Superconducting and Magnetic Phase Transitions in $\text{RE}_x\text{Y}_{1-x}\text{Rh}_{1.1}\text{Sn}_{3.6}$ (RE=Er, Ho)

A.W.M. VAN DE PASCH, F.J. LAZARO*, D.H.A. BLANK, E.P. HOUWMAN and J. FLOKSTRA

University of Twente, Department of Applied Physics, P.O. Box 217, 7500 AE, Enschede, The Netherlands; * ETSIIZ, University of Zaragoza, Spain

The superconducting (T_C) and magnetic ordering (T_m) critical temperatures in $\text{RE}_x\text{Y}_{1-x}\text{Rh}_{1.1}\text{Sn}_{3.6}$ (RE = Er, Ho) have been determined by magnetic measurements. For RE = Er superconductivity appears for any value of x , and reentry to a magnetically ordered state for $x \geq 0.6$, while for RE = Ho the compound becomes either superconducting or magnetically ordered, and is expected to remain paramagnetic for x near 0.5. Theories of Abrikosov-Gorkov and Roshen-Ruvalds are used to explain $T_C(x)$, leading to $I^2N(0)G = 0.23$ K and 0.8 K for Er and Ho respectively. Comparison of $T_m(x)$ with the theory of Oguchi-Obokata gives respectively $J = 0.30$ K and 0.96, using a Heisenberg model with $z = 6$.

1. INTRODUCTION

The discovery of some families of ternary compounds with superconducting and magnetic ordering properties renewed the studies on the interplay between these phenomena. With the introduction of different rare earth (RE) elements into these compounds the low temperature properties are varied considerably. Ordering temperatures as well as superconducting properties are strongly dependent on the strength of the RE magnetic moment. Information about the spin-spin and spin-electron interaction involved can be obtained by observing the effects of magnetic dilution on several physical properties.

This paper presents the results of such a study on the magnetic superconductor family of rhodium stannides $\text{RERh}_{1.1}\text{Sn}_{3.6}$, where we used RE = Ho and Er, diluted with Y. The three starting materials are reported to crystallize in the same structure with $\text{YRh}_{1.1}\text{Sn}_{3.6}$ having $T_C = 3.1$ K, $\text{HoRh}_{1.1}\text{Sn}_{3.6}$ having $T_m = 1.7$ K and $\text{ErRh}_{1.1}\text{Sn}_{3.6}$ being reentrant with $T_C = 1.1$ K and $T_m = 0.5$ K [1]. The phase diagrams of $\text{RE}_x\text{Y}_{1-x}\text{Rh}_{1.1}\text{Sn}_{3.6}$, obtained from magnetic measurements, will be explained by appropriate theories. (see also ref. 2).

2. EXPERIMENTAL

Crystals of $\text{Er}_x\text{Y}_{1-x}\text{Rh}_{1.1}\text{Sn}_{3.6}$ and $\text{Ho}_x\text{Y}_{1-x}\text{Rh}_{1.1}\text{Sn}_{3.6}$ for almost all the values from $x = 0$ to $x = 1$ with intervals of 0.1 were grown by the standard method. X-ray diffraction analysis shows that both the pure (Er or Ho) samples and the Y-diluted ones belong to the so-called phase II with presence of the tetragonal c axis directed along the three perpendicular directions of space within one crystal [1].

Different magnetic measurement techniques are used in order to determine the transition temperatures. Above 1 K the dynamical susceptibility was measured with an a.c. SQUID susceptometer with a typical excitation field of 0.2 μT and covering a wide range of frequencies (5 mHz-3 kHz). This task was also shared by another susceptometer based on a conventional mutual inductance bridge operated at 275 Hz and using an a.c. field of 5 μT . Below 1 K, d.c. magnetization was measured by a SQUID magnetometer mounted on a ^3He - ^4He dilution refrigerator.

Although T_C can be determined directly from a sharp transition from the paramagnetic to the

superconducting state, for a number of our samples the susceptibility curves $\chi'(T)$ exhibit a shoulder as shown in fig. 1. The experiments reveal that this phenomenon depends on the amplitude of the measuring a.c. field. As the lower part of the curve does not change with amplitude, we define the bulk transition temperature T_C by extrapolation as shown, ascribing the upper part of the transition to superconductivity in thin layers between crystallites, not able to carry much current. In the phase diagrams, figs. 2 and 3, we present T_C together with T_{CP} (deviation from paramagnetic behaviour) and T_{CS} (complete screening) for our samples.

Fig. 1. Phase transition of $\text{Er}_{0.8}\text{Y}_{0.2}\text{Rh}_{1.1}\text{Sn}_{3.6}$ for two different a.c. field values.
 a: $h_{ac} = 0.3 \mu\text{T}$; b: $h_{ac} = 3 \mu\text{T}$.

The magnetic ordering temperatures on the Ho series are taken from the cusp-like peaks appearing in $\chi'(T)$. For the Er series T_m is determined from the point of maximum slope in the $M(T)$ curves when passing from the complete screening value at the superconducting state to the saturation value at the ordered state. More details about these last kind of measurements can be found in ref. 3.

3. THEORY

The effect of paramagnetic impurities on the superconducting properties of a metal has been described by Abrikosov and Gorkov (AG) [4]. They define a pair breaking parameter ρ_{AG} given by

$$\rho_{AG} = 2\pi I^2 N(0) G x / T \quad (1)$$

with I the spin-electron interaction constant,

$N(0)$ the density of states at the Fermi-level and G the de Gennes factor. For a given concentration x , T_C is related to the non-magnetic T_{Co} by

$$\ln(T_{Co}/T_C) = \Psi\left(\frac{1}{2} + \rho_{AG}\right) - \Psi\left(\frac{1}{2}\right) \quad (2)$$

where Ψ is the digamma function.

At higher impurity concentration, spin-spin interaction (neglected by AG) will affect the pair breaking parameter. Roshen and Ruvalds (RR) [5] give an extension of AG-theory taking into account only nearest neighbour interaction U between spins. This leads to an additional spin pair term in the pair breaking parameter, resulting in

$$\rho_{RR} = \rho_{AG}(1 + 2GzUx/3T) \quad (3)$$

where z is the number of nearest neighbours in the magnetic lattice, and ρ_{RR} replaces ρ_{AG} in eq. (2).

The magnetic ordering temperature T_m for a randomly site-diluted ferromagnet is given by Oguchi and Obokata (OO) [6] as a function of concentration. In the Heisenberg model this leads to

$$2J/T_m = \ln((z'/(z'-4))) \quad (4)$$

with J an exchange constant and defining

$$z' = 1 + (z-1)x\{1-(1-x)^z\} \quad (5)$$

as the effective number of magnetic neighbours.

4. DISCUSSION

We applied the theoretical expressions for T_C and T_m to the experimental data in the figs. 2 and 3 resulting in the parameters given in table I. It is seen that the T_C values are well described by the RR model although determination of parameters is less accurate in the Ho-case. We emphasize that the compounds should be a good test for the RR-theory which accounts for pair breaking by spin pairs, because the magnetic atoms have only one nearest neighbour at 4.38 Å, whereas three next nearest neighbours are at 5.29 Å.

Comparison of the De Gennes factor and the AG-parameter $I^2N(0)G$ for Er and Ho (see table I) indicates that G is not a good scaling parameter,

Fig. 2. Phase diagram of $Er_xY_{1-x}Rh_{1.1}Sn_{3.6}$.

Fig. 3. Phase diagram of $Ho_xY_{1-x}Rh_{1.1}Sn_{3.6}$.

Table I. Overview of the interaction constants (in K) used for theoretical curves in figs. 2 and 3.

	J	$I^2N(0)G$	$2GzU/3$	G
Er	0.30	0.23	0.6	2.55
Ho	0.96	0.8	0.4	4.5

as we expect $I^2N(0)$ not to differ much for both compounds. This is most likely caused by crystalline electric field effects. The RR-parameter will also be influenced by this effect.

From the magnetic structure it is difficult to determine a value for the coordination number z . Using a Heisenberg model with $z = 6$, OO-theory accounts for the experimental values with the exchange constant given in the table. This J is to be compared to $I^2N(0)G$ when we expect an RKKY type exchange interaction. There is good agreement for both Er and Ho except for a numerical factor.

As the RR curve near $x = 1$ in fig. 2 is very steep, small deviations in the exact Er concentration due to different preparation conditions as reported in ref. 1 can have the dramatic effects mentioned on superconducting and magnetic properties. Experiments below 1 K are in progress in order to determine the low temperature part of the phase diagrams, particularly for testing the validity of the OO-model. More details about the susceptibility curves at the superconducting transition will be treated elsewhere.

We thank Mr. R. Rosman for participating in the experiments.

REFERENCES

- 1) S. Miraglia, J.L. Hodeau, M. Marezio, H.R. Ott, J.P. Remeika: Sol. St. Comm. **52** (1984) 135.
- 2) E.P. Houwman, A.W.M. van de Pasch and J. Flokstra: Physica B (1987) to be published.
- 3) D.H.A. Blank and J. Flokstra: paper presented at this conference.
- 4) A.A. Abrikosov and L.P. Gorkov: Sov. Phys. JETP **12** (1961) 1243.
- 5) W.A. Roshen and J. Ruvalds: Phys. Rev. **B31** (1985) 2929.
- 6) T. Oguchi and T. Obokata: J. Phys. Soc. Jpn. **27** (1969) 1111.