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Superconductivity and the magnetic phase diagram of $DyNi_2B_2C$ at very low temperatures

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Abstract

Detailed measurements of the resistivity ρ_{ab} as a function of temperature, magnetic field and orientation have been carried out on single crystals of tetragonal bodycentered $DyNi_2B_2C$. From the angular dependence of the metamagnetic transitions a magnetic phase diagram has been obtained. For $B\|[1\,0\,0]$, an anomalously large hysteresis effect of the metamagnetic and also of the superconducting transitions were observed in the low temperature range ($T < 2$ K). This large hysteresis leads to a reentrant behavior of the superconductivity in small external fields, which indicate a strong interplay between magnetism and superconductivity in $DyNi_2B_2C$.

Keywords: Superconductivity; Magnetic phase diagram; Borocarbides

The field dependence of the resistivity of a superconducting [1–3] $DyNi_2B_2C$ single crystal ($T_c \leqslant 7$ K) was measured at 1.4 K for different orientations of the magnetic field with respect to the magnetic easy $[1\,1\,0]$ axis. The superconductivity is suppressed by a magnetic field of 0.7 T. In the normal state there is a step in the resistivity at about 1.4 T with a weak angular dependence. For $\theta \geqslant 20^\circ$ and $B \geqslant 1.5$ T the resistivity shows a plateau followed by a step-like decrease. This decreasing step in the resistivity shows a strong angular dependence and the corresponding transition diverges as $\theta \Rightarrow 45^\circ$. Both steps correspond to metamagnetic transitions between phases with different net distributions of the Dy magnetic moments. A third transition was recently observed by magnetization measurements at $T = 2$ K and slightly smaller fields [4]. The angular dependencies of the described metamagnetic transitions obtained from resistivity and susceptibility measurements at 1.4 K are summarized in Fig. 1. Depending upon the angle θ between the applied magnetic field and the $[1\,1\,0]$ axis, up to three transitions can be observed. The two low field transitions are bounded while the third transition diverges as $\theta \Rightarrow 45^\circ$. The low field phase has been identified by neutron diffraction experiments [5] with the antiferromagnetic phase (AFM), which we denote as $\uparrow\downarrow$, where $\uparrow$ is a moment along the $[1\,1\,0]$ axis and $\downarrow$ is a moment along the $[\bar{1}\,\bar{1}\,0]$ axis. For magnetic field directions near to the $[1\,1\,0]$ axis we expect a saturated paramagnetic (or ferromagnetic (FM)) state $\uparrow\uparrow$ in the high field limit. For magnetic field directions near to the $[1\,0\,0]$ axis we expect a canted structure $\uparrow\rightarrow$ of the magnetic moments in the easy directions, where $\rightarrow$ is a moment along the $[\bar{1}10]$ axis. This expectation is experimentally confirmed by magnetization measurements [4] which show in this high field phase MM3 a magnetization $M \cong M_s/\sqrt{2}$. The net distribution of moments in the intermediate metamagnetic states MM1 and MM2 cannot be predicted definitely but the most probable net moment distribution in agreement with magnetization data is $\rightleftharpoons\rightleftharpoons\rightleftharpoons\uparrow\uparrow$ in MM2 and $\rightleftharpoons\rightleftharpoons\rightleftharpoons\uparrow\rightarrow$ in MM1, respectively. The angular dependencies of the magnetic fields $B_{MM'}$ which bind different phases M and M′ follow simple trigonometric functions. The fitted dependencies are

$$B_{A1} = \frac{0.81T}{\cos(\theta - 45^\circ)},$$

$$B_{A2} = \frac{1.00T}{\cos(\theta)},$$

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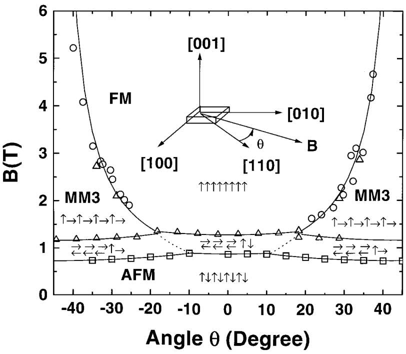

Fig. 1. Angular dependence of critical magnetic fields for $DyNi_2B_2C$ at $T = 1.4\,K$. Circles: $B_{3F}(\theta)$ from resistivity; triangles: $B_{13}(\theta)$ and $B_{2F}(\theta)$ from resistivity; squares: $B_{A1}(\theta)$ and $B_{A2}(\theta)$ from magnetization [1].

$$B_{12} = \frac{0.85T}{\sqrt{2}\cos(\theta + 45^\circ)},$$

$$B_{13} = \frac{1.18T}{\cos(\theta - 45^\circ)},$$

$$B_{2F} = \frac{1.26T}{\cos(\theta)},$$

$$B_{3F} = \frac{0.85T}{\sqrt{2}\cos(\theta + 45^\circ)}$$

which are shown as solid lines in Fig. 1.

The large hysteresis of the metamagnetic phases, especially the MM3 phase, in the orientation $B||[1\,0\,0]$ is best seen at lowest temperatures. In $\rho(B)$ curves at lowest temperatures one sees up to three step-like resistivity changes which belong to the superconducting or metamagnetic transitions, respectively. The transition B_{13} and due to that also the superconducting transition display increasing hysteresis – up to $\Delta B_{c2} = 0.6\,T = B_{c2}^{inc} - B_{c2}^{dec}$ – at 0.05 K which is shown in Fig. 2. We believe that the stability of the metamagnetic phase MM3 down to $B \approx 0.1\,T$ at lowest temperature is responsible for the depression of superconductivity down to the transition field of the MM3 phase. This behavior of the MM3 phase boundary B_{13} leads to parabolic shaped $B_{c2}(T)$ for decreasing field which predicts the reentrant behavior shown in Fig. 3 . Before the measurements of Fig. 3 B was increased from 0 to 2 T at temperature $T = 0.05\,K$, and then decreased down to various constant fields B_0 between $B_{c2}(T = 0.05\,K)$ and $B_{c2}^{max}(T = 2\,K)$ so that the sample will remain in the normal state. Fig. 3 shows the following superconducting transition with increasing temperature and then the return to the normal state at higher temperature.

For a more detailed discussion of the described superconducting and magnetic behavior of $DyNi_2B_2C$ see for instance Ref. [6].

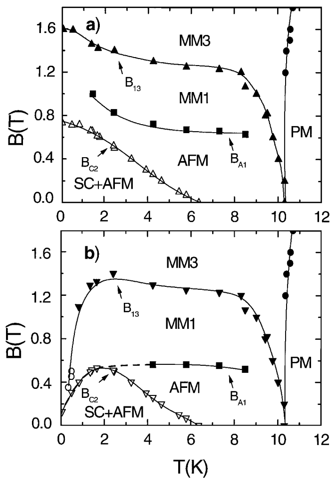

Fig. 2. (a) Phase diagram for $DyNi_2B_2C$ derived from the field-increasing part of $\rho_{ab}(B)$ with $B||[1\,0\,0]$; (b) phase diagram derived from the field-decreasing part of $\rho_{ab}(B)$ curves. The solid lines drawn through the data points serve as a guide to the eye. The value of $B_{A1}(T)$ at temperatures below 4 K cannot be determined by our resistivity measurements. The dashed line is proposed to be a possible boundary between AFM and MM1.

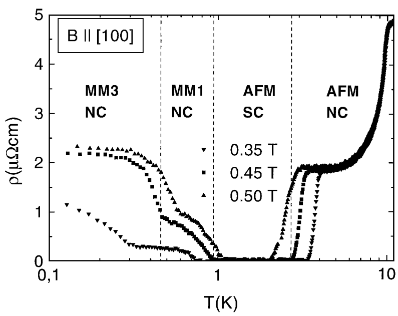

Fig. 3. Measurement of $\rho_{ab}(T)$ after the procedure described in the text. The dashed lines emphasize the transitions into the labeled metamagnetic phases at the fixed field of $B_0 = 0.45\,T$.

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