Anisotropic magnetic behavior of $GdBa_2Cu_3O_{6+y}$ single crystals

Vladimir N. Narozhnyi [a, b,1], Dieter Eckert [a], Günter Fuchs [a], Vladimir Nekvasil [c], Karl-Hartmut Müller [a]

[a] *Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden, PO Box 270116, D-01171 Dresden, Germany*
[b] *Institute for High Pressure Physics, Russian Academy of Sciences, Troitsk, Moscow Region, 142190, Russia*
[c] *Institute of Physics, Czech Academy of Sciences, Cukrovarnická 10, 16253 Praha 6, Czech Republic*

Abstract

Magnetic properties of high-quality Al-free nonsuperconducting $GdBa_2Cu_3O_{6+y}$ single crystals grown by flux method have been studied. The magnetic anisotropy below the Néel temperature $T_N \approx 2.3$ K corresponds to the direction of Gd^{3+} magnetic moments along the tetragonal c-axis. At $T < T_N$ clear indications of spin-flop transitions for $H \parallel c$ have been observed on magnetization curves at $H_{sf} \approx 10$ kOe. Magnetic phase diagrams have been obtained for $H \parallel c$ as well as for $H \perp c$. A pronounced anisotropy in the magnetic susceptibility (unexpected for Gd-based compounds) has been found above T_N.

Key words: $GdBa_2Cu_3O_{6+y}$; magnetic anisotropy; spin-flop transition; single crystal

Collinear antiferromagnetic ordering was found for $GdBa_2Cu_3O_{6+y}$ (Gd1236) with the Gd magnetic moments directed along the c-axis [1,2]. So far magnetism in Gd1236 single crystals were studied on Al-containing samples [3] or by indirect methods (e.g., NMR [4]). However, the reported results are controversial.

In this work we report on the magnetic properties of high quality Al-free nonsuperconducting Gd1236 single crystals grown in Pt crucibles by the flux method [5]. Atomic absorption spectroscopy has shown that the Pt contamination does not exceed $3 \cdot 10^{-3}$ at. % [6]. To reduce the oxygen concentration the samples were annealed at $T = 600$ C under high vacuum during 4 days. The magnetization M was measured by SQUID magnetometer. The data are compared with the results obtained earlier for $PrBa_2Cu_3O_{7-y}$ (Pr123) [7] as well as for the Gd-sublattice of mixed $Gd_{1-x}Pr_xBa_2Cu_3O_{7-y}$ [(Gd-Pr)123] single crystals [6].

The temperature dependence of susceptibility $\chi = M/H$, shown in Fig. 1 for two directions of the magnetic field H, has a maximum at $T \approx T_N$. The position of the maximum is field dependent. The anomaly is more pronounced for $H \parallel c$ (at least for small fields), which corresponds to the c-axis direction of the Gd^{3+} magnetic moments (in accord with neutron diffraction and Mössbauer spectrometry [1,2]). The maximum in

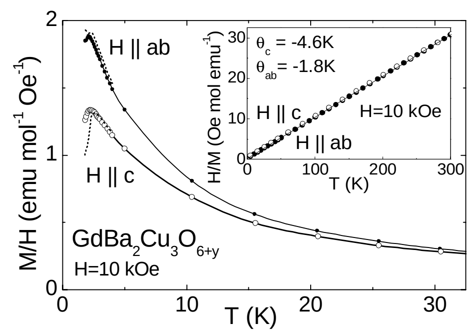

Fig. 1. Temperature dependence of the magnetic susceptibility (determined as M/H at $H = 10$ kOe) of a $GdBa_2Cu_3O_{6+y}$ single crystal for $H \parallel c$ (open circles) and $H \perp c$ (full circles). Dotted lines - the data for $H = 1$ kOe. Inset: temperature dependence of inverse magnetic susceptibility H/M. The line shows the best fit to the Curie-Weiss law for $H \perp c$.

[1] Corresponding author. Present address: Leibniz-Institut für Festkörper- und Werkstoffforschung Dresden, PO Box 270116, D-01171 Dresden, Germany. E-mail: narozh@ifw-dresden.de

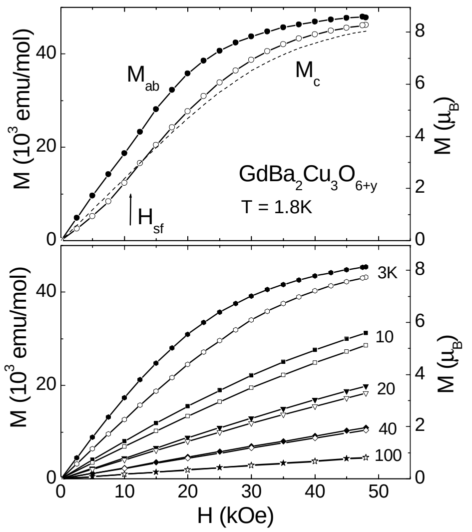

Fig. 2. Magnetization of the $GdBa_2Cu_3O_{6+y}$ single crystal for $H \parallel c$ (open symbols) and $H \perp c$ (full symbols). Full lines are guides for eye. The dashed line shows the data for $H \parallel c$ at $T = 2.4$ K which is slightly above T_N.

$\chi(T)$ disappears for $H \geq 15$ kOe at $T \geq 1.8$ K.

The $\chi^{-1}(T)$ curves can be well fitted to the Curie-Weiss law $\chi^{-1}(T) = (T - \theta)/C$ for $5 \leq T \leq 300$ K. The values of θ and the effective magnetic moment $m_{\rm eff}$ (determined from the Curie constants C) are -4.6 K and 8.90 $m_{\rm B}$ and -1.8 K and 8.88 $m_{\rm B}$ for $H \parallel c$ and $H \perp c$, respectively. $m^c_{\rm eff}$ and $m^{ab}_{\rm eff}$ are very close to each other as expected for the spin-only magnetic moment of Gd. The values of $m_{\rm eff}$ are little higher than the value of the free Gd^{3+} ion. This difference may be connected with some error in determination of the small mass of the sample ($m = 0.50$ mg; the accuracy of mass determination in this case is about 10%).

The anisotropy in χ in paramagnetic state is clearly seen in this figure. Phenomenologically the observed anisotropy can be connected with the difference between $\theta_{\rm c}$ and $\theta_{\rm ab}$. (From the fit the accuracy in θ determination is better than 0.1 K.) It is found that $|\theta_{\rm c}| > |\theta_{\rm ab}|$. The sign of magnetic anisotropy for Gd1236 is the opposite to the observed for Pr123 [6,7]. The different signs of magnetic anisotropy for Gd- and Pr-sublattices explain the crossover of magnetic anisotropy reported for (Gd-Pr)123 single crystals [6].

$M(H)$ curves clearly show an anisotropy below as well as above $T_{\rm N}$, see Fig. 2. At lowest T there is a clear tendency for isotropization in high fields. $M_{\rm ab} > M_{\rm c}$ is in accord with our data obtained earlier from subtraction of (Y-Pr)123 data from (Gd-Pr)123 results [6]. The general agreement with these previously indirectly obtained results on the magnetization of the Gd-sublattice is fair. Even the values and the anisotropy of θ correspond well to the directly measured for Gd1236.

Below $T_{\rm N}$, a distinct indication of a spin-flop transition can be seen for $H \parallel c$, see Fig. 2. The spin-flop field $H_{\rm sf}$ was determined as an inflection point of the $M(H)$ dependence at $T < T_{\rm N}$. $H_{\rm sf}$ is practically temperature independent in the studied temperature interval, see Fig. 3. As expected, the spin-flop transition disappears above $T_{\rm N}$. No anomaly has been detected for $H \perp c$ at all T.

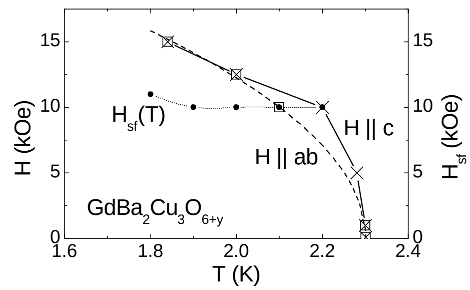

Fig. 3. Magnetic phase diagram of $GdBa_2Cu_3O_{6+y}$ for $H \parallel c$ (crosses and full line) and $H \perp c$ (open squares and dashed line). The temperature dependence of the spin-flop field is shown by the dotted line and full circles.

A magnetic phase diagram is constructed from the field dependence of $T_{\rm N}$, determined for two directions of H (see Fig. 3). The field dependence of $T_{\rm N}$ for $H \perp c$ is described by a quadratic dependence similar to that observed by us earlier for Pr-1237 [7]. Below $H_{\rm sf}$ the $T_{\rm N}(H)$ dependence for $H \parallel c$ is weaker than for $H \perp c$. At the same time above $H_{\rm sf}$ the $T_{\rm N}(H)$ dependencies are close for both directions of H.

The pronounced magnetic anisotropy found for Gd1236 may be connected with several mechanisms including: (i) dipole-dipole interaction of the Gd ions; (ii) interaction between Gd and Cu sublattices; (iii) anisotropic exchange interaction; (iv) crystal-field effects on the excited Gd^{3+} states. Further investigations are necessary to clarify the situation.

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