Critical Scaling of the Magnetization and Magnetostriction in the Weak Itinerant Ferromagnet UIr

W. Knafo¹,²,³, C. Meingast¹, S. Sakarya⁴, N.H. van Dijk⁴, Y. Huang⁵, H. Rakoto³, J.-M. Brote³, and H. v. Löhneysen¹,²

¹ Forschungszentrum Karlsruhe, Institut für Festkörperphysik, D-76021 Karlsruhe, Germany
² Physikalisches Institut, Universität Karlsruhe, D-76128 Karlsruhe, Germany
³ Laboratoire National des Champs Magnétiques Pulsés, 143 Avenue de Rangueil, 31400 Toulouse, Cedex 4, France
⁴ Delft University of Technology, Mekelweg 15, 2629 JB Delft, The Netherlands
⁵ Van der Waals - Zeeman Institute, University of Amsterdam, Valckenierstraat 65, 1018 XE Amsterdam, The Netherlands

(Dated: July 28, 2008)

The weak itinerant ferromagnet UIr is studied by magnetization and magnetostriction measurements. Critical behavior, which surprisingly extends up to several Tesla, is observed at the Curie temperature $T_C \approx 45$ K and is analyzed using Arrott and Maxwell relations. Critical exponents are found that do not match with any of the well-known universality classes. The low-temperature magnetization $M_s \approx 0.5 \mu_B \approx const.$ below $3$ T rises towards higher fields and converges asymptotically around $50$ T with the magnetization at $T_C$. From the magnetostriction and magnetization data, we extract the uniaxial pressure dependences of $T_C$, using a new method presented here, and of $M_s$. These results should serve as a basis for understanding spin fluctuations in anisotropic itinerant ferromagnets.

PACS numbers: 71.27.+a, 74.70.Tx, 75.30.Cr, 75.30.Gw, 75.50.Cc

The fact that a superconducting pocket develops at the quantum critical point (QCP) of several heavy-fermion systems indicates that magnetic fluctuations, which are enhanced at the QCP, may play an important role for forming the Cooper pairs [1, 2, 3], suggesting that superconductivity might be mediated by these fluctuations [4], instead of phonons as in conventional superconductors. The recent observation of magnetic-field induced superconductivity in URhGe confirmed that magnetism plays a central role for the superconducting properties of such systems [5]. The issue of understanding the interplay between magnetism and superconductivity is not restricted to heavy-fermion physics, since a magnetic pairing mechanism might be operative for the cuprate superconductors as well [1, 4, 5]. A precise characterization of the properties of the magnetically ordered state is, thus, an important first step in understanding how superconductivity can develop in correlated electron systems.

The weak itinerant ferromagnet UIr has recently attracted attention because it becomes superconducting under pressure [8]. Further, it is the second known case (after CePt₃Si [9]) of superconductivity in a noncentrosymmetric crystal with strong electronic correlations. UIr orders ferromagnetically below $T_C \approx 46$ K, its low-temperature saturated moment $M_s \approx 0.5 \mu_B$/U-atom being much smaller than the effective moment $M_{eff} \approx 3.6 \mu_B$/U-atom extracted from the high temperature susceptibility [10, 11]. The small ratio $M_s/M_{eff} = 0.14$ is probably due to the combination of strong longitudinal magnetic fluctuations, consequence of the itinerant character of the 5f electrons [12], and of crystal-field effects [11, 13]. Hydrostatic pressure destabilizes ferromagnetism and leads to a QCP at $p_C \approx 24$ kbar, in the vicinity of which superconductivity develops with a maximum critical temperature $T_{sc}^{max} \simeq 0.14$ K [8]. As summarized in Table I, UIr has strong similarities with the itinerant ferromagnets UGe₂ and URhGe, which become superconducting under pressure [14] and at ambient pressure [10], respectively, and, to a lesser degree, with ZrZn₂, which is an archetype of itinerant ferromagnetism, without superconductivity [15, 16].

In this Letter, we present a study of the magnetic properties of UIr. Power laws, characteristics of critical ferromagnetism, are observed at $T_C$ in the magnetization $M(H)$ and, for the first time in a ferromagnet,

| $T_C$ (K) | $M_s$ (µB) | $M_s/M_{eff}$ | $p_C$ (kbar) | $T_{sc}^{max}$ (K) |
|-----------|------------|--------------|-------------|----------------|
| UIr       | 45         | 0.5          | 0.14        | 0.14          |
| UGe₂      | 53         | 0.5          | 0.43        | 0.80          |
| URhGe     | 9.5        | 0.43         | 0.11        | 0.25          |
| ZrZn₂     | 28.5       | 0.11         | 0.09        | -             |

*: in URhGe, reentrant superconductivity is associated with $T_{sc}^{max} \simeq 0.4$ K at $\mu_B H \simeq 12$ T ($H \parallel b$) [5].
in the magnetostriction $\lambda(H)$. Surprisingly, this critical regime extends to fields of several Tesla. A description of the critical magnetization and magnetostriction is made using Arrott and Maxwell relations, from which we derive a new method to extract the uniaxial pressure dependences of $T_C$. The pressure dependences of $M_s$ are also extracted. These results confirm the anisotropic nature of magnetism in UIr [11]. A connection is made with Moriya-like spin-fluctuation theories [12, 20, 21].

Single crystals of UIr were grown by the Czochralski technique in a tri-arc furnace. The magnetization up to 10 T was measured at several temperatures using a VSM insert in a PPMS from Quantum Design, with field sweep rates of 1 mT/s. Magnetization was also measured at $T = 4.2$ K using a pulsed field up to 52 T at the Laboratoire National des Champs Magnétiques Pulsés in Toulouse, with a pulse rise of 40 ms (see also [13]). Magnetostriction was measured using a high-resolution capacitive dilatometer [22, 23] with field sweep rates of 0.5 T/min. The cell is rotatable, allowing both longitudinal and transverse measurements of the length $L$, which was measured along the (10\textbf{1}), (10\textbf{1}), and (010) axes of UIr. In all measurements, the magnetic field $H$ was applied along the easy (10\textbf{1}) axis.

In Fig. 1 the magnetization of UIr is shown in a $M$ versus $H$ log-log plot, at $T = 4$, 45 ($\approx T_C$), and 60 K and for $H \parallel (10\textbf{1})$. At 4 K, after a domain alignment achieved at 0.04 T, $M(H)$ is nearly constant and equals $M_s \approx 0.5 \mu_B/\text{U-atom}$ for $0.04 < \mu_0 H < 3$ T. At $T_C$, $M(H)$ follows a power law $M \propto H^{1/\delta}$, with $\delta \approx 4.04 \pm 0.05$, indicative of a critical regime up to the highest measured field of 10 T. The magnetization is also shown in the paramagnetic regime, at 60 K. Above 2 T, the $M(H)$ data at 4 K increase significantly and, quite surprisingly, appear to merge with the high-field extrapolation of the power law (dashed line) above roughly 50 T. Even around 50 T, $M(H)$ continues to increase, being still a factor of roughly 5 smaller than the effective moment. The above behavior contrasts strongly with the magnetization curves of localized ferromagnetic systems such as EuS, for which $M(H)$ at $T_C$ only shows a power law at relatively small fields, and saturates at high fields to a field-independent saturated moment $M_s$ [24]. We attribute the unusually large field range of the power-law behavior at $T_C$ and of the field-induced increase of $M(H)$ at 4 K to the strong itinerant character of UIr. In this picture, the magnetization increases above 2 T because the magnetic field quenches the longitudinal fluctuations.

In Fig. 2 the magnetostriction of UIr, defined by:

$$\lambda_i = \frac{1}{L_i} \frac{\partial L_i}{\partial (\mu_0 H)} = -\frac{\partial M}{\partial p_i},$$

where $p_i$ the uniaxial stress applied along $i$, is shown at 4 and 45 K ($\approx T_C$) in a $\lambda$ versus $H$ log-log plot, for $L \parallel (10\overline{1})$, (10\textbf{1}), and (010) and $H \parallel (10\textbf{1})$. At 4 K and for $0.04 < \mu_0 H < 3$ T, the coefficients $\lambda_i(H)$ are roughly constant. For $0.03 < \mu_0 H < 3$ T, critical power laws are, for the first time in a ferromagnet, observed in the magnetostriction at $T_C$, which varies as $\lambda_i \propto H^{-1/\delta_i}$ with $\delta_i \approx 2.63, 2.47, \text{ and } 2.51 \pm 0.03$, for $i = (10\overline{1}), (10\textbf{1}), \text{ and } (010)$, respectively. Above 3 T, deviations from the critical regime at $T_C$, but also from the constant-$\lambda$ regime at 4 K, are observed, indicating a crossover towards a high-field regime. The crossover in $\lambda_i(H)$ at 4 K and $T_C$, as well as the one in $M(H)$ at 4 K, could be associated with the quenching of the longitudinal magnetic fluctuations. However, and contrary to the magnetostriction, the magnetization at $T_C$ shows no apparent crossover between a "low-field" critical regime and a "high-field" quenching of the longitudinal fluctuations.

![Fig. 1](image1.png)

**FIG. 1:** (color online) Magnetization versus field of UIr at $T = 4$, 45, and 60 K, with $H \parallel (10\textbf{1})$. The dashed line corresponds to the power law at $T_C$.

![Fig. 2](image2.png)

**FIG. 2:** (color online) Magnetostriction versus field of UIr, measured at $T = 4$ and 45 K for $L \parallel (10\overline{1}), (10\textbf{1}), \text{ and } (010)$, with $H \parallel (10\textbf{1})$. The dashed lines correspond to the fits of the data at $T_C$ by power laws.
Critical regime of UIr. The presence of strong longitudinal support, as well as an experimental determination of the critical regime of UIr, and their normalized ratio of the magnetization and magnetostriction close to the magnetization and for different universality classes [28]. This raises the question whether the critical regime of UIr is non-universal or if it belongs to an unknown universality class. Theoretical reasons suggest that the values of the exponents $\delta$, $\beta$, and $\gamma$ obtained for UIr do not belong to any of the well-known universality classes [28].

In the following, we characterize the critical properties of the magnetization and magnetostrictionclose to $T_C$, using the Arrott equation of state [27]:

$$M^{1/\beta} = c_1 \left( \frac{H}{M} \right)^{1/\gamma} - c_2 (T - T_C) .$$  

(2)

Magnetization was measured up to 10 T at nine temperatures between 41.5 and 49.5 K. A best fit of Eq. (2) to the $M(H,T)$ data for $42.5 \leq T \leq 47.5$ K and $0.2 \leq \mu_0 H < 3$ T yields $T_C = 45.15 \pm 0.2$ K, $\beta = 0.355 \pm 0.05$, $\gamma = 1.07 \pm 0.05$, $c_1 = 3.0 \times 10^{11}$ (A/m)$^{1/\beta}$, and $c_2 = 7.0 \times 10^{12}$ (A/m)$^{1/\beta}$K$^{-1}$. Fig. 2 shows the resulting plot of $M^{1/\beta}$ versus $(H/M)^{1/\gamma}$. Excellent fits are obtained in the whole $T$ range, with slight deviations for $\mu_0 H \gtrsim 5$ T. At $T = T_C$, Eq. (2) gives:

$$M(H,T_C) = c_1^e H^{1/\delta},$$

(3)

with $\delta = (\beta + \gamma)/\beta$. Using the exponents $\beta$ and $\gamma$ determined above, we obtain $\delta = 4.01$, which agrees very well with the value of $\delta = 4.04$ from the fit of $M(H)$ at 45 K. As shown in Table 1, the exponents $\beta$, $\gamma$, and $\delta$ obtained for UIr do not belong to any of the well-known universality classes [28]. This raises the question whether the critical regime of UIr is non-universal or if it belongs to an unknown universality class. Theoretical support, as well as an experimental determination of the magnetic exchange, are needed to describe these unusual critical properties. The presence of strong longitudinal magnetic fluctuations could possibly play a role in the critical regime of UIr.

The $H$-power law of $\lambda_i$ at $T_C$ is easily derived by taking the $p_i$ derivative of Eq. (2) and by assuming that $\partial T_C/\partial p_i$ is the relevant pressure derivative (i.e., $\partial c_1/\partial p_i = 0$), which gives

$$\lambda_i(T_C) = -A \frac{\partial T_C}{\partial p_i} H^{-1/\delta'},$$

(4)

where $A = c_4^{-\gamma/\delta'} c_2 \gamma / \delta$ and $\delta' = (\beta + \gamma)/(1 - \beta)$. Using the values of $\beta$ and $\gamma$ determined above, we obtain the exponent $\delta' = 2.20$, which agrees, within 15%, with the exponents $\delta' \simeq 2.63$, 2.47, and 2.51 obtained from the fit of $\lambda_i(H)$ at $T_C$ for $i = (10\overline{1})$, $(101)$, and $(010)$, respectively. To our knowledge, this is the first time that the isothermal magnetostriction of a ferromagnet at $T_C$ is expressed as a power law of $H$, in function of the critical exponents $\beta$ and $\gamma$ [24]. Further, Eq. (1) directly yields $\partial T_C/\partial p_i = -0.24 \pm 0.05$, $-0.84 \pm 0.1$, and $-0.48 \pm 0.05$ K/kbar, for $i = (10\overline{1})$, $(101)$, and $(010)$, respectively, $A$ and $\delta' = (\beta + \gamma)/(1 - \beta)$ being extracted from the fit of $M(H,T)$. These results agree perfectly with those obtained in Ref. [25] using the Ehrenfest relation:

$$\frac{\partial T_C}{\partial p_i} = \frac{\Delta \alpha_i V_m T_C}{\Delta C_p},$$

(5)

where $\Delta \alpha_i$ and $\Delta C_p$ are the jumps in the thermal expansivity and specific heat at $T_C$, respectively, and $V_m = 2.45 \times 10^{-5}$ m$^3$/mol is the molar volume (Table 1). The sum of the three uniaxial pressure dependences leads to the hydrostatic pressure dependence $\partial T_C/\partial p_h = -1.6 \pm 0.2$ K/kbar [24], which agrees well with the variation of $T_C$ under hydrostatic pressure [8].

Using Eq. (1), we extract the values of $\partial M_s/\partial p_i = -\lambda_i(T = 4$ K), with $\lambda_i(T = 4$ K) taken at $\mu_0 H = 1$ T for $i = (10\overline{1})$, $(101)$, or $(010)$, from the low-temperature dependence of $\lambda_i$ at $T_C$, for $i = (10\overline{1})$, $(101)$, and $(010)$, respectively. The presence of strong longitudinal magnetic fluctuations could possibly play a role in the critical regime of UIr.

| TABLE II: Critical exponents $\beta$, $\gamma$, $\delta$, and $\delta'$ from the fit of the magnetization and for different universality classes [28]. |
|---|---|---|---|---|
| $\beta$ | $\gamma$ | $\delta$ | $\delta'$ |
| UIr (best fit) | 0.355 | 1.07 | 4.01 | 2.20 |
| 3D Heisenberg | 0.367 | 1.388 | 4.78 | 2.77 |
| 3D XY | 0.345 | 1.316 | 4.81 | 2.54 |
| 3D Ising | 0.326 | 1.238 | 4.80 | 2.32 |
| 2D Ising | 0.125 | 1.75 | 15 | 2.14 |
| Mean Field | 0.5 | 1 | 3 | 3 |

FIG. 3: (color online) Arrott plot of magnetic isotherms for $41.5 \leq T \leq 49.5$ K. Thin red lines show fits of Eq. (2) to the data, thick green line denotes the isotherm at $T_C$. |
magnetostriction (Fig. 2), see Table III. The sum over \( \lambda \) yields the hydrostatic pressure dependence \( \partial M_s / \partial p_h = -9.5 \times 10^{-3} \mu_B / \text{kbar} \), which agrees very well with measurements of \( M_s \) under pressure [8].

As seen from Table III, \( T_C \) and \( M_s \) are much more sensitive to uniaxial pressures applied along the hard axes (10\( T \)) and (010) than to uniaxial pressures applied along the easy axis (10\( T \)). The strong anisotropy of these pressure dependences (factor of up to five between different axes) results presumably from single-ion, exchange, and/or hybridization anisotropies. To compare these effects, we introduce the ratio:

\[
\rho_i = \frac{\partial \ln T_C / \partial p_i}{\partial \ln M_s / \partial p_i},
\]

which is equal to 2.4, 1.9, 1.6, and 1.8 for \( i = (10T) \), (10\( T \)), (010), and \( h \) (\( h = \) hydrostatic), respectively (Table III). Not surprisingly, \( \rho_i \) is more isotropic than \( \partial T_C / \partial p_i \) and \( \partial M_s / \partial p_i \), varying by about 50% from one axis to another. In Moriya's theory of spin fluctuations [12], \( T_C \) is given by:

\[
T_C \propto M_s^{3/2} T_A^{3/4} T_0^{1/4},
\]

where \( T_A \) and \( T_0 \) are two energy scales related to correlated and uncorrelated spin fluctuations, respectively. From Eq. 7, Takahashi and Kanomata [21] derived

\[
\frac{\partial \ln T_C / \partial p_i}{\partial \ln M_s / \partial p_i} = 3 - \frac{2 \gamma_{0,A}}{\gamma_m},
\]

with \( \gamma_{0,A} = (3 \gamma_A + \gamma_0) / 4 \) and the Grüneisen parameters \( \gamma_A = -\partial \ln T_A / \partial \ln V \), \( \gamma_0 = -\partial \ln T_0 / \partial \ln V \), and \( \gamma_m = \partial \ln (M_s^2) / \partial \ln V \). In such models, the magnetic anisotropy is not considered and all the formulas are isotropic. A straightforward generalization of the expressions of Takahashi and Kanomata to the anisotropic case of UIr leads to the very anisotropic parameters \( \gamma_{0,A,i} / \gamma_m,i = -0.47, -0.18, -0.06, \) and -0.17, for \( i = (10T), \) (10\( T \)), (010), and \( h \), respectively. We note that one could apply alternative models, such as that of Kaiser and Fulde [30], to describe the magnetostriction of itinerant ferromagnets.

In heavy-fermion systems, a stronger anisotropy seems to stabilize superconductivity (compare cf. CeCoIn\(_5\) and CeIn\(_3\) [1, 14, 31]). As proposed in Ref. [32], anisotropy could also be of importance for the development of superconductivity in U-based heavy-fermion systems. Indeed, since it fixes the easy and hard magnetic axes, anisotropy has a crucial influence on the magnetic fluctuations, and has to be considered in the scenarios of magnetically mediated superconductivity [6]. The anisotropy of the results reported here, which depends on the quantity extracted \( \gamma_{0,A,i} / \gamma_m,i, \partial T_C / \partial p_i, \) and \( \partial M_s / \partial p_i \) are more anisotropic than \( \rho_i \), suggests that the spin fluctuation theories [12, 21] should incorporate the magnetic anisotropy for a better description of UIr.

In conclusion, we have studied the magnetic properties of the itinerant ferromagnet UIr at ambient pressure. Special attention was given to the critical regime at \( T_C \), which surprisingly persists up to several Tesla in the magnetization and magnetostriction. A crossover to a high-field regime, where the magnetic fluctuations are increasingly quenched by the field, was observed above 3 T. In the high-field region \( \mu_B H \gtrsim 50T \), the low-temperature magnetization and the magnetization at \( T_C \) were found to merge asymptotically. The critical exponents \( \beta = 0.355 \) and \( \gamma = 1.07 \), extracted from our data do not correspond to any of the well-known universality classes. Furthermore, anisotropic values of \( \partial T_C / \partial p_i \) and \( \partial M_s / \partial p_i \), were found with the smallest stress dependence for the easy direction. These results may motivate further microscopic investigations of UIr and may be used to develop spin fluctuation theories [12, 21] for the treatment of real, and generally anisotropic, systems. In the future, the magnetization and magnetostriction of UIr might be studied under pressure to determine the critical magnetic properties at the onset of superconductivity. Such developments, combined with similar studies on the itinerant ferromagnets UGe\(_2\), URhGe, and ZrZn\(_2\), could be decisive for determining what stabilizes superconductivity at a magnetic quantum instability [6].

We acknowledge useful discussions with F. Hardy and T. Schwarz. This work was supported by the Helmholtz-Gemeinschaft through the Virtual Institute of Research on Quantum Phase Transitions and Project VH-NG-016.

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Due to the monoclinic structure of UIr, the approximation \( \frac{\partial X}{\partial p_i} = \sum_i \frac{\partial X}{\partial p_i} \), with \( X = T_C \) or \( M_s \) and \( i = (10\overline{1}), (101), \) or \( (010) \), is valid within about 1\% \cite{Sakarya2006}. Indeed, the angles between \( (10\overline{1}), (101), \) or \( (010) \) are slightly different from 90\°.