PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 58, Nos 5 & 6
May & June 2002
pp. 907–911

Magnetism and superconductivity in $ErNi_2B_2C$

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Abstract. We have performed a series of neutron diffraction experiments from the magnetic order and the vortex lattice in single crystal $ErNi_2B_2C$. The incommensurate magnetic structure develops additional even harmonics below the 'ferromagnetic' ordering temperature, T_F of 2.3 K. This feature and the existence of rods of diffuse scattering suggest the development of ferromagnetic microdomain walls. The magnetic structure is very sensitive to the application of a magnetic field with changes in modulation vector and harmonic content. Studies of the vortex lattice show the presence of a 45° reorientation transition and a distorted hexagonal to square transition as a function of applied field. Further distortions of the vortex lattice occur at T_N, but no changes are seen at T_F.

Keywords. (RE)Ni_2B_2C; $ErNi_2B_2C$; vortex lattice; non-locality; magnetism; superconductivity.

PACS Nos 74.25.Ha; 74.60.-w; 74.70.Dd; 75.25.+z

1. Introduction

Superconductivity is usually destroyed very easily by small amounts of magnetic impurities when the Cooper pair is scattered by the localised magnetic potential and the paired-particle destroyed to form two individual electrons. However, for a range of ternary and higher compounds with ordered magnetic ground states, it is possible for superconductivity to coexist with the ordered magnetic state. This usually occurs in systems where the two effects are related to electrons associated with different sublattices in the material. For example, in the $RENi_2B_2C$ [1] compounds the magnetism arises from the $4f$ electrons associated with RE ions, while the electrons which pair to form the superconducting state are believed to be associated with the $3d$ electrons from the Ni. However, these processes usually only allow superconductivity to easily coexist with antiferromagnetism and in most cases an attempt to form a ferromagnetic component to the magnetism rapidly destroys the superconducting state.

$ErNi_2B_2C$ is an important material in the investigation of the influence of correlations between superconductivity and magnetism. It becomes superconducting at 10.8 K and then develops an a-axis modulated incommensurate magnetic state below 5.8 K. Below 2.3 K, there is also a ferromagnetic component to the magnetism. In this paper we report some of the features observed in a series of neutron diffraction studies of the magnetic ordering and the morphology of the vortex lattice in $ErNi_2B_2C$. The studies of the magnetic ordering and vortex lattice morphology were performed using the D10, D23 and D22 instruments of the Institut Laue Langevin in Grenoble, France.

2. Magnetic structure

$ErNi_2B_2C$ orders magnetically at 5.8 K with an incommensurate magnetic modulation vector of 0.554 along the *a* (or *b*) direction. The magnetic structure is a transverse polarised spin density wave with the magnetic moments along the *b* direction and the modulation periodicity along the *a* direction, or vice versa because of twinning. The incommensurate modulation produces a pattern of ∼18–19 unit cells and ∼36–38 spins, or rather ferromagnetically aligned planes, but with every second spin reversed. The system rapidly 'squares up' as the temperature is lowered as observed in neutron diffraction experiments by the occurrence of odd harmonics of the modulation.

A spontaneous, weak ferromagnetic component below $T_F = 2.3$ K in $ErNi_2B_2C$ has been suggested because of a change of slope in the specific heat [2] and from the magnetic field dependence of the magnetisation [3]. In neutron diffraction this change in magnetic character is illustrated by the appearance of 'even' harmonics of the modulation which increase in intensity below 1.8 K. Figure 1 shows the presence of odd harmonics above 2.3 K and the coexistence of odd and even harmonics below this temperature. Recently, polarised neutron measurements have confirmed that these even harmonics have magnetic character [4] and are therefore not associated with a coupling between the spin density wave and the crystallographic lattice. These even harmonics are believed to be associated with the formation of ferromagnetic domain walls where neighbouring spin planes which should be antiferromagnetically aligned flip the spins in one plane to produce a biplane of

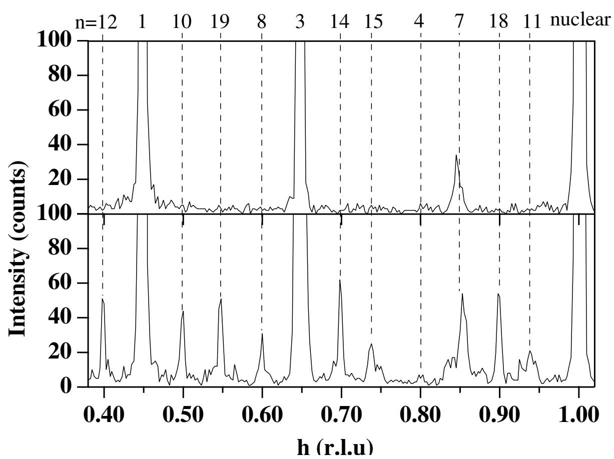

Figure 1. Parts of neutron diffraction scans along the [h01] direction for $ErNi_2B_2C$ at 2.5 K (upper trace) and 1.7 K (lower trace). The index *n* corresponds to harmonic order of the magnetic modulation. The higher temperature data shows the development of a squared moment distribution while below T_F even harmonics of the modulation become obvious.

ferromagnetic alignment. In addition to the even harmonics, we observe rods of ferromagnetic elastic scattering along the [100] and [010] directions below T_F, which are believed to be due to variations in the positions of the microdomain walls and possibly a lack of correlation between the directions of the wall magnetisation, at least in zero field. Such rods of diffuse scattering, with no intensity modulation along the rod, correspond to the presence of uncorrelated two dimensional objects. The whole spin arrangement must respond to these new features; this is illustrated by a change in the intensities of the odd harmonics as these features increase in importance. Normally such a model would be checked by modelling the diffraction intensity profile of the various odd and even harmonics; however it has so far not been possible to produce a unique model of the moment arrangement.

The presence of these ferromagnetic microdomain walls and their partially uncorrelated nature would probably explain the observation of enhanced pinning below T_F [5–8]. Their presence would also possibly allow the establishment of a spontaneous vortex state in zero applied field. An understanding of any changes in magnetic order as a function of applied field is obviously a requirement for such studies. As can be seen from figure 2, there is considerable readjustment in terms of harmonic content and modulation vector as a function of applied field, and it should be stressed that these changes are very dependent on the relative orientation of the applied field to the crystal. It is worth noting that one of the metamagnetic spin rearrangements appears to correlate directly with H_{C2} for this temperature and orientation.

3. Vortex lattice

Borocarbide crystals tend to be of a rather high quality with minimal pinning, which allows rather subtle features of the vortex lattice in the mixed state to be clearly observed. In particular, these materials are an ideal system for the observation of non-local effects.

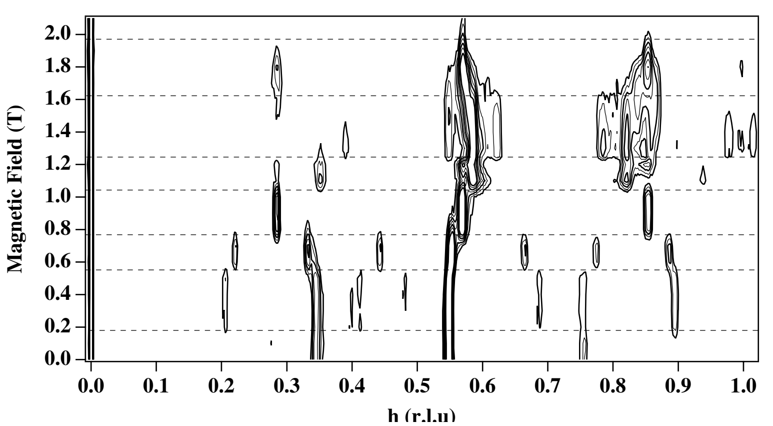

Figure 2. Logarithmic contours of neutron diffraction intensities along [h02] as a function of applied field ($H \parallel [100]$) at 1.2 K for $ErNi_2B_2C$. This data illustrates the flexibility of the magnetic structure in its response to an applied field and the formation of the vortex state. Note the distinct change at H_{C2} of 1.3 T.

Early studies of $ErNi_2B_2C$ demonstrated that there existed a transition from a distorted hexagonal to square arrangement in the morphology of the vortex lattice [9]. A slightly later study [10] demonstrated that this transition was not directly related to the presence of magnetism since it also existed in YNi_2B_2C. Further, this work also confirmed the presence of lower field 45° reorientation transition for the rhombic lattice unit cell, as predicted by non local models of the vortex lattice morphology in tetragonal materials [11,12]. The sensitivity of the morphology of the vortex lattice to changes in the non-local character of the superconductivity suggests that such studies may be a useful tool to probe the connection between superconductivity and magnetism.

Figure 3 shows neutron small angle diffraction patterns from the vortex lattice in $ErNi_2B_2C$ at various temperatures and applied fields. This is the first time that all three possible alignments and morphologies have been observed for this material. The applied field for the hexagonal to square transition in this material is rather temperature dependent showing continuity through T_F but a distinct and sharp dip at T_N, before rising again in the paramagnetic state to meet the extrapolated line from lower temperatures. This effect is presumably due to a well-defined change in coherence length associated with the onset of the magnetic ordering [13], as seen for magnetic fields along the *c*-direction in the paramagnetic state of $TmNi_2B_2C$ at low temperatures when the magnetic susceptibility is large.

Previous studies of the vortex lattice [14] through T_F seemed to indicate that there were large changes in the orientation and mosaic width of the vortex lattice as a function of temperature and applied magnetic field even with the applied field aligned along the *c*-direction. In our experiments, we used high harmonics of the magnetic order to accurately align the crystal orientation against the neutron beam and the vortex lattice to align the field from the electromagnet against the neutron beam and hence the crystal. In this way we are sure that the field is along the *c*-axis to within 0.2°. We find no large changes in reflection rocking curve width or direction of the mean field in the crystal on cooling the sample

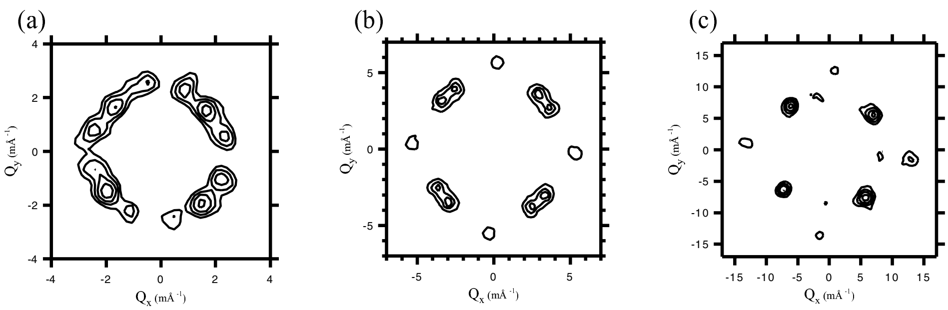

Figure 3. Diffraction patterns from the vortex lattice in $ErNi_2B_2C$ as produced by field cooling through T_C with the applied field along the *c* direction and annealed by field 'wiggling'. These data illustrate the changes in morphology of the vortex lattice as a function of applied magnetic field (**a**) data taken at 4 K and 20 mT showing two domains of a distorted hexagonal lattice with the unit cell diagonal along the [100] direction, (**b**) data taken at 5.8 K and 200 mT again showing two domains of a distorted hexagonal lattice but with the unit cell diagonal along [110] directions and (**c**) a single domain square lattice observed at 2 K and 450 mT.

below T_F. Presumably, the previous studies were measuring the influence of a misalignment either through the chopping of the flux-lines into smaller, easier to pin portions of flux-lines created by intersection at an angle with the ferromagnetic microdomain walls or the scattering from the domain walls themselves.

4. Concluding remarks

The borocarbide superconductors display most of the features associated with the coexistence of magnetism and superconductivity and the interaction between these two fundamental quantities. In particular, $ErNi_2B_2C$ appears to be an ideal system for such studies. Neutron diffraction experiments of both the variations in magnetic order and changes in the morphology of the vortex lattice in the mixed state have and will supply considerably detailed information on the distribution of magnetic moments and magnetic field within such superconductors. There has been a considerable body of theoretical work on the influence of magnetism on the bulk superconducting properties. Experiments are now sampling these effects and their interactions at a microscopic level and require further and extended theoretical models and calculations.

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