Critical phenomena of canonical spin glass systems with large Dzyaloshinsky-Moriya anisotropy

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Abstract. We have studied critical phenomena of spin glass transition for larger Dzyaloshinsky-Moriya anisotropy Heisenberg spin glass system, PtMn. The analysis of non-linear magnetizations in the framework of the existence of a phase transition at $T_g$ yields the critical exponents $\delta = 2.5 \pm 0.3$, $\gamma = 1.5 \pm 0.3$ and $\beta = 1 \pm 0.3$. These results suggest that the universality class of spin glass transition on PtMn is the same as those of CuMn, AgMn and AuFe systems. Experimentally, there is an indication of a unique universality class for Heisenberg spin glass materials.

1. Introduction
In all real Heisenberg spin glass (SG) materials in addition to the pure spin–spin exchange interactions there are anisotropic interaction terms, principally of the Dzyaloshinsky–Moriya (D-M) type. When weak anisotropy terms are introduced into a numerical model, the spin sector becomes weakly re-coupled to the chiral sector and the onset of chiral ordering can be expected to be revealed through the spin behavior [1, 2, 3]. Careful and detailed experimental studies [4, 5, 6, 7, 8] established the existence of the critical divergence of the non-linear susceptibility thus demonstrating that the SG transition in laboratory samples is indeed a thermodynamic transition. The Heisenberg SG material which has been the most intensively studied is AgMn which, together with CuMn, is one of the canonical weak D-M anisotropy Heisenberg SGs [4, 5, 6]. These independent sets of careful measurements using either DC or AC techniques are entirely consistent with each other, whereas only a few experiments for the strong D-M anisotropy Heisenberg SG systems, AuMn and AuFe, have been done. It should be noted that these Au based SG systems show the same universality class of the SG transitions as that for the weak D-M anisotropy systems [7, 8]. It is very instructive to compare these experimental results with the most recent estimates from simulations for the chiral critical exponents at the pure chiral ordering transition in the 3d Heisenberg SG model. Thus the experimental exponent values for Heisenberg SG systems are very similar to the numerical values for the critical exponents at a pure chiral ordering transition.

It is well known that the D-M anisotropy of the canonical SG alloy depends on the atomic radius of the host metal [9]. The order of the magnitude of the D-M anisotropy is as follows; CuMn < AgMn < AuFe, AuMn < PtMn. Therefore the effect of the large D-M anisotropy, which might change the universality class, to the critical phenomena is the interesting problem. The purpose of this article is to obtain the critical exponents of the SG transition for PtMn, which has the largest D-M anisotropy in
the canonical SG systems, and to compare the experimental results with those of the theoretical works based on the chirality scenario of SG transition [1, 2, 3].

2. Experiments and analysis
The samples used for the measurements are PtMn (8 at. % Mn) alloys. We prepared ingots of the sample alloys by melting constituent elements in an argon arc-furnace. A cylindrical sample of 6 mm in diameter and 10 mm length was cut out by a spark cutting machine from the ingot. The sample was sealed in a vacuous quartz ampoule and annealed at 1000 °C for 36 hours and quenched to iced water. The magnetization \( M \) as a function of the magnetic field \( H \) at the various temperatures around SG transition temperature \( T_g \) was measured with a commercial SQUID magnetometer MPMS-7XL. In order to accurately measure the small non-linear part of the magnetizations, we used a vibrating RSO mode in all the measurements and a magnet reset procedure for eliminating the remnant magnetic field of the superconducting magnet. The SG transition temperature, \( T_g = 13.85 \) K, was determined from the cusp positions in the zero field cooled magnetization and in the AC magnetization measurements. Above high temperature region (\( T > 200 \) K) we obtained the effective moment, 6.0 \( \mu_B \), and the Weiss temperature, -42.5 K.

The magnetization \( M \) in the paramagnetic regime can be expanded as the odd powers of the applied field \( H \) as

\[
M = \chi_0 H + \chi_2 H^3 + \chi_4 H^5 + \cdots
\]  

(1)

where \( \chi_0 \) is a linear susceptibility and \( \chi_2, \chi_4 \) are non-linear susceptibilities respectively. The leading term of the non-linear susceptibilities \( \chi_2 \) is obtained from the initial slope of \( M/H \chi_0 \) versus \( H^2 \) plot.

\[
\frac{M}{H} - \chi_0 = \chi_2 (H^2) + \chi_4 (H^2)^2 + \cdots \approx \chi_2 (H^2) = Q
\]  

(2)

It should be noted that the non-linear magnetization corresponds to the conjugate field \( H^2 \) induced SG order parameter in the small field limit. The critical exponents \( \gamma \) and \( \delta \) of SG transition and the reduced temperature \( \varepsilon \) are defined as \( \chi_2 \propto \varepsilon^{-\gamma} \) (\( \varepsilon \equiv (T - T_g)/T_g \)) and \( Q \propto (H^2)^{1/\delta} \) at \( T_g \).

![Figure 1](image.png)

**Figure 1.** Reduced temperature \( \varepsilon \) dependence of the absolute value of the non-linear susceptibility \( \chi_2 \) in a log-log scale. The critical exponent \( \gamma \) is determined as the slope of the plot shown in the figure.
Figure 1 shows the reduced temperature $\varepsilon$ dependence of $\chi_2$ derived from the procedure mentioned above in a log-log scale. We determined the value of $\gamma = 1.5$ from the slope of the plot. We note that the value $\gamma = 1.5$ is close to those reported for the weak anisotropy Heisenberg SG systems [2-4].

Figure 2 shows the squared field dependence of the non-linear magnetization divided by $H$ in a log-log scale. Two asymptotic behaviors were observed and we find $\delta = 2.5$ in low fields and $\delta = 4.9$ in high fields, which was previously reported on CuMn + Au [4] system and was interpreted as a crossover from Ising to Heisenberg critical behavior of SG transition. However, it should be noted that 'fake' critical behavior is sometimes observed in the region far from the 'true' critical region. We can obtain the critical exponent $\beta = 1.0$ from the scaling relation, $\beta \delta = \gamma + \beta$, of the second order phase transition.

3. Discussion
The values of the critical exponents of SG transition was scattered in the early stage of the research [10]. The thoughtful analysis of the non-linear susceptibility in the restricted field and temperature range provides the same values of the critical exponents for the canonical SG transition at least [5, 7, 14]. Therefore, it has been thought that the SG transitions of the canonical SG systems belong to the same universality class and that they are the thermodynamic phase transition. However, a possibility that the universality class of AuFe system, which has strong D-M anisotropy, is different from the other canonical systems has recently been suggested [14].

The values of critical exponents of various canonical SG systems are summarized with this work in Table I. The exponents were obtained following the same experimental dc protocol as in the case of the AgMn, that is, measurements were all made in a restricted range of field, $\chi_2 < 0.1 \chi_0$, and within a restricted range of temperatures, $\varepsilon < 0.1$. These conditions ensure that the estimates for the different materials are as reliable as the results for AgMn, and material-to-material comparisons are fully valid. It would be of great interest to re-measure Heisenberg SG exponents for a variety of different systems using AC and DC experimental techniques together with the improved form of data analysis, noting the 'true' critical region. In the region far from the 'true' critical region, the temperature and field.
dependences of non-linear magnetizations behave like the mean field one and provide the different critical exponents [5, 7, 14].

The values of critical exponents for all canonical SG alloys are almost the same, though the values of PtMn seems slightly small because of the strong antiferromagnetic interaction suggested from the large Weiss temperature in this system. The antiferromagnetic interaction suppresses the divergence of the non-linear susceptibility at $T_g$ [15]. Therefore, we conclude that the values of the critical exponents are different from those of AuFe in [14] and that the universality class of PtMn belongs to the same universality class of the other canonical systems. These values well coincide with those of the chirality theory [13]. However, the direct observation of the critical phenomena in chiral susceptibilities, anomalous Hall effect [8, 16], is necessary for the final conclusion.

Table 1. Critical exponents of SG transition for various systems.

| System            | $\beta$ | $\gamma$ | $\delta$ | Ref. No. |
|-------------------|---------|----------|----------|----------|
| CuMn (+Au)        | 1.0     | 2.2      | 3.2      | 6        |
| AgMn              | 0.9     | 2.1      | 3.3      | 4        |
| AgMn              | 1.0     | 2.2      | 3.1      | 5        |
| AuFe              | 1.0     | 2.0      | 3.0      | 7        |
| AuMn              | 1.0     | 2.2      | 3.1      | 8        |
| PtMn              | 1.0     | 1.5      | 2.5      | This Work|
| (FeMn)TiO$_3$     |         | 4.0      | 8.4      | 11       |
| Gaussian Ising    |         | 5.8      | 8.5      | 12       |
| Chirality theory  |         | 2.0      | 2.75     | 13       |

In summary, we have studied critical phenomena of the SG transition for larger D-M anisotropy Heisenberg spin glass system, PtMn. The analysis of non-linear magnetizations in the framework of the existence of a phase transition at $T_g$ yields the critical exponents $\delta = 2.5 \pm 0.3$, $\gamma = 1.5 \pm 0.3$ and $\beta = 1 \pm 0.3$. These results suggest that the universality class of SG transition on PtMn is the same as those of CuMn, AgMn and AuFe systems. Experimentally, there is an indication of a unique universality class for Heisenberg SG materials.

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References
[1] Kawamura H 1992 Phys. Rev. Lett. 68 3785
[2] Imagawa D and Kawamura H 2004 Phys. Rev. Lett. 92 077204
[3] Kawamura H 2010 J. Phys. Soc. Jpn. 79 011007
[4] Levy L P and Ogielski T 1986 Phys. Rev. Lett. 57 3288
[5] Bouchiat H 1986 J. Phys. (Paris) 47 71
[6] de Courtenay N, Bouchiat H, Hurdequint H and Fert A 1986 J. Phys. (Paris) 47 1507
[7] Taniguchi T and Miyako Y 1988 J. Phys. Soc. Jpn. 57 3520
[8] Taniguchi T 2007 J. Phys. Condens. Matter 19 145213
[9] Fert A, de Courtenay N and Bouchiat H 1988 J. Phys. (Paris) 49 1173
[10] Binder K and Young A P 1988 Rev Mod. Phys. 58 801
[11] Gunnarsson K, Svedlindh P, Nordblad P, Lundgren L, Aruga H and Ito A 1991 Phys. Rev. B 43 8199
[12] Katzgraber H G, Korner M and Young A P 2006 Phys. Rev. B 73 224432
[13] Viet D X and Kawamura H 2010 Phys. Rev. B 80 224432
[14] Campbell I A and Petit D C M C 2010 J. Phys. Soc. Jpn. 79 011006
[15] Wada K and Takayama H 1980 Prog. Theor. Phys. 64 327
[16] Taniguchi T et al. 2004 Phys. Rev. Lett. 93 246605