phenomenologically discussed the physical properties of ferromagnetic superconductors at LT26.

2. The pressure coefficient of the Curie temperature

In this section, the pressure coefficient of the Curie temperature $T_C$ is derived. We assume that the superconducting transition temperature is much lower than the Curie temperature. This assumption is valid in UGe$_2$. The magnetisation $M$ is determined by the following equation [13]

$$ M = -\frac{1}{2} \sum_{\sigma} \int_{0}^{\infty} d\epsilon N(\epsilon) \tanh \left[ \frac{\epsilon - E_F - \sigma IM}{2T} \right], $$

(1)

where $I$ is the electron-electron interaction. $E_F$ is the Fermi energy. $N(\epsilon)$ is the density of states. $\sigma$ is 1 and -1 for the up-spin band and the down-spin band, respectively. In order to obtain the analytical expression of the magnetisation, $N(\epsilon)$ is replaced with $N(0)$ where $N(0)$ is the density of states at the Fermi energy. In the right hand-side, we perform the integral calculation over $\epsilon$. We derive the equation of the magnetisation

$$ M = I N(0) M + T N(0) \ln \left( \frac{\cosh \left( \frac{E_F + IM}{2T} \right)}{\cosh \left( \frac{E_F - IM}{2T} \right)} \right). $$

(2)

In $T \to T_C$, this equation is expanded around the small $M$. Subsequently, $M$ is equal to a zero at $T = T_C$. We obtain the Curie temperature

$$ T_C = \frac{T_F}{\ln(2IN(0) - 1)}. $$

(3)

If $1 < IN(0) < \frac{e+1}{2}$, the Curie temperature $T_C$ is higher than the Fermi temperature $T_F$. If $\frac{e-1}{2} < IN(0)$, the Curie temperature $T_C$ is lower than the Fermi temperature $T_F$. If the superconducting order does not exist at $T=0$ K, no ferromagnetic order exists at $T=0$ K.

From Eq. (3) we differentiate the Curie temperature $T_C$ about pressure $P$. We obtain the pressure coefficient of the Curie temperature $T_C$

$$ \frac{\partial T_C}{\partial P} = \frac{\frac{\partial T_F}{\partial P}}{\ln(2IN(0) - 1)} - \frac{2T_F \frac{\partial IN(0)}{\partial P}}{1 (2IN(0) - 1)^2}. $$

(4)

In the next section, the pressure coefficient of $T_C$ will be obtained numerically.

3. Results

In this section, we provide the pressure coefficient of $T_C$, $\frac{\partial T_C}{\partial P}$, obtained from Eq.(4) numerically. Next, we compare the results with the experimental data in UGe$_2$.

Fig. 1 shows $\frac{\partial T_C}{\partial P}$ as the function of $\frac{\partial T_F}{\partial P}$ and $\frac{\partial IN(0)}{\partial P}$, which corresponds to the pressure coefficient of $I/E_F$, with $IN(0) = 3$ and $T_F = 10000$ K. From Fig. 1, $\frac{\partial T_C}{\partial P}$ decreases in increase of $\frac{\partial IN(0)}{\partial P}$, or the pressure coefficient of $I/E_F$. On the other hand, $\frac{\partial T_C}{\partial P}$ increases in increase of $\frac{\partial T_F}{\partial P}$. Fig. 2 shows $\frac{\partial T_C}{\partial P}$ as the function of the ferromagnetic exchange energy constant $IN(0)$ and $\frac{\partial IN(0)}{\partial P}$ with $\frac{\partial T_F}{\partial P} = 5 \times 10^{-9}$ K/Pa and $T_F = 10000$ K. From Fig. 2, $\frac{\partial T_C}{\partial P}$ decreases in increase of
Figure 1. The pressure coefficient of the Curie temperature of the ferromagnetic superconductors with the ferromagnetic exchange energy constant $IN(0) = 3$, and the Fermi temperature $T_F = 10000$ K.

Figure 2. The pressure coefficient of the Curie temperature as the function of the ferromagnetic exchange energy constant $IN(0)$ and $\frac{\partial(IN(0))}{\partial P} 1$/Pa with $\frac{\partial T_F}{\partial P} = 5 \times 10^{-9}$ K/Pa and the Fermi temperature $T_F = 10000$ K.
IN(0) around $\frac{\partial(IN(0))}{\partial P} = 0$, while it increases in increase of $IN(0)$ between $\frac{\partial(IN(0))}{\partial P} = 5 \times 10^{-12}$ and $\frac{\partial(IN(0))}{\partial P} = 1 \times 10^{-11}$. However, there are no local maximums.

We compare the numerical results with the experimental data in UGe$_2$. From Tateiwa et al. [7], $\frac{\partial T_C}{\partial P}$ lies between $-10^{-8}$ K/Pa and $-10^{-9}$ K/Pa. From Fig. 1 and Fig. 2, $\frac{\partial T_C}{\partial P}$ is about $-10^{-8}$ K/Pa when $\frac{\partial(IN(0))}{\partial P} \approx 10^{-12}$ 1/Pa and $\frac{\partial T_F}{\partial P}$ lies between $10^{-8}$ K/Pa and $10^{-9}$ K/Pa. $\frac{\partial T_C}{\partial P} \approx -10^{-8}$ K/Pa and $\frac{\partial T_F}{\partial P} \approx 10^{-8}$ K/Pa are qualitatively consistent with the results of Aso et al. [10] and the experimental data [7] although $T_C$ is larger than the experimental data because of us using the mean field approximation and the constant density of states. $\frac{\partial T_F}{\partial P}$ and $\frac{\partial(IN(0))}{\partial P}$ need to be directly estimated by the other experimental measurements because the results of Aso et al. were indirectly observed. The next section will be dedicated to conclusions.

4. Conclusions

Prior theoretical work about pressure effects on the ferromagnetic superconductors has been based on the Landau expansion of the free energy phenomenologically [11, 15, 16]. There have been no theoretical investigations founded on the microscopic model. We have succeeded in obtaining the pressure coefficient of the Curie temperature of the ferromagnetic superconductors and the numerical results based on the microscopic model derived by Linder et al. [13, 14]. The numerical results have enabled us to explain the experimental data [7, 10] from the theoretical point of view qualitatively.

4.1. Acknowledgments

The authors would like to thank Y. Takahashi, O. Stockert, M. Kanno, and M. Nakamori for stimulating conversations. One of the authors (R. K.) would like to also thank K. Grube, H. v. Löhneysen, F. Steglich, A. de Visser, M. B. Maple, K. Ishida, V. P. Mineev, Z. Li, and V. Taufour for stimulating conversations and T. Mamedov and M Maksymenko for sending him preprints prior to the publications. This work is supported by the Kinki University Technical College Research Fund.

References

[1] Tachiki M and Maekawa S 1984 Phys. Rev. B 29 2497
[2] Matsumoto H, Teshima R, Umezawa H and Tachiki M 1983 Phys. Rev. B 27 158
[3] Saxena S S, Agarwal P, Ahilan K, Grosch F M, Haselwimmer R K W, Steiner M J, Pugh E, Walker I R, Julian S R, Monthoux P, Lonzarich G G, Huxley A, Sheikin I, Braithwaite D and Flouque J 2000 Nature 406 587
[4] Huy N T, Gasparini A, Nijs D E de, Huang Y K, Klaasse J C P, Gortenmulder T, Visser A de, Hamann A, Görlich T and Löhneysen v H 2007 Phys. Rev. Lett 99 067006
[5] Aoki D, Huxley A, Resouce E, Braithwaite D, Flouque J, Brison J P, Lhotel E and Paulsen C, 2001 Nature 413, 613
[6] Levy F, Sheikin I, Grenier B, Marcenat C and Huxley A 2009 J. Phys.:Condens. Matter 21 164211
[7] For example, Tateiwa N, Hanazono K, Koike Y, Metoki N, Haga Y, Settai R and Onuki Y 2001 J. Phys. Soc. Jpn. 70 2876
[8] Pfleiderer C, McMullan G J and Lonzarich G G 1994 Physica B 199-200 634
[9] Matsumoto M and Sigrist M 2005 J. Phys. Soc. Jpn 74 2310
[10] Aso N, Motoyama G, Uwatoko Y, Ban S, Nakamura S, Nishioka T, Homma Y, Haga Y, Settai R and Onuki Y 2001 J. Phys. Soc. Jpn. 70 2876
[11] Shopova D V and Uzunov D I 2009 Phys. Rev. B 79 064501
[12] Huang C L, Chou C C, Tseng K F, Huang Y L, Hsu F C, Yeh K W, Wu M K and Yang H D 2009 J. Phys. Soc. Jpn. 78 084710
[13] Linder J and Sudbo 2007 Phys. Rev. B 76 054511
[14] Konno R and Hatayama N 2011 J. Phys.: Conf. Ser. 286 012010
[15] Mineev V P be submitted to J. Phys.: Conf. Ser.
[16] Shimizu A, Ozawa H, Ichinose I and Matsui T be submitted to J. Phys.: Conf. Ser.