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Influence of Pressure on Superconductivity in YB_6

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Magnetoresistivity measurements on a superconducting system of YB_6 ($T_c \approx 7.5$ K) down to 60 mK at hydrostatic pressures up to 47 kbar are presented. The superconducting transition temperature, as well as the third critical field H_{c3} reveal a linear decrease with increasing pressure with slopes of $d\ln H_{c3}/dp = -1.1$ %/kbar, and $\mathrm{d}\ln T_c/\mathrm{d}p = -0.59$ %/kbar. From the latter a critical pressure, $p_c \approx 170$ kbar, at which T_c vanishes, is determined.

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Among large number of boron-rich binary compounds MB_x ($x \geq 6$), superconductivity has been observed only in eight systems: MB_6 (M = Y, La, Th, Nd) and MB_{12} (M = Sc, Y, Zr, Lu) [1]. Among these, yttrium hexaboride (YB_6) exhibits the highest transition temperature, $T_c \geq 7$ K [2]. In recent years some of the properties of YB_6 have been intensely investigated, such as the specific heat, resistivity, magnetic susceptibility and thermal expansion [2], optical properties [3], the electronic band structure [4, 5] and point-contact spectra [6]. From these studies we can conclude that YB_6 is a conventional type-II BCS superconductor, where the strong coupling in Cooper pairs with $2\Delta/k_BT_c \approx 4.0$ is mediated by the phonon mode of Y atoms located at ≈ 8 meV.

To our knowledge there is a single experimental study of the pressure (p) effect on the superconducting properties of YB_6 [7]. In particular, the effect on transition temperature T_c, the upper critical field H_{c2}, and the magnetic penetration depth λ has been measured up to 9.2 kbar. It was shown that T_c, $H_{c2}(0)$, and the coherence length $\xi(0) \propto H_{c2}(0)^{-1/2}$ change linearly with pressure as follows: $dT_c/dp = -0.055$ K/kbar, $dH_{c2}/dp = -4.84$ mT/kbar and $\mathrm{d}\xi(0)/\mathrm{d}p = 0.28$ nm/kbar, respectively. No pressure effect on $\lambda(0) = 199.0$ nm was observed within the experimental accuracy. This implies that one of the fundamental parameters of superconductors, the Ginzburg-Landau parameter $\kappa(0) = \lambda(0)/\xi(0)$, which establishes the border between type-I and type-II, is pressure dependent and decreases linearly with pressure. Thus pressure “softens” the YB_6 superconductor and drives it towards type-I superconductivity.

We present the investigations of the influence of the hydrostatic pressure on the behavior of magnetoresistivity in YB_6 at significantly higher pressures, up to 47 kbar. As a result we obtain the pressure dependence of superconducting transition temperature T_c and the third critical field, $H_{c3}(0)$.

A high-quality single crystal of YB_6 was grown by the rf-heat floating zone method in the atmosphere of argon at a pressure of 5 bar. The high pressure experiments were performed in a piston cylinder cell-PCC ($p \leq 22$ kbar) and in a diamond anvil cell-DAC ($p \geq 30$ kbar). Golden wires were spot-welded on the sample under a microscope thanks to hydraulic micromanipulators. Daphne oil or liquid argon as pressure transmitters and Pb or ruby manometers were used in PCC and DAC, respectively. The temperature and magnetic field dependences of the resistance between 2 and 300 K were performed in a PPMS instrument (Quantum Design, USA), where the commercial resistivity sample holder was adapted for DAC. The electrical resistivity was measured in a home-made dilution ^{3}He-^{4}He minirefrigerator below 2 K down to 60 mK. Four probe ac measurement was carried out thanks to special current source with an active common mode reduction (Pico Precision, Slovakia).

Resistive measurements in magnetic field were performed in a configuration favourable for measurement of the third critical field, H_{c3}, i.e. with the current and voltage probes placed on surface parallel with the applied magnetic field. In our case, when $H_{c2}(0) = 280$ mT was obtained by the specific heat measurements [6], the ratio of $H_{c3}(0)/H_{c2}(0) = 1.6$ is quite close to the theoretical value of 1.695. We assume the same pressure and temperature dependence of the both, H_{c3} and H_{c2} quantities. The third critical field has been determined from the magnetoresistive superconducting transitions at the steepest slope, around 50% of the normal state resistance $R(H)$ (see Fig. 1).

Figure 2 shows the resulting temperature dependences of $H_{c3}(T)$ at pressures of 4.5, 14, 22, 30 and 47 kbar, generated in PCC and DAC. This graph reveals a systematic decrease of the zero-field transition temperature

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T_c, as well as of the zero-temperature value of H_{c3} with increasing pressure (some of $H_{c3}(0)$ values were extrapolated from WHH fits [8], as shown in Fig. 2). The $H_{c3}(T)$ curves taken at different pressures are not parallel but their slope near $T_c(0)$ systematically decreases with increasing pressure. This is related to the fact that pressure effect on the upper critical field is significantly higher than that on T_c. Both quantities decrease linearly in the measured pressure range. The linear fits give $\mathrm{d}T_c/\mathrm{d}p = -0.044$ K/kbar. Note that this value is smaller than $\mathrm{d}T_c/\mathrm{d}p = -0.055$ K/kbar obtained by Khasanov et al. [7] on a sample with $T_c = 6.6$ K, but the latter was measured only up to 9.2 kbar. The relative change of the transition temperature with pressure is $\mathrm{d}\ln T_c/\mathrm{d}p = -0.59$ %/kbar. The linear fit of the pressure dependence of H_{c3} yields $\mathrm{d}H_{c3}/\mathrm{d}p = -4.64$ mT/kbar and the relative change $\mathrm{d}\ln H_{c3}/\mathrm{d}p = -1.1$ %/kbar. The critical pressure, at which critical temperature should vanish, $T_c = 0$, is extrapolated to $p_c \approx 170$ kbar.

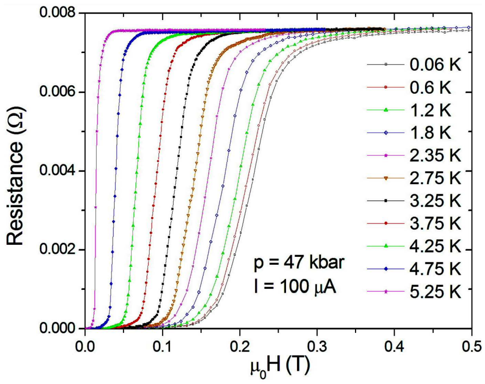

Fig. 1. Field dependences of resistance of YB$_6$ at the highest applied pressure of 47 kbar.

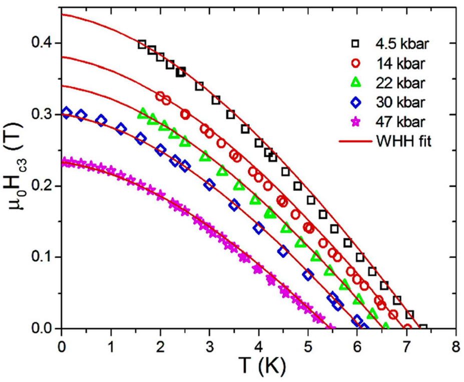

Fig. 2. Temperature dependences of the third critical field at different pressures. Red lines represent WHH fits.

Xu et al. [5] have performed extensive *ab initio* studies of the effect of pressure on the electronic, vibrational and superconducting properties of YB$_6$ up to 400 kbar. Their theory predicts a negative pressure effect on T_c with a coefficient of $-(0.024 \div 0.027)$ K/kbar in the pressure range 0–200 kbar, which is approximately two times smaller than in our case. Above 200 kbar the same theory predicts much slower decrease of T_c with steepness of $-(0.003 \div 0.011)$ K/kbar. In this respect it is worth noting that our slope $\mathrm{d}T_c/\mathrm{d}p$, observed up to 47 kbar, is weaker than that observed by Khasanov et al. [7] at pressures up to 9.2 kbar. Taking into account a quadratic pressure dependence of volume in YB$_6$ [5], our T_c vs. p dependence can be also fitted by the quadratic relation. Then, this gives $\Delta T_c/\Delta p \approx -0.031$ K/kbar in pressure range of 0–200 kbar and $p_c \approx 325$ kbar, which gives a better agreement of the observed experimental data with the theoretical studies [5]. Xu et al. have also shown that a dominant contribution to the electron-phonon interaction of YB$_6$, coming from low-lying Einstein-like vibrations of Y atoms, being at about 8 meV at ambient pressure, will be shifted to higher energies with pressure. Thus, the negative pressure effect on T_c can be well described by the hardening of Y phonons. The experiments which are under way will help to clear this point.

In conclusion, the magnetoresistive measurements at pressures up to 47 kbar have shown a negative linear pressure effect on the transition temperature and the third critical field. This behavior seems to be due to hardening of the Einstein-like Y phonon mode, responsible for the electron-phonon coupling. Further experiments are needed to corroborate this.

Acknowledgments

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