Magnetic study of FeSi$_{1-x}$Ge$_x$ across the nonmagnetic-ferromagnetic transition

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Abstract. Magnetic properties of FeSi$_{1-x}$Ge$_x$ have been investigated using polycrystalline samples. A transition from nonmagnetic state with an energy gap for $x = 0$ to a weak ferromagnetic state for $x = 0.5$ has been confirmed, which was previously reported by Yeo et al. using single crystalline samples. Pauli-paramagnetic contribution to the low temperature susceptibility, $\chi_{\text{spin}}(0)$, has been estimated for the samples with $x \leq 0.3$ by fitting the observed data. It significantly increases with the increase of $x$, reaching the value $\chi_{\text{spin}}(0) = 0.75 \times 10^{-3}$ emu/mol, which is comparable to those of the nearly ferromagnetic metals YCo$_2$ and Pd. Using the Arrot plot, the parameter $F_1$ of the spin-fluctuation theory has been estimated. $F_1$ shows a drastic decrease from the order of $10^6$ K for $x = 0$ to $9.5 \times 10^3$ K for $x = 0.5$, which is very similar to the $x$ dependence of $F_1$ in Y(Co$_{1-x}$Al$_x$)$_2$ across the nonmagnetic-ferromagnetic phase boundary. These results suggest that the evolution of the magnetism in FeSi$_{1-x}$Ge$_x$ can be well understood in terms of the transition from nearly ferromagnetic to weak itinerant ferromagnetic metal.

1. Introduction
FeSi crystallizes in the cubic B20-type structure. Physical properties of FeSi have extensively been studied over several decades because of its unusual magnetic behavior. The ground state is nonmagnetic semiconductor with an energy gap of about 60 meV, as directly observed by the photoelectron spectroscopy measurement [1]. Upon heating, the magnetic susceptibility increases rapidly and exhibits a maximum at 500 K [2]. Above the maximum, the magnetic susceptibility decreases with temperature, showing a Curie-Weiss like behavior. Jaccarino et al. first explained this unusual magnetic behavior in terms of an activation behavior, but they had to assume unrealistically sharp band structures [2]. Later, Moriya and Takahashi suggested based on their self-consistent renormalization (SCR) theory, that the anomalous magnetic behavior in FeSi is explained by temperature-induced magnetic moments, which arises through thermally excited spin-fluctuations [3, 4, 5]. The existence of temperature-induced moments was indeed confirmed by neutron scattering experiments [6, 7].

In the SCR theory, a negative mode-mode coupling constant was assumed to explain the magnetism of FeSi. This should lead a negative constant $F_1$, which corresponds to the fourth-order expanded coefficient of the free energy in magnetization. However, recent magnetization measurement using a single crystalline FeSi sample revealed that the coefficient $F_1$ is actually positive and show an exponential increase at low temperatures [8]. Very similar temperature dependence of $F_1$ has also been observed in the semiconductor FeSb$_2$ [9]. Takahashi has given a clue to solve this discrepancy by taking the effect of quantum spin-fluctuation into
consideration [10, 11]. The theory of Takahashi explained both the temperature dependence of the magnetic susceptibility and the positively increasing $F_1$ of FeSi. Hence, the magnetism of FeSi has well been explained within the framework of itinerant electron magnetism with enhanced spin fluctuations.

On the other hand, another model based on the localized moment picture was proposed [12, 13]. They claimed that the temperature variation of the magnetic and electrical properties of FeSi can be explained by the Kondo insulator formation. Schlesinger et al. pointed through the optical conductivity measurement that the energy gap of FeSi disappears much faster at elevated temperatures than expected from its gap size, and suggested that this damping can be explained within the framework of a Kondo insulator picture [14]. However, resonant X-ray inelastic scattering experiments did not detect any signature of valence admixture in the Fe 3d state over different temperatures [15, 16]. This result is in favor of itinerant electron model.

Magnetic properties of the solid solution system FeSi$_{1-x}$Ge$_x$ is also intriguing. Bauer et al. showed that the energy gap of FeSi becomes narrower by substituting Ge for Si, and a metallic state evolves at $x = 0.5$ [17]. This is consistent with the increase of the gap size of FeSi under pressure [17, 18], since alloying with Ge acts as a negative pressure on FeSi. Later, a local density approximation calculation suggested that a first-order phase transition from a nonmagnetic insulator to a ferromagnetic metal occurs in FeSi$_{1-x}$Ge$_x$ at around $x = 0.4$ [19]. This phase transition was indeed observed experimentally at $x_c \approx 0.3$ by Yeo et al. [20] Furthermore, they revealed that the electronic specific heat coefficient $\gamma$ shows a sharp peak at $x_c$, suggesting the evolution of strongly correlated electronic state around this chemical composition. This phase transition is quite unique since usual metal-insulator transitions occur from a nonmagnetic metal to a magnetically-ordered insulator. In addition, the compounds near $x_c$ is likely to be a semiconductor with strong electronic correlation.

This motivated us to start the research of the electronic properties of FeSi$_{1-x}$Ge$_x$, since such correlated-electron state can enhance various electronic properties such as thermoelectric power and heat capacity. In this paper, we first focus on the sample preparation, characterization, and the magnetic properties. We will show by our magnetization results that the phase transition in FeSi$_{1-x}$Ge$_x$ is well understood in terms of itinerant electron system. Thermal properties of the same samples will be presented as another paper.

### 2. Experimental

Polycrystalline samples of FeSi$_{1-x}$Ge$_x$ were synthesized by means of arc melting and subsequent annealing. Pure elements of Fe (4N), Si (11N), and Ge (6N) were weighted and placed on a water-cooled Cu hearth, and arc-melted under an argon atmosphere. Ge was found to be volatile during the melting process. Therefore, extra amounts of Ge were loaded to compensate the loss. The weight loss after arc-melting was less than 1% of the total mass. Hereafter we refer these arc-melted samples to as-cast samples. The as-cast ingots were sealed in quartz tubes under vacuum and annealed for several days. Samples of FeSi$_{1-x}$Ge$_x$ with $x = 0$ to 0.22 were annealed at 1227 K. On the other hand, the sample with $x = 0.3$ was found to be partially melted when rapidly heated up to 1273 K. Therefore, the $x = 0.3$ sample was first annealed at 1173 K for one day, then heated up to 1273 K and annealed for 3 days. The sample for $x = 0.5$ was annealed at 1173 K, above which the sample was found to be partially melted.

Powder X-ray diffraction (XRD) was collected using the Cu Kα radiation. The XRD patterns were analyzed by the Rietveld method using the FullProf software [21]. Magnetic susceptibility and magnetization were measured using a superconducting quantum interference device (SQUID) magnetometer, MPMS-5S, provided from Quantum Design.
Figure 1. Powder X-ray diffraction patterns of FeSi$_{1-x}$Ge$_x$ samples. Left panel shows the patterns of the as-cast samples. Right panel shows those of the annealed samples.

Figure 2. Lattice constants of the FeSi$_{1-x}$Ge$_x$ annealed samples as a function of $x$. Broken line shows the Vegard’s relation estimated from $a = 4.4853$ Å of FeSi [8] and $a = 4.689$ Å of FeGe [22].

3. Results and discussion

In Figure 1, powder x-ray diffraction patterns of the as-cast and the annealed FeSi$_{1-x}$Ge$_x$ samples are shown. It is found that the as-cast samples show split peaks, indicating that the samples contain multiple phases with different lattice parameters. After annealing, the XRD shows single-phased patterns. The patterns were well explained by the cubic FeSi-type structure. In Figure 2, lattice constants of the annealed FeSi$_{1-x}$Ge$_x$, determined by the Rietveld method are presented as a function of the Ge concentration $x$.

The lattice constants increases linearly with the Ge composition $x$, in accordance with the Vegard’s relation. The dashed line in the figure represents the linear extrapolation from the
Figure 3. Magnetization $M$ of FeSi$_{1-x}$Ge$_x$ annealed samples measured at $T = 300$ K as a function of magnetic field $H$.

Figure 4. Temperature dependence of the magnetic susceptibility, $M/H$, of FeSi$_{1-x}$Ge$_x$. $M/H$ of the $x = 0$ to 0.3 samples, shown in panel (A), are measured at $H = 1$ T, while that of the $x = 0.5$ sample, shown in panel (B), is measured at $H = 0.1$ T. Panel (C) shows inverse of the magnetic susceptibility, $H/M$, of the $x = 0.5$ sample as a function of temperature. Panel (D) shows magnetization of FeSi$_{0.5}$Ge$_{0.5}$ as a function of $H$.

lattice constants of FeSi, $a = 4.4853$ Å [8], and that of FeGe, $a = 4.689$ Å [22]. The lattice constants of FeSi$_{1-x}$Ge$_x$ obtained in the present study well agree with the linear extrapolation. In Figure 3, magnetization $M$ of FeSi$_{1-x}$Ge$_x$ annealed samples measured at $T = 300$ K are shown as a function of magnetic field $H$. $M$ shows almost linear field dependence for all the $x$. This indicates these samples are free from ferromagnetic impurities such as Fe.

In Figure 4, temperature dependence of the magnetic susceptibility $M/H$ of FeSi$_{1-x}$Ge$_x$ is shown.
temperature is roughly estimated to be \( T \approx 5 \) K, and exhibits a rapid increase below 50 K, indicating a ferromagnetic transition. The Curie constant \( C \) shown in Figure 4 (C). In Figure 4 (D), field dependence of the magnetization \( M = H \) for the sample, on the other hand, shows a Curie-Weiss behavior from 300 K down to about 100 K, and exhibits a rapid increase below 50 K, indicating a ferromagnetic transition. The Curie temperature is roughly estimated to be \( T_C = 50 \) K from the inverse of the susceptibility \( H/M \), shown in Figure 4 (C). In Figure 4 (D), field dependence of the magnetization \( M = H \) is plotted. At \( T = 5 \) K, ferromagnetic behavior is observed. The spontaneous magnetic moment is estimated to be as small as 0.2 \( \mu_B \). This value is close to that obtained by Yeo et al. for \( x = 0.53 \) sample, though they reported a higher Curie temperature, \( T_C = 200 \) K [20].

Thus, the phase transition from a nonmagnetic semiconductor \( (x = 0) \) to a ferromagnetic metal \( (x > 0.3) \) reported by Yeo et al. [20] has been basically reproduced in our experiment. However, Yeo et al. reported that the phase boundary is at around \( x = 0.25 \) and the sample with \( x = 0.27 \) is a ferromagnet, while our results suggest that the phase boundary is at \( x > 0.3 \). This may be because our samples are polycrystalline samples, which possibly contain some distribution of Si/Ge concentration over the samples, and also because some amount of Ge may have been lost due to the evaporation during the arc melting process. In addition, Yeo et al. used the energy dispersive spectroscopy (EDS) method for the determination of the chemical compositions, and they pointed in their paper that the Si/Ge ratios can have errors of about 5% [20].

For the sample with \( x = 0.5 \), \( M/H \) data above 250 K have been fit with a Curie-Weiss law, \( M/H = C/(T - \theta) + \text{const.} \), where \( C \) and \( \theta \) are the Curie constant and Weiss temperature, respectively. We obtained the value \( C = 1.86 \text{ emu K/Fe-mol} \), which corresponds to the effective magnetic moment of \( p_{\text{eff}} = 3.87 \mu_B \). This value is close to that reported by Yeo et al. [20], about 3 \( \mu_B \), obtained using a single crystalline sample. When the Landé \( g \)-factor of \( g = 2 \) is assumed, this value of the moment close to the theoretical value 3.87\( \mu_B \) for the spin \( S = 3/2 \). For the case of itinerant electron picture, this does not necessarily indicate that each Fe ion has a local spin of \( S = 3/2 \). However, the result undoubtedly demonstrates that all the Fe sites carry magnetic moments, and FeSi\(_{0.5}\)Ge\(_{0.5}\) does not have an energy gap.

Next, low-temperature upturn in the magnetic susceptibilities of FeSi\(_{1-x}\)Ge\(_x\) samples with \( x = 0 \) to 0.3 have been analyzed with a Curie-Weiss function. In Figure 5, the fitting results are plotted. The Curie constants obtained by the low-temperature fittings are of the range of 0.01 emu K/mol. This is as small as about 0.5% of the Curie constant for FeSi\(_{0.5}\)Ge\(_{0.5}\) at high temperature. We therefore can conclude that the upturns in the susceptibility at low temperature are due to small amount of impurities and defects. Thus, the intrinsic susceptibility can be estimated by subtracting the Curie-Weiss contribution at low temperature from the observed data. The corrected data are plotted in Figure 5 by blue solid lines. The intrinsic susceptibility of FeSi, shown in Figure 5(A), decreases with temperature, and becomes diamagnetic below 100 K. This corresponds to the nonmagnetic ground state of FeSi without any density of states (DOS) at the Fermi level, consistent with the previous results [2].

For \( x > 0 \), the intrinsic susceptibility shows similar behavior to FeSi: decreasing monotonically and reaching to a constant value below about 50 K. Notably, the constant value at low temperature shows positive values for \( x > 0 \) as is shown in Figure (B) to (D). This indicates that finite Pauli-paramagnetic susceptibility remains at \( T = 0 \) K, suggesting that the DOS at the Fermi level has a certain value for \( x \geq 0.1 \). Furthermore, the Pauli-paramagnetic susceptibility tends to be enhanced with the increase of \( x \). This is qualitatively consistent with the specific heat results by Yeo et al [20]. They showed that the electronic specific heat coefficient \( \gamma \) is close
enhanced Pauli paramagnetic systems such as YCo. This value of the Pauli-paramagnetic susceptibility is comparable to those of the exchange-reaches relatively a large value of $\chi_{\text{spin}}(0)$. The values of $\chi_{\text{spin}}(0)$ show a rapid increase around $x = 0.2$, and the value for $x = 0.3$ reaches relatively a large value of $\chi_{\text{spin}}(0) \approx 0.75 \times 10^{-3}$ emu/mol. It is notable that this value of the Pauli-paramagnetic susceptibility is comparable to those of the exchange-enhanced Pauli paramagnetic systems such as YCo$_2$ ($\chi(0) = 1 \times 10^{-3}$ emu/Co-mol) [24] and Pd
Figure 6. Spin contribution to the Pauli-paramagnetic susceptibility at $T = 0$ K, $\chi_{\text{spin}}(0)$, as a function of the Ge concentration $x$ for FeSi$_{1-x}$Ge$_x$.

($\chi(0) = 1.2 \times 10^{-3}$ emu/mol) [25]. These systems are well known as nearly-ferromagnetic metals. Indeed, a slight substitution of Al for Co in YCo$_2$ leads to an itinerant ferromagnetic phase for $x \geq 0.13$ [26]. Therefore, the transition in FeSi$_{1-x}$Ge$_x$ from $x = 0.3$ to 0.5 appears to be very similar to that in Y(Co$_{1-x}$Al$_x$)$_2$; from a nearly ferromagnetic metal with exchange-enhanced Pauli paramagnetic state to a weak itinerant ferromagnetic metal with a low $T_C$ and a small spontaneous ferromagnetic moment.

In order to discuss the evolution of the magnetic correlation with the increase of Ge composition, we show the Arrot plot of FeSi$_{1-x}$Ge$_x$ at $T = 300$ K. This is a plot of $M^2$ as a function of $H/M$, and is written as:

$$M^2 = \zeta \frac{H}{M} - \frac{\zeta}{\chi},$$

where $\zeta$ is the slope of the $M^2$ vs. $H/M$, and $\chi$ is the magnetic susceptibility. This relation is derived from the Landau expansion of the free energy $F$ in magnetization $M$,

$$F(M) = \frac{1}{2\chi}M^2 + \frac{1}{4\zeta}M^4 - HM,$$

where the last term represents the Zeeman energy. By applying the thermal equilibrium relation $\frac{\partial F}{\partial M} = 0$, equation (1) is obtained.

The Arrot plot for FeSi$_{1-x}$Ge$_x$ measured at $T = 300$ K is presented in Figure 7 (A). The fitting using equation (1) has been done for the highest field regions since the linear range is very narrow because of the contribution from paramagnetic impurities. The value of the slope for $x = 0$ is $\zeta = 129.0$ emu$^3$/mol$^3$Oe. In the previous paper by Koyama et al. [8], they used the parameter $\gamma$ as the forth order coefficient in the Landau expansion of the free energy. Using their definition, our value of $\zeta$ corresponds to $\gamma = 4.6 \times 10^3$ (Oe g$^3$/emu$^3$). This value is in good agreement with that they obtained at $T = 300$ K using an FeSi single crystalline sample. In Figure 7 (A), it is clearly seen that the slope of the Arrot plot becomes steeper with the increase of $x$. The value of $\zeta$ is plotted as a function of $x$ in Figure 7 (B). $\zeta$ shows a rapid increase at $x = 0.3$, where the system is considered to be a nearly ferromagnetic state. For $x = 0.5$ where weak ferromagnetic behavior is observed, $\zeta$ is further increased but tends to be saturated. This behavior is very similar to that observed for Y(Co$_{1-x}$Al$_x$)$_2$, where $\zeta$ increases more than 10 times larger when the system approaches from nearly ferromagnetic to weak ferromagnetic state [26].
systematic evolution from a nonmagnetic semiconductor to a ferromagnetic metal with increasing
We have investigated the magnetization of FeSi$_1-x$Ge$_x$ single-crystalline samples up to higher magnetic fields.

Next, we discuss about the $x$ dependence of $F_1$, which is an important parameter in the SCR theory. We used the following relation to calculate $F_1$: $F_1 = 1.872 \times 10^6 \zeta^{-1}$ [27]. The values of $F_1$ thus estimated are plotted in Figure 7 (B). $F_1$ decreases drastically from $10^6$ K range for $x = 0$ to $8.4 \times 10^3$ K for $x = 0.5$. The parameter $F_1$ is approximated to

$$F_1 = \frac{4k_BT_{\alpha}^2}{15T_0}$$ (3)

in the SCR theory, where $T_{\alpha}$ and $T_0$ are parameters related to the spin excitation spectrum in the momentum and in the frequency space, respectively [27, 28]. When a system approaches a magnetically ordered phase from a nonmagnetic side, the spin fluctuation spectrum develops and the spectrum shape becomes quite sharp in the momentum space. This corresponds to a rapid decrease in $T_{\alpha}$. Therefore, the rapid decrease of $F_1$ values shown in Figure 7 (B) is consistent with the evolution of ferromagnetic correlation. In the case of Y(Fe$_{1-x}$Al$_x)_2$, the $F_1$ values show very similar behavior, decreasing from $F_1 = 4.8 \times 10^4$ K for $x = 0.11$, which is close to the ferromagnetically ordered phase, to $F_1 = 9.5 \times 10^3$ K for $x = 0.16$, where an itinerant ferromagnetic state emerges [28]. This trend of $F_1$ is in a very good agreement with our result shown in Figure 7 (B).

Here, we should mention that such discussion of the composition dependence of $\zeta$ and $F_1$ should be done using low temperature data. In our case, however, the Arrot plot using the data at $T = 5$ K did not show any linear range because of the dominant contribution from paramagnetic impurities. Nevertheless, the drastic decrease of $F_1$ in Figure 7 (B) strongly supports that the variation in magnetism of FeSi$_{1-x}$Ge$_x$ is understood as a transition from the nearly ferromagnetic ($x \leq 0.3$) to itinerant weak ferromagnetic metal ($x > 0.3$). To make a more accurate discussion, it would be helpful to measure the magnetization using high quality single-crystalline samples up to higher magnetic fields.

4. Conclusion
We have investigated the magnetization of FeSi$_{1-x}$Ge$_x$ using polycrystalline samples. A systematic evolution from a nonmagnetic semiconductor to a ferromagnetic metal with increasing
x has been confirmed, basically consistent with the previous report using single crystalline samples [20]. Our results show that the low-temperature susceptibility contains finite values of Pauli-paramagnetic susceptibility, and this contribution is increasingly enhanced with the increase of x, indicating the enhancement in the DOS at the Fermi level. For the sample with x = 0.3, magnetic susceptibility shows a broad maximum at around 200 K and the low temperature susceptibility is described by a large Pauli-paramagnetic susceptibility \( \chi(0) = 0.75 \times 10^{-3} \text{emu/mol} \). This behavior is very similar to that of the nearly-ferromagnetic metals such as YCo and Pd. The FeSi\(_{0.5}\)Ge\(_{0.5}\) sample exhibits a ferromagnetic transition at \( T_C \sim 50 \text{ K} \) with a small spontaneous magnetic moment of 0.2 \( \mu_B/\text{Fe} \). This indicates that FeSi\(_{0.5}\)Ge\(_{0.5}\) is classified as a weak itinerant ferromagnetic metal.

The evolution of ferromagnetic state with x has been analyzed using the Arrot plot (\( M^2 \) vs. \( H/M \) plot). The slope of the Arrot plot, \( \zeta \), shows a rapid increase with increasing x across the nonmagnetic-ferromagnetic phase boundary. Using the plot, the values of \( F_1 \) have been derived, which is an important parameter in the SCR theory to describe the spin fluctuation spectrum. \( F_1 \) of FeSi\(_{1-x}\)Ge\(_x\) is found to show a drastic decrease from \( 10^6 \) K for \( x = 0 \) to \( 8.4 \times 10^5 \) K for \( x = 0.5 \). This crossover is very similar to that observed in the typical itinerant electron system Y\((\text{Co}_1-x\text{Al}_x)\) with in creasing x across the transition from the nearly ferromagnetic state to the weak ferromagnetic region. These results suggests that FeSi\(_{1-x}\)Ge\(_x\) for \( x > 0 \) can be described as an itinerant electron system with enhanced ferromagnetic spin-fluctuations.

**Acknowledgment**

This work has been partly supported by Grand-in-Aid from the Japan Society for the Promotion of Science (JSPS), number 15K05190. The author thanks Namiko Onodera for the help of sample preparation and XRD measurements. The magnetization measurements using a SQUID magnetometer were carried out with the support of Tsukuba Magnet Laboratory, NIMS.

**References**

[1] Ishizuka K, Kiss T, Shimojima T, Yokoya T, Togashi T, Watanabe S, Zhang C Q, Chen CT, Onose Y, Tokura Y and Shin S 2005 Phys. Rev. B 72 232302
[2] Jaccarino V, Wertheim G K, Wernick J H, Walker L R and Arajs S 1967 Phys. Rev. 160 476
[3] Moriya T 1985 Spin Fluctuations in Itinerant Electron Magnetism (Berlin: Springer)
[4] Moriya T and Takahashi Y 1978 J. Phys. Soc. Japan 45 397
[5] Takahashi Y and Moriya T 1979 J. Phys. Soc. Japan 46 1451
[6] Shirane G, Fischer J E, Endoh Y and Tajima K 1987 Phys. Rev. Lett. 59 351
[7] Tajima K, Endoh Y, Fischer J E and Shirane G 1988 Phys. Rev. B 38 6954
[8] Koyama K, Goto T, Kanomata T, Note R and Takahashi Y 2000 J. Phys. Soc. Japan 69 219
[9] Koyama T, Nakamura H, Kohara T and Takahashi Y 2010 J. Phys. Soc. Japan 79 093704
[10] Takahashi Y 1997 J. Phys.: Condens. Matter 9 2593
[11] Takahashi Y 1998 J. Phys.: Condens. Matter 10 L671
[12] Aeppli G and Fisk Z 1995 Comments Condens. Matter Phys. 16 155
[13] Mandrus D, Sarrao J L, Migliori A, Thompson J D and Fisk Z 1995 Phys. Rev. B 51 4763
[14] Schlesinger Z, Fisk Z, Zhang H T, Maple M B, DiTusa J F and Aeppli G 1993 Phys. Rev. Lett. 71 1748
[15] Tsujii N, Yamaoka H, Ohashi H, Jarrige I, Nomoto D, Takahiro K, Ozaki K and Kawatsura K 2008 Physica B 403 922
[16] Yamaoka H, Tsuji N, Ohashi H, Nomoto D, Jarrige I, Takahiro K, Ozaki K, Kawatsura K and Takahashi Y 2008 Phys. Rev. B 77 115201
[17] Bauer E, Galatanu A, Hauser R, Reichl Ch, Wiesinger G, Zaussinger G, Galli M and Marabelli F 1998 J. Mag. Mag. Mater. 177–181 1401
[18] Reichl Ch, Wiesinger G, Zaussinger G, Bauer E, Galli M and Marabelli F 1999 Physica B 250–261 866
[19] Anisimov V I, Hlubina R, Korotin M A, Mazurenko V V, Rice T M, Shorikov A O and Sigrist M 2002 Phys. Rev. Lett. 89 257203
[20] Yeo S, Nakatsuji S, Bianchi A D, Schlottmann P, Fisk Z, Balicas L, Stampe P A and Kennedy R J 2003 Phys. Rev. Lett. 91 046401
[21] Rodrigues-Carvajal J 1993 Physica B 192 55
[22] Lebech B, Bernhard J and Freltoft T 1989 J. Phys.: Condens. Matter 1 6105
[23] Mendelsohn L B, Biggs F and Mann J B 1970 Phys. Rev. A 2 1130
[24] Yoshimura K, Shimizu T, Takigawa M, Yasuoka H and Nakamura Y 1984 J. Phys. Soc. Japan 53 503
[25] Takigawa M and Yasuoka H 1982 J. Phys. Soc. Japan 51 787
[26] Yoshimura K and Nakamura Y 1985 Solid State Comm. 56 767
[27] Takahashi Y and Yoshimura K 2012 Itinerant electron magnetism and spin fluctuation (in Japanese, Uchida Rokakuho Publishing Co., Tokyo)
[28] Yoshimura K, Takigawa M, Takahashi Y, Yasuoka H and Nakamura Y 1987 J. Phys. Soc. Japan 56 1138