PHYSICAL REVIEW B VOLUME 49, NUMBER 17 1 MAY 1994-I

Scaling in the magnetoresistance of single-crystalline UBe_{13}

B. Andraka
Department of Physics, University of Florida, Gainesville, Florida 32611-2085

G. R. Stewart
Department of Physics, University of Florida, Gainesville, Florida 32611-2085
and University of Augsburg, Augsburg, Germany

(Received 30 August 1993; revised manuscript received 13 January 1994)

We have measured longitudinal magnetoresistance on a high-quality single crystal of UBe_{13}. We were able to scale all the magnetoresistance results for fields between 0 and 14 T and for temperatures between 1.4 and 15 K using the following scaling relation $(T-0.75\ \mathrm{K})^{0.6}/H$. This scaling is inconsistent with both a Kondo model and a quadrupolar Kondo model and suggests existence of ferromagnetic correlations in UBe_{13}.

UBe_{13} remains a favorite subject of extensive experimental and theoretical studies for a number of reasons.[1] On one hand, unusual physical properties of this compound in the superconducting state, below about 0.9 K, offer an exciting possibility of unconventional superconductivity. On the other hand, normal-state behavior of UBe_{13} exhibits similarities to somewhat better understood Ce-based heavy-fermion systems; thus, UBe_{13} might serve as a bridge to better understanding the U family of heavy fermions. Especially remarkable similarities in the low-temperature specific heat[2] and electrical resistivities[3] of UBe_{13} and $CeCu_2Si_2$ provided reasons to consider UBe_{13} as a clear-cut example of a U Kondo system. However, the magnetic-field response of the thermodynamic and transport properties of UBe_{13} is highly unusual and not fully compatible with a simple Kondo model.

Therefore two other models have been considered in the context of UBe_{13}: (1) periodic Kondo lattice model[4] and (2) a quadrupolar Kondo (single impurity) model.[5] There are no convincing results produced to date which favor one or the other of these two models.

One of the most outstanding and characteristic properties of UBe_{13} is its magnetoresistance.[6–9] The magnetoresistance is large, and strongly temperature and field dependent, thus it is a potentially important tool in solving the normal state of UBe_{13}. Previous attempts to interpret the magnetoresistance using the $S=\frac{1}{2}$ Coqblin-Schrieffer model[10] have led to an unphysical result, i.e., T_K is temperature dependent and approaches zero at $T\to 0$ K.

Obviously a poor fit of transport properties for a translationally invariant system to a single-impurity model is not in itself surprising. However, deviations from the model for UBe_{13} cannot be simply associated with the periodicity of the system. The magnetoresistance of Ce-based compounds[11] has been calculated by Kawakami and Okiji[12] in the framework of the periodic Anderson model. According to their model, the periodicity results in a reduction of the absolute value of the magnetoresistance (as opposed to an increase for UBe_{13}) with respect to the single impurity behavior (the reduction is larger the lower the temperature). Moreover, at temperatures smaller than $0.2T_K$, a positive magnetoresistance should be observed at low fields. Such behavior has indeed been found for $CeAl_3$ (Ref. 13) and $CeCu_6$.[14]

On the other hand, our previous magnetoresistance results[9] for the doped material, $U_{0.8}Y_{0.2}Be_{13}$, are fairly compatible with the Kondo impurity model, which is somewhat unexpected in light of the preceding discussion. Taken altogether, this discussion points to some important intersite interactions not included in the Kondo lattice model. Therefore we have attempted to reexamine in the present work the longitudinal magnetoresistance of UBe_{13} using a scaling approach. The scaling analysis is a powerful tool which can provide basic information on the nature of the phenomenon without relying on tedious and approximate numerical solutions. In particular, it can distinguish between single ion (quadrupolar, or normal Kondo) and lattice (Kondo lattice) origin of the investigated property. In one of our previous works[15] we have demonstrated relevance of intersite U interactions in another heavy-fermion metal, $U_{0.2}Y_{0.8}Pd_3$, via a scaling analysis of the field dependence of the specific heat.

UBe_{13} single crystals were synthesized via an aluminum-flux growth technique. The crystals were of the highest presently available quality according to such criteria as T_c values and values of the specific-heat discontinuities at T_c.[16] The electrical resistance measurements were performed with a standard dc-four probe method. Magnetic fields were applied in the sample current direction in order to minimize a "normal" magnetoresistance caused by a Lorentz force. The temperature in magnetic fields was measured with a Lake Shore capacitance sensor. The capacitance sensor was calibrated against a germanium-resistance thermometer at zero field before and after each new field was set. We have not detected any drifts in the capacitance sensor calibration. Also, we have not observed any differences between the resistance measurements performed while warming up versus cooling down the sample. The range of our measurements was 1.4 to 15 K. On average, 200 resistance versus temperature points were taken at each of the following fields: 0, 2, 4, 6, 8, 10, 12, and 14 T.

Several typical curves of a magnetoresistance versus temperature are shown in Fig. 1. The relative magnetoresistance $\Delta R/R_0$ is defined as the following ratio:

$$\frac{\Delta R}{R_0}=\frac{R(H,T)-R(0,T)}{R(0,T)},$$

where $R(H,T)$ is the resistance at temperature T and field H. In the case of the $S=\frac{1}{2}$ Kondo model,[10] the relative magnetoresistance depends on T and H only through their ratio $(T+T^*)/H$; i.e., $\Delta R/R_0 = f[(T+T^*)/H]$, where T^* plays the role of the Kondo temperature. Thus, in principle, it should be possible for a Kondo system to superimpose all the magnetoresistance versus temperature curves by performing a simple transformation of the x axis: $T \to x = (T+T^*)/H$. The inadequacy of the Kondo model is demonstrated in Fig. 2 which shows the results for such a transformation for curves corresponding to two fields, 6 and 14 T. The use of only one adjustable parameter in this transformation allows us to match any two curves at a single point only.

In the search for a better description of the UBe_{13} magnetoresistance we have examined the following scaling: $(T+T^*)^\beta/H$. The Kondo scaling can be considered as a particular case of this more general scaling with β, the field scaling dimension, equal to 1 and T^* assuming only positive values. Figure 3 shows the magnetoresistance versus $\ln[(T+T^*)^\beta/H]$, where $T^*=-0.75$ K and $\beta=0.6$, for all seven applied fields. T^* and β were chosen to match two pairs of points for the 6 and 14 T fields. Subsequently, as shown clearly in Fig. 3, we found that this choice of parameters allows us to adequately scale all the magnetoresistance results. In order to further check this postulated scaling and to determine error bars on T^* and β we performed separate scaling analyses for each pair of the magnetoresistance curves corresponding to adjacent fields, i.e., for 2 and 4 T, for 4 and 6 T, ..., 12 and 14 T. For each pair of fields we determined the

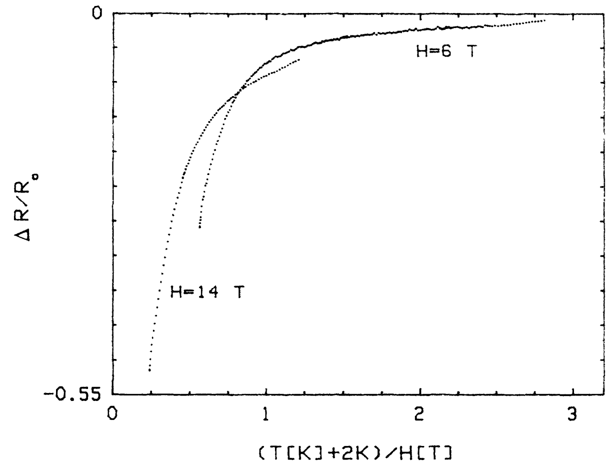

FIG. 2. $\Delta R/R_0$ vs $(T+2\ \mathrm{K})/H$ for $H=6$ and 14 T.

best values of T^* and β. T^* obtained this way spans the -1.1 to -0.7 K range, while all β coefficients are between 0.54 and 0.62. There was no correlation between the values of these coefficients and values of the fields used to determine them.

We have checked this scaling on our previously investigated,[9] high-quality, polycrystalline UBe_{13} sample. Despite a sizable discrepancy in the absolute values of the magnetoresistance [$\Delta R/R_0$ (14 T) values at 1.3 K are -0.64 and -0.52 for the polycrystalline and single-crystalline samples, respectively] both samples exhibit an identical scaling in the magnetoresistance (see Fig. 4). Note that in the case of the polycrystalline sample R was measured as a function of the field at a constant temperature (versus constant field and varying temperature in this study) which can be considered as an additional check of the postulated phenomenological scaling relationship.

Both obtained parameters T^* and β are highly unusual and are clearly inconsistent with a pure Kondo interpretation of the magnetoresistance. The value of the β coefficient does not *a priori* preclude a single-site in-

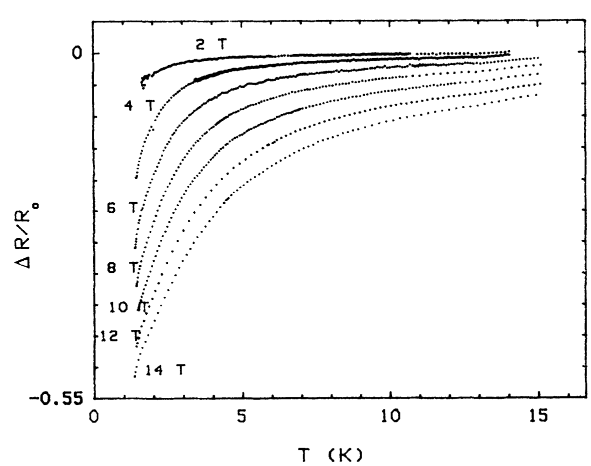

FIG. 1. $\Delta R/R_0$ vs T for $H=2$, 4, 6, 8, 10, 12, and 14 T.

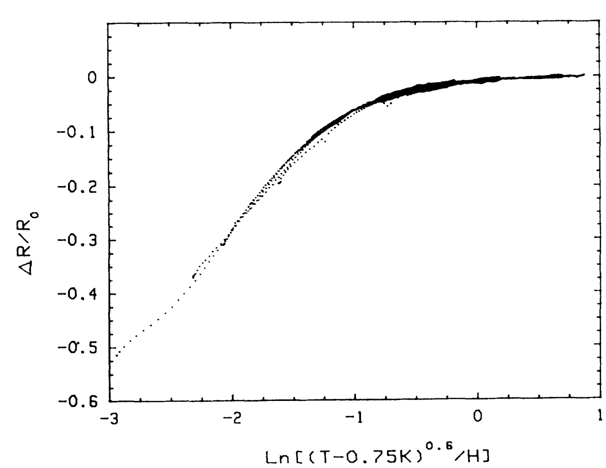

FIG. 3. $\Delta R/R_0$ vs $\ln[(T-0.75\ \mathrm{K})^{0.6}/H]$ for $H=2$, 4, 6, 8, 10, 12, and 14 T.

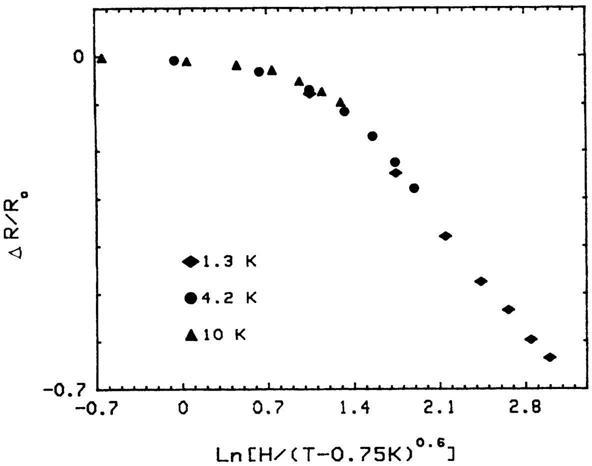

FIG. 4. $\Delta R/R_0$ vs $\ln[H/(T-0.75\ \mathrm{K})^{0.6}]$ for the polycrystalline sample described in Ref. 9.

terpretation. However, we are not aware of any relevant single-site-type theory yielding the field scaling dimension equal to our measured β. Only the two-channel $S=\frac{1}{2}$ magnetic Kondo model[17] has a somewhat similar scaling, $T^{0.5}/H$. However, this scaling poorly describes our magnetoresistance data for both large and small values of T/H. Moreover, other experimental results for UBe_{13}, like magnetic susceptibility and the field dependence of the specific heat,[1] exclude such an interpretation. The other model considered in the context of UBe_{13}, the quadrupolar Kondo model,[5] has, according to the latest theoretical investigation,[18] the scaling $T^{0.25}/H$. Therefore, our magnetoresistance results seem to rule out the quadrupolar Kondo effect interpretation as well.

The negative value of T^* suggests existence of ferromagnetic correlations in UBe_{13}. This is an unexpected result. Up to now only antiferromagnetic correlations have been considered for UBe_{13} as well as for other heavy-fermion superconductors, in agreement with the sign of the Curie-Weiss constant at the high-temperature susceptibility. The magnetic correlations have been probed for UBe_{13} via quasielastic neutron scattering for finite Q (momentum transfer) values.[19] Surprisingly, no Q-dependence consistent with antiferromagnetic correlations has been found. Extension of such experiments to lower Q values ($Q \approx 0$) would be of interest to further verify our hypothesis of ferromagnetic correlations existing in UBe_{13}.

We acknowledge fruitful discussions with P. Kumar and A. Tsvelik. This work was supported by National Science Foundation Grant No. DMR-9208866 (B.A.) and by U.S. Department of Energy Grant No. DE-FG05-86ER45268 (G.R.S.).

[1] G. R. Stewart, Rev. Mod. Phys. **56**, 755 (1984); A. de Visser and J. J. M. Franse, J. Magn. Magn. Mater. **100**, 204 (1991); N. Grewe and F. Steglich, in *Handbook on the Physics and Chemistry of Rare Earths,* edited by K. A. Gschneidner, Jr. and L. Eyring (Elsevier, Amsterdam, 1991), Vol. 14, Chap. 97, p. 343.

[2] H. Rietschel, B. Renker, R. Felten, F. Steglich, and G. Weber, J. Magn. Magn. Mater. **76&77**, 105 (1988).

[3] H. R. Ott, H. Rudiger, Z. Fisk, and J. L. Smith, Phys. Rev. Lett. **50**, 1595 (1983).

[4] R. Felton, F. Steglich, G. Weber, H. Rietschel, F. Gompf, B. Renker, and J. Beuers, Europhys. Lett. **2**, 323 (1986).

[5] D. L. Cox, Phys. Rev. Lett. **59**, 1240 (1987); J. Magn. Magn. Mater. **76&77**, 53 (1988).

[6] G. R. Stewart, Z. Fisk, J. L. Smith, H. R. Ott, and F. M. Mueller, in *Proceedings of LT-17*, edited by U. Eckern, A. Schmidt, W. Weber, and H. Wühl (North Holland, Amsterdam, 1984), p. 321; G. R. Stewart, J. Appl. Phys. **57**, 3049 (1985).

[7] B. Batlogg, D. J. Bishop, E. Bucher, B. Golding, Jr., A. P. Ramirez, Z. Fisk, J. L. Smith, and H. R. Ott, J. Magn. Magn. Mater. **63&64**, 441 (1987).

[8] U. Rauchschwalbe, F. Steglich, and H. Rietschel, Physica **148B**, 33 (1987).

[9] B. Andraka, W. W. Kim, J. S. Kim, and G. R. Stewart, Phys. Rev. B **44**, 5040 (1991).

[10] P. Schlottmann, Phys. Rep. **181**, 1 (1989).

[11] One can expect some differences in behavior of Ce- and U-based systems because of different electronic configuration of Ce and U ions. In particular, one might argue that a screening of one $4f$ electron of Ce by conduction electrons can be more effective than the screening of three $5f$ electrons of U.

[12] N. Kawakami and A. Okiji, J. Phys. Soc. Jpn. **55**, 2114 (1986).

[13] A. Briggs, J. Flouquet, O. Laborde, and F. Lapierre, J. Magn. Magn. Mater. **31-34**, 407 (1983).

[14] A. S. Edelstein, C. J. Tranchita, O. D. McMasters, and K. A. Gschneidner, Jr., Solid State Commun. **15**, 81 (1974); A. Sumiyama, U. Oda, H. Nagano, Y. Onuki, K. Shibutani, and T. Komatsubara, J. Phys. Soc. Jpn. **55**, 1294 (1986).

[15] B. Andraka and A. Tsvelik, Phys. Rev. Lett. **67**, 2886 (1991).

[16] B. Andraka and G. R. Stewart (unpublished).

[17] A. Tsvelik, J. Phys. C **18**, 159 (1985).

[18] A. Tsvelik (unpublished).

[19] G. H. Lander, S. M. Shapiro, C. Vettier, and A. J. Dianoux, Phys. Rev. B **46**, 5387 (1993).