Critical behavior near the ferromagnetic Curie phase transition in CeCuGe

B.M. Sondezi-Mhlungu, A.M. Strydom

Physics Department, University of Johannesburg,P.O. Box 524, Auckland Park, 2006,South Africa

E-mail: `bmhlungu@uj.ac.za`

Abstract. Isothermal magnetization of a hexagonal, highly ordered ferromagnetic CeCuGe was measured in order to study the critical scaling behavior in this polycrystalline compound around the ordering temperature. From the analyses of the magnetization data, T_C was confirmed by following modified Arrot plot and Kouvel-Fischer techniques. The critical exponents, β, γ and δ obtained from the fit of the spontaneous magnetization, initial susceptibility and isothermal magnetization revealed that the system behaves as Mean-Field around the ordering temperature.

1. Introduction

A large number of ternary equiatomic CeTX compounds where T is a transition metal and X is a metal atom exhibit various ground states. Among them only a few exhibit ferromagnetic ordering at low temperatures. CePdX (X = P, As, Sb) have been reported to exhibit ferromagnetic ordering at low temperature, (T_C = 17.5 K, for CePdSb; T_C = 4 K for CePdAs and T_C = 5 K for CePdP) [1, 2] having the hexagonal ZrBeSi-type crystal structure for X = P and As; and LiGaGe-type structure for X = Sb. Rare earth containing, particularly Ce-based compounds show very interesting magnetic properties resulting from a strong hybridization of Ce-4f electrons with the conduction electrons. Although a fairly large number of studies have been done on these compounds, there are still more questions to be considered and answered. Ce-based compounds are stable under normal condition and can be driven to unstable state by application of hydrostatic pressure and applied magenetic field. CeCuGe as one of the few Ce-based intermetallic compound to be earlier reported to order ferromagnetically at low temperature, T_C = 10 K [3, 4] will be reported in this work. The metallic behaviour comes, assuming that the magnetic Ce retains a single f-electron. CeCuGe compound is a highly ordered, crstallizing in hexagonal ZrBeSi-type structure, (space group P$6_3/mmc$, number 194). This transition has been observed through specific heat, C_p [4, 5] magnetization, $M(T,H)$ and resistivity, $\rho(T)$ [3, 6] data. The λ-type anomaly associated with ordering temperature has been observed in the $C(T)$ versus T curve [4, 7]. The temperature dependent magnetic susceptibility curve is characterized by a sharp increase in the magnetization around T_C; and the resistivity curve is characterised by a point of inflection at the transition.

This focus of this particular report is on the critical exponents of CeCuGe around ferromagnetic phase transition and the subsequent classification of the system. Inorder to determine critical exponents close to ferromagnetic transition temperature;(10 K), a number of isotherms (M versus

H; $B = \mu_0 H$ and H will be used as the approximation of the applied magnetic field throughout the text) around the transition temperature, 10 K are measured.

2. Experimental Procedure

Polycrystalline CeCuGe sample was prepared in an arc furnace under ultra high-purity argon atmosphere. Stoichiometric amounts of the elements (purities in wt. %) Ce (99.99), Cu (99.995) and Ge (99.9999) were used. The ingots was remelted several times to promote homogeneity. Powder X-ray diffraction measurement performed at room temperature confirmed that the material was homogeneous and single phase. Rietveld refinement profile according to ZrBeSi-type structure (space group P6$_3$/mmc, number 194) was performed and the lattice parameters of the sample were confirmed [6, 3, 5]. A SQUID magnetometer was used to measure magnetization in the temperature range of 2 - 400 K in the presence of applied magnetic field of 0.0005 T. In addition, a number of magnetization isotherms (magnetization as a function of applied magnetic field) were measured for the calculation of critical exponents.

3. Results and Discussion

As a first evaluation and the confirmation of the ferromagnetic Curie transition temperature T_C, the temperature dependence of the magnetization (M vs T) of CeCuGe cooled in applied magnetic field $H = 0.0005$ T is shown in Fig.1. The graph is characterised by a strong increase of M vs T at the ferromagnetic ordering temperature. The maximum slope corresponding to the ordering temperature is indicated by an arrow at about 10 K. In the vicinity of this transition, the existence of diverging correlation length $\xi = \xi \left|1 - \frac{T}{T_C}\right|^{-\nu}$ leads to universal scaling laws for spontaneous magnetization, M_s and susceptibility, χ. These are characterised by the set of critical exponents, β, which corresponds to the spontaneous magnetization below T_C, γ, which corresponds to the inverse initial susceptibility, $\chi_0^{-1}(T)$ above T_C and δ which corresponds to the critical magnetization isotherm [8] at T_C.

These critical exponents in the vicinity of critical temperature are defined by the expressions:

$$M_s(T) = M_0(-t)^{\beta}, \quad t < 0 \tag{1}$$

$$\chi_0^{-1}(T) = (h_0/M_0)(t)^{\gamma}, \quad t > 0 \tag{2}$$

$$M = DH^1/\delta, \quad t = 0 \tag{3}$$

where t is a reduced temperature ($\frac{T-T_C}{T_C}$) and m_0, h_0 and D are critical amplitudes [9, 8, 10, 11].

In order to determine critical exponents in and eventually define the behavior of the system around T_C, modified Arrot plots were plotted whereby $M^{1/\beta}$ vs $(H/M)^{1/\gamma}$ is shown in Fig.2.

Only few isotherms are shown for the sake of clarity. The region of scaling is indicated by a solid line in each isotherm shown in Fig.2. From the intercepts of the fitted $M^{1/\beta}$ vs $(H/M)^{1/\gamma}$ straight lines (from Fig.2), spontaneous magnetization, M_s were determined from the y-axis and initial susceptibility, χ_0^{-1} were extrapolated from the x-axis intersection. The values obtained from extrapolating the data through scaling profile were plotted as a function of temperature. The scaling procedure for the isotherms that showed almost parallel lines resulted in the critical exponents $\beta = 0.7356$ and γ= 0.9303 associated with spontaneous magnetization $M_s(T)$ and the initial inverse susceptibility; $\chi_0^{-1}(T)$, respectively. The corresponding δ value can be obtained from Widon scaling relation [12]; $\delta = 1 + \gamma/\beta$ which gives $\delta = 2.2647$.

During the fitting process the transition temperature, T_C was also a fitting parameter. The transition temperature according to the fit of the $T < T_C$ data yields the temperature value of

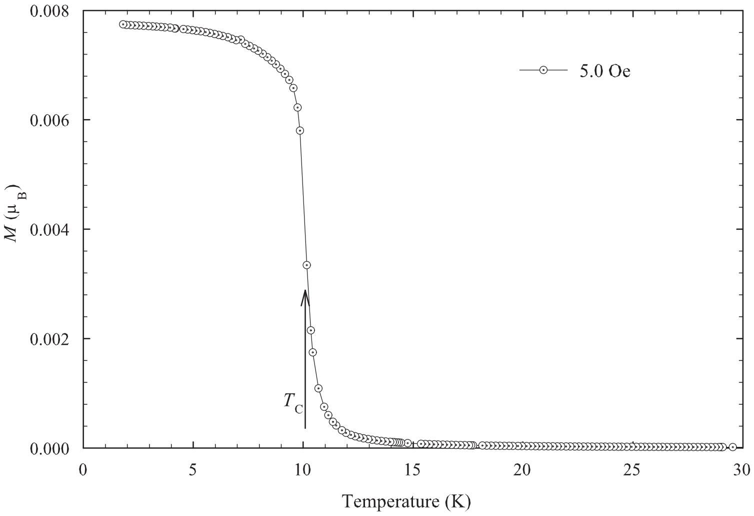

Figure 1. Magnetization versus temperature of CeCuGe measured in 0.005 T.

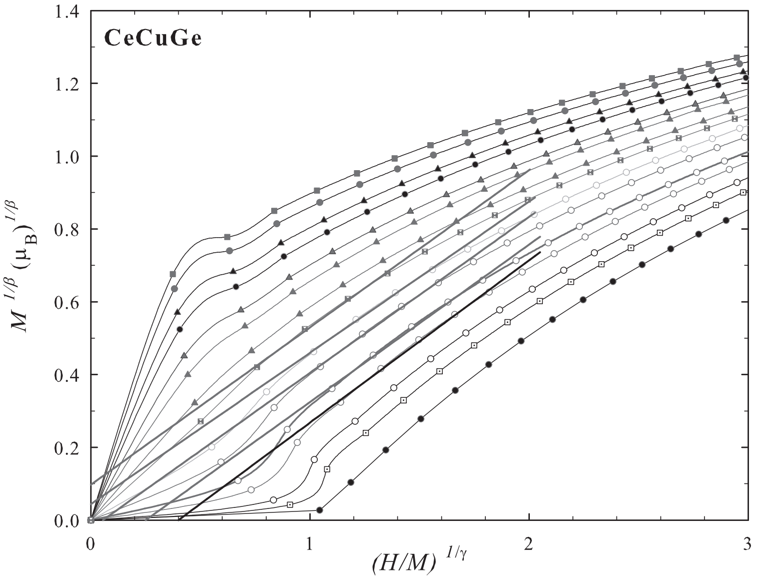

Figure 2. Modified Arrot plot; $M^{1/\beta}$ vs $H/M^{1/\gamma}$ of CeCuGe isotherms. Data points were depopulated for clarity purposes.

10.081 K whilst the fit of $T > T_C$ data yields 10.128 K. From the fitting parameters obtained in this step, the exponents T_C, β and γ are computed using Kouvel-Fischer method. Although $M_s(T)$ and $\chi_0^{-1}(T)$ were used to extract the critical exponents obtained above, new values of T_C, β and γ can be determined with high precision from the equations:

$$Y(T) = -M_s \left(\frac{\partial M_s}{\partial T}\right)^{-1} = -\frac{T - T_C}{\beta} \tag{4}$$

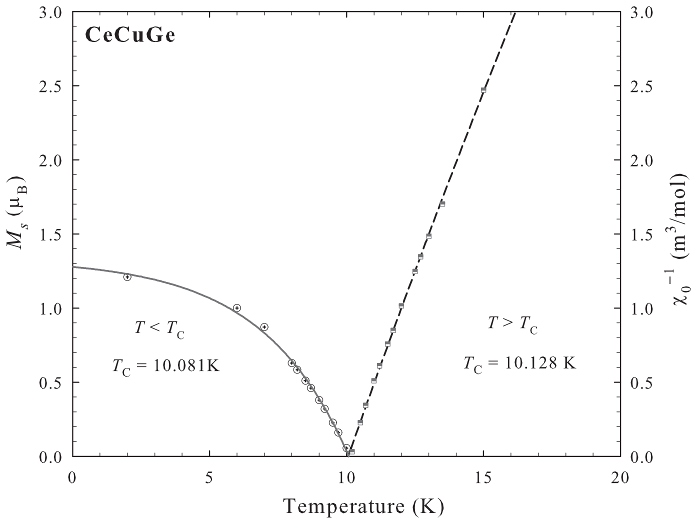

Figure 3. The plots of spontaneous magnetization, M_s and initial susceptibility, χ_0^{-1} as a function of temperature (T). The fits of the power laws, for the respective data are shown as dotted line and the critical values are shown labeled in the graph.

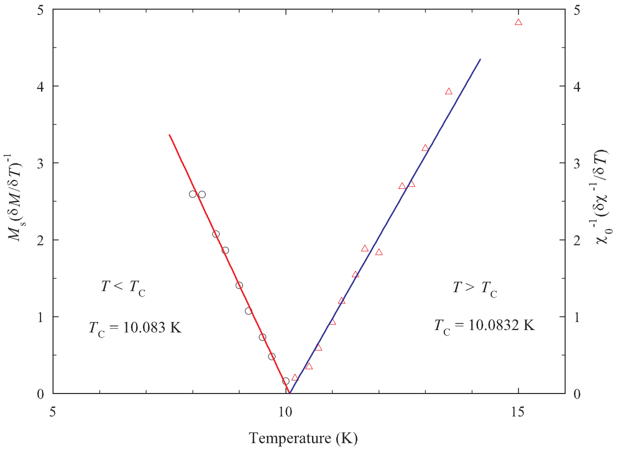

Figure 4. The plots of $Y(T)$ and $X(T)$ vs T and the linear fits according to Kouvel-Fischer method are indicated by solid lines.

$$X(T) = \chi_0^{-1}\left(\frac{\partial\chi^{-1}}{\partial T}\right) = \frac{T - T_C}{\gamma} \tag{5}$$

The Kouvel-Fischer method suggests that the straight line plots (see Fig.4 of $Y(T)$ and $X(T)$ vs T) gives the lines with the gradients -$\frac{1}{\beta}$ and $\frac{1}{\gamma}$. The extrapolation of these lines to the T-axis gives the value of T_C [9]. These linear fits resulted in $\beta = 0.6372 \pm 0.01$ and $\gamma = 0.9620 \pm 0.01$ and $T_C = 10.083 \pm 0.1$ K obtained from both the fit of $Y(T)$ and $X(T)$ vs T data. Computing for the critical exponent δ from the expression; $\delta = 1 + \gamma/\beta$ the value $\delta = 2.5097 \pm 0.01$ is obtained.

Table 1. The table of critical exponents predicted by different models and the data obtained in this work for CeCuGe, the transition temperature T_C as a parameter obtained from the fit is shown in the table. The results were obtained from Kouvel-Fischer method.

	β	γ	δ	$\mathrm{T}_C(K)$	References
CeCuGe	0.6372	0.9620	2.5097	10.083	This work
MFT	0.5	1.0	3.0	-	[13]
3D Ising Model	0.325	1.24	4.82	-	[13]
3D HM	0.365	1.336	4.60	-	[13]

4. Conclusion

The magnetization data measured in CeCuGe indicated a paramagnetic to ferromagnetic (PM-FM) transition around 10 K. This transition was confirmed by modified Arrot plot and Kouvel-Fischer techniques. The critical exponents around the critical temperature T_C for this ferromagnetic compound from both methods converged to similar values which allowed the system to be classified as Mean Field. The ordering temperature obtained after the fitting models were used gives confirms 10.083 K. The critical exponents obtained were $\beta = 0.6372$, $\gamma = 0.9620$ and $\delta = 2.5097$ which can be associated with the values of Mean-Field Theory.

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