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Magnetic phase diagram of $ErNi_2B_2C$

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Abstract

The magnetic phase diagram of the superconductor $ErNi_2B_2C$ ($T_c = 11$ K and $T_N = 6$ K) has been studied by neutron diffraction as a function of temperature and magnetic field applied along the symmetry directions [0 1 0], [1 1 0] and [0 0 1] of the tetragonal crystal structure. A series of commensurate magnetic structures, consistent with a transversely polarized spin–density wave with modulation vectors $\boldsymbol{Q} = n/m\boldsymbol{a}^*(0.55 \leqslant n/m < 0.60)$ and the spins along $\boldsymbol{b}^*$, have been observed. The experimental data are compared with the results of a mean-field model that has been established from an analysis of bulk magnetization and zero-field neutron diffraction data. The model accounts for most of the observed features but fails to explain the occurrence of a small component $\boldsymbol{Q}_\delta \approx -0.005\boldsymbol{b}^*$ observed close to H_{c2} when the field is applied along [1 1 0].

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1. Introduction

In the borocarbides, $RENi_2B_2C$ with RE = Dy, Ho, Er and Tm, superconductivity and antiferromagnetism coexist at comparable temperatures $6\text{ K} \leqslant T_c \leqslant 16$ K and $1.5\text{ K} \leqslant T_N \leqslant 11$ K [1]. $ErNi_2B_2C$ has attracted attention because magnetization studies have indicated weak ferromagnetism below $T_c = 2.3$ K in zero field and because several magnetic phases develop in an applied magnetic field [2]. Neutron diffraction studies in zero field [3] have corroborated these results and confirmed the earlier findings [1] that the magnetic phases are characterized by a transversely polarized spin-density wave with an ordering vector $\boldsymbol{Q} \approx 0.55\boldsymbol{a}^*$ (or $\boldsymbol{b}^*$) and the spins lying in the basal plane of the tetragonal crystal structure. If $\boldsymbol{Q} = 0.5\boldsymbol{a}^*$ was a stable configuration the magnetic structure would consist of ferromagnetic sheets, and since the unit cell contains two Er-ions the stacking sequence would be double layers: up-up-down-down etc. However, nesting at the Fermi surface [4] results in phases with $\boldsymbol{Q} \geqslant 0.55\boldsymbol{a}^*$ and introduces phase slips in the stacking of the commensurate sequences.

Recently a mean-field model has been established and shown to account for most of the observed experimental data [5]. The model suggests that the magnetic transitions result from a series of structures with ordering vectors $\boldsymbol{Q} = n/m\boldsymbol{a}^*$ (or $\boldsymbol{b}^*$) with $0.55 \leqslant n/m \leqslant 0.60$. The present neutron diffraction study aims to establish the modulation vectors of the stable magnetic phases and to compare the results with the predictions of the

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mean-field model. A detailed account of these studies will be published elsewhere [6].

2. Experimental details and mean-field model

A single crystal of approximate size $2\times2\times0.5$ mm^3 was prepared as described in Ref. [7]. The neutron diffraction experiments were performed at BENSC using the E1 triple axes spectrometer and a 4 T horizontal cryomagnet for fields along [0 1 0] and [1 1 0], and the E4 two-axes spectrometers with a 14.5 T vertical cryomagnet for fields along [0 0 1]. Monochromator and analyzer crystals were pyrolythic graphite and typical collimations were 40–60 in., resulting in longitudinal and transverse resolutions between 0.005 and 0.010 rlu.

The mean-field model described in details in Ref. [5], includes crystal field parameters, RKKY-exchange, the classical dipole–dipole interaction, and a quadrupole coupling. Crystal-field and quadrupole parameters have been established from neutron scattering and X-ray experiments. The exchange coupling has been derived from a fitting of the bulk magnetization [2,7] and neutron diffraction data [3].

3. Results and discussion

Two stable structures have been identified with ordering vector $\boldsymbol{Q} = 11/20\boldsymbol{a}^*$ (or $\boldsymbol{b}^*$) in zero field [5]. Above $T_c = 2.3$ K there is an equal number of up and down spins, but below T_c one of the spin directions becomes more populated, leading to weak ferromagnetism. At low temperatures the structures are squared-up and not sinusoidal as they are close to T_N.

A field applied along [0 1 0] results in the formation of two different domains. Since the spins are Ising like the most favorable domain has $\boldsymbol{Q} = n/m\boldsymbol{a}^*$. When increasing the field H more up-spins are formed. At 1.8 K, $\boldsymbol{Q}$ changes from 16/29 $\boldsymbol{a}^*$ in zero field to $4/7\boldsymbol{a}^*$ in the field range between 7 and 11 kOe, and is followed by a change to 10/17 $\boldsymbol{a}^*$ for 11 kOe$< H <$ 13 kOe. Above 13 kOe and below the paramagnetic transition at 20 kOe, $\boldsymbol{Q}$ reverts to $4/7\boldsymbol{a}^*$. The transitions and phases change gradually with temperature and at 4 K the $4/7\boldsymbol{a}^*$ phase appears only near 9 kOe and transforms into a phase with $\boldsymbol{Q} \approx 18/31\boldsymbol{a}^*$ for 11 kOe$< H <$ 20 kOe. The transverse domain stays at $\boldsymbol{Q} \approx 16/29\boldsymbol{b}^*$ and decreases gradually in intensity as the field is increased. The H–T phase diagram agrees with data derived from bulk measurements [2,7,8].

When applied along [0 0 1] the critical field for the antiferromagnetic phase is as high as ~170 kOe at 1.8 K. The phase diagram, studied in fields up to 120 kOe (the magnetic torque detached the crystal at higher fields), shows a gradual change of $\boldsymbol{Q}$ from $\approx$11/20 to $\approx 5/9\boldsymbol{a}^*$ (or $\boldsymbol{b}^*$) as the field and/or the temperature is increased.

Studies performed with the field along the [1 1 0] direction reveal a series of ordering vectors $\boldsymbol{Q} = \boldsymbol{Q}_p + \boldsymbol{Q}_\delta$ as a function of field and temperature. The principal ordering vector $\boldsymbol{Q}_p$ along $\boldsymbol{a}^*$ or $\boldsymbol{b}^*$ range from $\boldsymbol{Q}_p \approx 11/20$ to $\approx$18/31 rlu, as shown in Fig. 1a. A peculiarity is the small, but clearly observable rotation of the principal ordering vector $\boldsymbol{Q}_p$ by an orthogonal component $\boldsymbol{Q}_\delta$, which occurs close to and above the superconducting critical field, H_{c2}.

The mean-field model has been a valuable tool in the interpretation of the neutron diffraction and the bulk magnetization data. It accounts for the stability of many of the observed phases; however, it fails to account for the small finite $\boldsymbol{Q}_\delta$ shown in Fig. 1b.

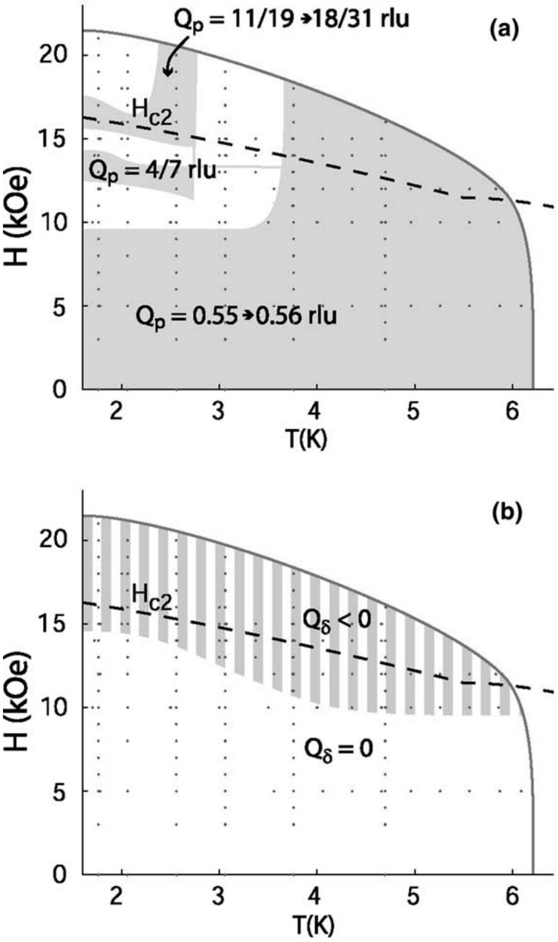

Fig. 1. Magnetic phase diagram of ErNi$_2$B$_2$C with the magnetic field applied along the [1 1 0] direction. Single-phase regions are marked in (a) with their different values of the principal component, $\boldsymbol{Q}_p$, of the ordering vector; remaining regions are multiphased. A small orthogonal component $\boldsymbol{Q}_\delta \approx -0.005$ rlu develops in the streaked region of the phase diagram shown in (b).

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