PHYSICAL REVIEW B VOLUME 33, NUMBER 7 1 APRIL 1986

Experimental values of the gap exponents for the paramagnetic region

B. Fugiel and J. Zioło
Institute of Physics, Silesian University, Uniwersytecka 4, PL-40-007 Katowice, Poland
(Received 26 July 1985)

Results are presented for measurements of the initial paramagnetic susceptibility (i.e., for zero magnetic field) and also of the first three nonlinear terms of the susceptibility expansion in a series relative to a magnetic field, for the compound $HgCr_2Se_4$ in the temperature range $T_c+1\ \mathrm{K} \lesssim T \lesssim T_c+20$ K (i.e., for $10^{-2} \lesssim \epsilon \lesssim 10^{-1}$). From the temperature functions obtained for the four coefficients of expansion of the paramagnetic susceptibility, three values of the gap exponents were found: $\Delta_4 = 1.68 \pm 0.04$, $\Delta_6 = 1.64 \pm 0.1$, and $\Delta_8 = 1.47 \pm 0.33$.

The gap exponents Δ_{2n} have been determined using the experimental method reported in Ref. 1 of examining the nonlinear (quadratic) paramagnetic effect. In this method measurements are made of changes in susceptibility $\Delta\chi = \chi_B - \chi_0$ induced by the application of an external magnetic field, where χ_B is the susceptibility at $B \neq 0$, and χ_0 is the susceptibility at $B=0$. Making use of the measurement method described in Ref. 1, based on binding $\Delta\chi$ as a function of B at various temperatures, the coefficients of the zero, second, fourth, and sixth terms were determined in the expansion of the paramagnetic susceptibility in a series relative to a magnetic field, i.e.,

$$\chi_B = \chi_0 + \chi_2 B^2 + \chi_4 B^4 + \chi_6 B^6 + \cdots \quad . \tag{1}$$

The main purpose of our work was to determine the experimental values of the gap exponents and, moreover, to compare these values with the theoretical relations $\Delta_4 = \Delta_6 = \Delta_8$ arising from the scaling laws.

It is known that above the Curie temperature the free energy in a nonzero magnetic field may be expressed as follows:[2,3]

$$F(H) = F(0) - \beta^{-1} \sum_{n=1}^{\infty} \frac{(\beta H)^{2n} \Gamma_{2n}}{(2n)!} \quad , \tag{2}$$

where $\beta = 1/kT$,

$$\Gamma_{2n} = \sum_{\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{2n}} G^{\phi \cdots \phi}(\mathbf{x}_1, \mathbf{x}_2, \ldots, \mathbf{x}_{2n}) \quad ,$$

and $G^{\phi \cdots \phi}$ are correlation functions described in Refs. 2 and 3. The temperature behavior of the values Γ_{2n} in the vicinity of T_c is given by the relation

$$\Gamma_{2n} \sim \epsilon^{-2\Delta_{2n}} \Gamma_{2n-2} \quad , \tag{3}$$

where $\epsilon = (T - T_c)/T_c$ and Δ_{2n} is the gap exponent. From Eq. (2) and the definition of susceptibility it may be concluded that if we express the paramagnetic susceptibility in the form of a series relative to the magnetic field induction [Eq. (1)], then the following relations are satisfied:

$$\beta^{-1}\chi_0 \sim \Gamma_2, \quad \beta^{-3}\chi_2 \sim \Gamma_4 \quad ,$$
$$\beta^{-5}\chi_4 \sim \Gamma_6, \quad \beta^{-7}\chi_6 \sim \Gamma_8 \quad . \tag{4}$$

Knowledge of the temperature relations, such as given by Eq. (3), between the coefficients in the expansion [Eq. (1)] in the vicinity of T_c permits the explicit determination of the gap exponents Δ_{2n}.

Measurements of χ_0, χ_2, χ_4, and χ_6 were carried out for the compound $HgCr_2Se_4$ (polycrystalline sample, $T_c \simeq 106.5$ K) in the temperature range $T_c + 1\ \mathrm{K} \lesssim T \lesssim T_c + 20$ K, and for a frequency of the measuring field of 1 MHz. Demagnetization effects were taken into account. Values of coefficients in the nonlinear terms of expansion [Eq. (1)] were obtained by measurement of the susceptibility variation $\Delta\chi = \chi_B - \chi_0$ induced by the magnetic field[1] followed by numerical separation of the particular terms of this expansion. Figure 1 shows the temperature functions $(T/T_c)\chi_0$, $(T/T_c)^3\chi_2$, $(T/T_c)^5\chi_4$, and $(T/T_c)^7\chi_6$ in a log-log scale. Assuming the following exponential temperature depen-

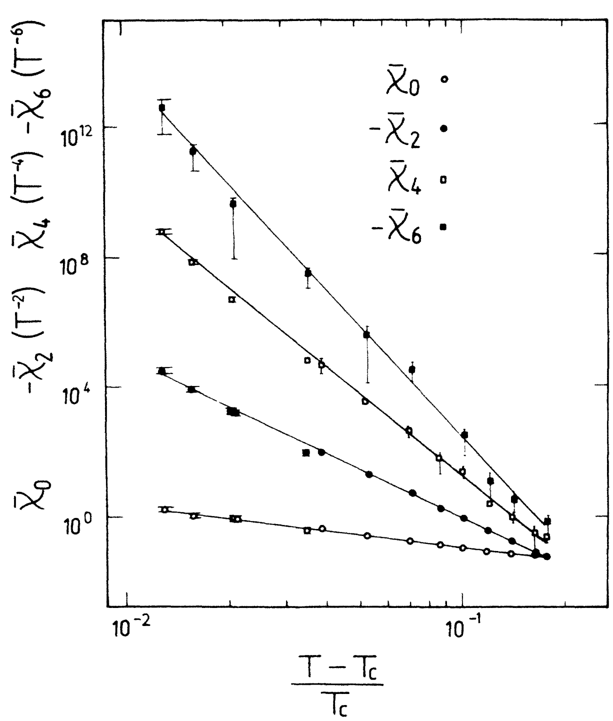

FIG. 1. Functions $\bar{\chi}_0 = (T/T_c)\chi_0$, $-\bar{\chi}_2 = -(T/T_c)^3\chi_2$, $\bar{\chi}_4 = (T/T_c)^5\chi_4$, and $-\bar{\chi}_6 = -(T/T_c)^7\chi_6$ vs $(T-T_c)/T_c$ in a log-log scale. The magnitudes are given in the international system of units (SI). The susceptibility in Eq. (1) is defined by the relation $\chi_B = \partial M/\partial H$, where M is the magnetic moment per unit volume, and H is the magnetic field strength.

TABLE I. Experimental values of exponents γ, γ_2, γ_4, and γ_6 and Δ_4, Δ_6, and Δ_8.

γ	γ_2	γ_4	γ_6	Δ_4	Δ_6	Δ_8
1.30 ± 0.02	4.66 ± 0.05	7.94 ± 0.15	10.87 ± 0.5	1.68 ± 0.04	1.64 ± 0.1	1.47 ± 0.33

dences of the magnitudes (cf. Refs. 3 and 4):

$$\frac{T}{T_c}\chi_0 \sim \epsilon^{-\gamma}, \quad \left(\frac{T}{T_c}\right)^3 \chi_2 \sim \epsilon^{-\gamma_2}, \quad \left(\frac{T}{T_c}\right)^5 \chi_4 \sim \epsilon^{-\gamma_4}, \quad \left(\frac{T}{T_c}\right)^7 \chi_6 \sim \epsilon^{-\gamma_6}, \tag{5}$$

one can determine (cf. Fig. 1) the values of γ, γ_2, γ_4, and γ_6 as shown on Table I. This table also gives the values of the gap exponents; $\Delta_4=\frac{1}{2}(\gamma_2-\gamma)$, $\Delta_6=\frac{1}{2}(\gamma_4-\gamma_2)$, and $\Delta_8=\frac{1}{2}(\gamma_6-\gamma_4)$ satisfying the relations

$$\frac{\Gamma_4}{\Gamma_2} \sim \epsilon^{-2\Delta_4}, \quad \frac{\Gamma_6}{\Gamma_4} \sim \epsilon^{-2\Delta_6}, \quad \frac{\Gamma_8}{\Gamma_6} \sim \epsilon^{-2\Delta_8}. \tag{6}$$

As is known from scaling laws,[4] the gap exponents appearing in these relations take equal values. Agreement between theoretical and experimental values was satisfactorily confirmed for experimentally determined values of Δ_4 and Δ_6 ($\Delta_4 \simeq \Delta_6$). The lower value of exponent Δ_8 may be associated with the considerable error in the determination of exponent γ_6, as may be seen in Fig. 1. The relations [Eq. (5)] were obtained in a relatively wide range of temperatures, stretching from about 1°–20° above the Curie temperature. It has not yet been possible, however, to use this method to separate the coefficients of expansion [Eq. (1)] with satisfactory accuracy for the range of temperatures corresponding to values $\epsilon \lesssim 10^{-2}$. For $\epsilon \lesssim 10^{-2}$, very strong temperature dependences of the measured magnitudes are observed, and for this reason, very exact temperature stabilization is required (better than 10^{-3}–10^{-4} K). Moreover, in this temperature region very weak external magnetic fields should be applied. For T very close to T_c, the values of the external field for which only the first four terms in Eq. (1) are predominant may be comparable with the value of the magnetic field of the Earth.

The results of our measurements confirm the theoretical predictions (equality of the gap exponents proposed in Refs. 4 and 5). The values of the exponents of the functions χ_0 and χ_2 vs ϵ presented in this paper are also in good agreement [without considering the factors T/T_c and $(T/T_c)^3$, respectively] with those reported in Refs. 1 and 6. However, it is particularly noteworthy that relations [Eq. (5)] hold over a surprisingly wide range of temperatures.

[1] B. Fugiel, J. Ziołko, and M. Drzazga, Phys. Rev. B **28**, 6470 (1983).
[2] A. Z. Patashinskii and V. L. Pokrovskii, Zh. Eksp. Teor. Fiz. **50**, 439 (1966) [Sov. Phys. JETP **23**, 292 (1966)].
[3] A. Z. Patashinskii and V. L. Pokrowskii, *Fluctuation Theory of Phase Transitions* (Pergamon, Oxford, 1979).
[4] H. E. Stanley, *Introduction to Phase Transitions and Critical Phenomena* (Pergamon, Oxford, 1971).
[5] G. A. Baker, Jr., H. E. Gilbert, J. Eve, and G. S. Rushbrooke, Phys. Rev. **164**, 800 (1967).
[6] I. D. Luzyanin and V. P. Havronin, *The investigation of the behavior of the nonlinear dynamical susceptibility above T_c in cubic ferromagnets $CdCr_2Se_4$ and $CdCr_2S_4$* (Leningrad Institute of Nuclear Physics, Leningrad, 1984) (in Russian).