Specific heat in the mixed state of non-magnetic borocarbides

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Abstract

The temperature and magnetic field dependence of the specific heat $c_p(T,H)$ in the superconducting (sc) mixed state has been measured for polycrystalline $Y_xLu_{1-x}Ni_2B_2C$ and $Y(Ni_{1-y}Pt_y)_2B_2C$ samples. The deviations from the usual linear-in-H law of the linear-in-T electronic specific heat contribution $\gamma(H)\cdot T$ can be possibly ascribed to unconventional pairing. The $\gamma(H)$ dependence is discussed in the unitary d-wave scenario as well as in the intermediate transition region in between dirty and clean s-wave limits. From a consideration of $\gamma(H)$ data, unconventional pairing cannot be ruled out.

Key words: unconventional superconductivity; borocarbides; specific heat

The unusual shape of the upper critical field $H_{c2}(T)$ near T_c, the nearly T^3 scaling of the electronic specific heat $c_{es}(T)$ in the sc state and the negative curvature of $\gamma(H)$ point to a possible unconventional ordering parameter in borocarbides [1,2]. The observed $\gamma(H) \propto \sqrt{H}$-law for YNi_2B_2C and $LuNi_2B_2C$ was regarded initially as evidence for d-wave pairing [3,4], the disorder related transition from a $\sqrt{H}$ to a linear-in-H dependence was subsequently used to rule out d-wave superconductivity in non-magnetic borocarbides [5]. Nevertheless, we discuss the deviation from the linear $\gamma(H)$ behaviour in the framework of unconventional superconductivity. It has been recently pointed out that possibly an unconventional mechanism is responsible for superconductivity in borocarbides [6,7].

Polycrystalline $Y_xLu_{1-x}Ni_2B_2C$ with $x = 0$, 0.25, 0.5, 0.75, 1, and $Y(Ni_{1-y}Pt_y)_2B_2C$ samples with $y = 0$, 0.05, 0.1, 0.15, 0.2, 0.25, 0.5, and 0.75 were prepared by a standard arc melting technique. A detailed description of the sample preparation is given in Ref. [2]. The specific heat was measured between $4.2\,\mathrm{K} \le T \le 20\,\mathrm{K}$ increasing the temperature after the samples were cooled down from $T > T_c$ in applied fields $\mu_0 H \le 8\,\mathrm{T}$ using a quasi-adiabatic step heating technique.

The $\gamma(H)$-values obtained by extrapolating c_p/T vs. T^2 curves are represented in Fig. 1. For all samples

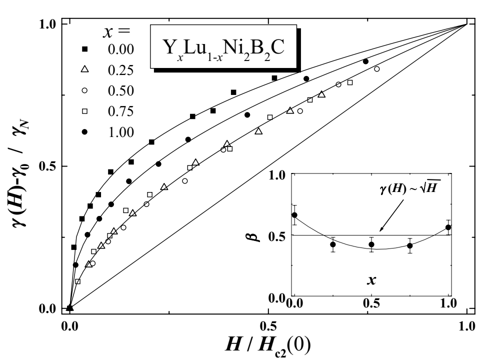

Fig. 1. Magnetic field dependence of the specific heat contribution $\gamma(H)$ of the vortex core electrons in the mixed state ($H \le H_{c2}$) normalized by the Sommerfeld value γ_N and $H_{c2}(0)$ for $Y_xLu_{1-x}Ni_2B_2C$. Residual $\gamma_0 = \gamma(H=0)$ values have been subtracted. The inset shows the curvature parameters $\beta(x)$ according to $\gamma(H) - \gamma_0 \propto H^{1-\beta}$.

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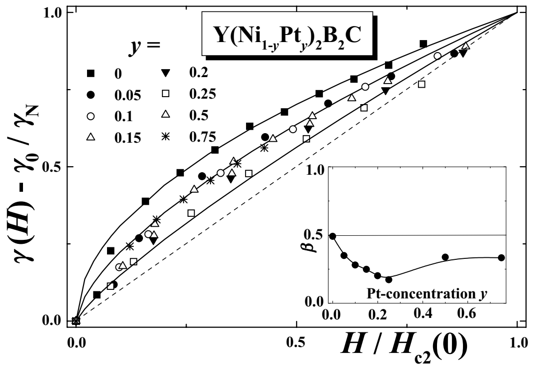

Fig. 2. Field dependence of the specific heat contribution $\gamma(H)$ in the mixed state for $Y(Ni_{1-y}Pt_y)_2B_2C$. The inset shows the curvature parameters $\beta(y)$ according to $\gamma(H) - \gamma_0 \propto H^{1-\beta}$.

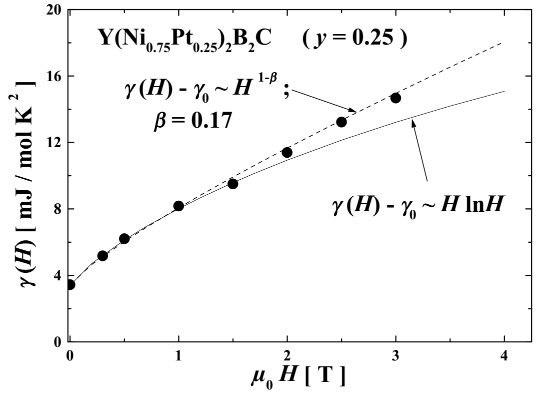

Fig. 3. Magnetic field dependence of $\gamma(H)$ for $Y(Ni_{0.75}Pt_{0.25})_2B_2C$. The solid line is a fit according to $\gamma(H) - \gamma_0 \propto H \ln H$. The dashed line is a fit according to $\gamma(H) - \gamma_0 \propto H^{1-\beta}$ with $\beta = 0.17$.

$\gamma(H)$ is a sublinear function of H. β measures the sublinearity (*i.e.* a negative curvature) of $\gamma(H)$ according to $\gamma(H) - \gamma_0 \propto H^{1-\beta}$. We obtained a reduction of β caused by structural disorder (replacement of Y by Lu). Similar results are obtained by the isoelectronical substitution of Ni by Pt (see Fig. 2). We note that our curvatures for $LuNi_2B_2C$ and YNi_2B_2C exceed slightly the value of $\beta = 0.5$ representing the $\sqrt{H}$-dependence. To the best of our knowledge the strong sublinearities for $\gamma(H)$, measured by the exponent β, of the borocarbides under consideration are the largest reported so far for any superconductor except for the related system MgB_2 ($\beta = 0.77$) [8]. The observed $\gamma(H) \propto H^{1-\beta}$ law with $\beta \approx 0.5$ points to unconventional pairing responsible for this peculiarity since according to Ref. [9] $\gamma(H) \propto \sqrt{H}$ is a signature for a nodal gap with d-wave symmetry while $\gamma(H) \propto H$ is usually expected for superconductors with isotropic s-wave order parameter. According to Refs. [10,11] Volovik's clean limit d-wave approach can be generalized to describe also strong impurity scattering. Then at low magnetic fields $H \ll H_{c2}(0)$ the specific heat coefficient $\gamma(H)$ follows a $H \ln H$ dependence. Our data can be described equally well by these $H \ln H$ dependence for $H/H_{c2}(0) \leq 0.3$ as well as by the $H^{1-\beta}$ behaviour. This is shown in Fig. 3: obviously, the $H\ln H$ behaviour is not very distinct from the power law at low fields $\mu_0 H \leq 1.5$ T. At higher H the $H\ln H$ dependence may deviate since it was derived for low $H \ll H_{c2}(0)$, only [10]. Hence, unconventional pairing cannot be ruled out in nonmagnetic borocarbides on grounds of $\gamma(H)$ data.

Remarkably, a sublinear $\gamma(H)$-law has been reported also for MgB_2 [8,12] and has been addressed theoretically for a clean s-wave two-band superconductor (TBSC)[13]. It was found that β depends sensitively on the ratio of the two gaps of the strongly and weakly coupled bands. That appealing picture proposed for MgB_2 might be transferred to borocarbides under consideration which are also well-known TBSC's [14].

To summarize, specific heat data at low magnetic fields are discussed in the context of a dirty d-wave scenario as well as within the conventional extended s-wave picture in the intermediate transition region in between the clean and the dirty limits. At low fields the $H\ln H$ dependence of $\gamma(H)$ predicted for d-wave pairing in the dirty (unitary) limit is not very distinct from the $H^{1-\beta}$ behaviour which favores s-wave superconductivity in that transition region. Thus, considering results on $\gamma(H)$, a possible unconventional pairing in borocarbides cannot be ruled out. This conclusion is also supported by the recent observation of point nodes in the gap function of YNi_2B_2C in magnetic field dependent thermal conductivity measurements [7].

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