Pressure induced softening of YB$_6$: pressure effect on the Ginzburg-Landau parameter $\kappa = \lambda/\xi$

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Measurements of the transition temperature $T_c$, the second critical filed $H_{c2}$ and the magnetic penetration depth $\lambda$ under hydrostatic pressure (up to 9.2 kbar) in the YB$_6$ superconductor were carried out. A pronounced and negative pressure effects (PE) on $T_c$ and $H_{c2}$ with $dT_c/dp = -0.0547(4)$ K/kbar and $\mu_0dH_{c2}(0)/dp = -4.84(20)$ mT/kbar, and zero PE on $\lambda(0)$ were observed. The PE on the coherence length $d\xi(0)/dp = 0.28(2)$ nm/kbar was calculated from the measured pressure dependence of $H_{c2}(0)$. Together with the zero PE on the magnetic penetration depth $\lambda(0)$, our results imply that the Ginzburg-Landau parameter $\kappa(0) = \xi(0)/\lambda(0)$ depends on pressure and that pressure "softens" YB$_6$, e.g. moves it to the type-I direction.

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The Ginzburg-Landau parameter $\kappa = \lambda/\xi$ ($\lambda$ is the magnetic penetration depth and $\xi$ is the coherence length) is one of the fundamental parameters for superconductors. The parameter $\kappa$ establishes the border between type-I ($\kappa < 1/\sqrt{2}$) and type-II ($\kappa > 1/\sqrt{2}$) superconductors by determining point where the surface energy, associated with the domain wall between the superconducting and the normal state areas, changes their sign from "plus" to "minus". Remarkably, two physical quantities entering $\kappa$ ($\lambda$ and $\xi$) depend on different properties of the superconducting material. Indeed, for BCS superconductors the zero temperature coherence length obeys the relation

$$\xi(0) = \frac{\hbar \langle v_F \rangle}{\pi \Delta(0)}, \quad (1)$$

Here, $\langle v_F \rangle$ is the average Fermi velocity and $\Delta(0)$ is the zero temperature value of the superconducting energy gap. The zero-temperature penetration depth is given by

$$\frac{1}{\lambda^2(0)} = \frac{e^2}{\pi^2 \hbar c^2} \int_{S_F} ds |v_F(s)|, \quad (2)$$

where the integral runs over the Fermi surface $S_F$. Assuming spherical Fermi surface Eq. (2) reduces to

$$\lambda^{-2}(0) \propto S_F \langle v_F \rangle. \quad (3)$$

A quick glance to Eqs. (1) and (3) reveal that $\lambda(0)$ is determined by the normal state properties only [$S_F$ and $\langle v_F \rangle$] while $\xi(0)$ is determined by both – the normal $\langle |v_F| \rangle$ and the superconducting $\Delta(0)$ state properties of the material. This means that if one would be able to affect only the superconducting (normal) state properties, the Ginzburg-Landau parameter $\kappa$ will change. As a consequence, superconductors can be driven to the more type-I or to the more type-II directions.

Experiments under pressure open a possibility to probe this phenomena. The reason for this can be understood by considering the simple metal superconductors, like Sn, In, Pb, Al, etc., where the conduction electrons possess $s$, or $p$ character. Since the $s$ and $p$ electrons in simple metals are nearly free, one expects approximately $v_F \propto S_F \propto V^{+2/3}$ ($V$ is the unit cell volume). For typical values of the bulk modulus $B = 400-800$ kbar [2] it leads to $d \ln v_F/dp = d \ln S_F/dp = 2/3 \cdot B^{-1} = 0.08-0.17 \%$/kbar. Note that this effect is almost one order of magnitude smaller than the corresponding pressure effect on $T_c$: Sn ($d \ln T_c/dp = -1.3.0 \%$/kbar), In ($-1.12 \%$/kbar), Pb ($-0.51 \%$/kbar), Al ($-2.47 \%$/kbar) [1]. Taking into account this and the fact that within BCS theory $\Delta(0)$ is simply proportional to $T_c$ ($2\Delta(0)/k_B T_c = 3.52$, see e.g. [1]), Eq. (1) implies that the pressure shift of the coherence length $\xi(0)$ is almost the same as the one of $T_c$

$$\frac{d \ln \xi(0)}{dp} = \frac{d \ln \langle v_F \rangle}{dp} - \frac{d \ln \Delta(0)}{dp} = \frac{2}{3} B^{-1} - \frac{d \ln T_c}{dp}. \quad (4)$$

From the other hand, the pressure effect on $\lambda(0)$ [see Eq. (3)] is determined by the pressure induced change of the Fermi surface and the Fermi velocity

$$\frac{d \ln \lambda(0)}{dp} = \frac{1}{2} \frac{d \ln S_F}{dp} - \frac{1}{2} \frac{d \ln \langle v_F \rangle}{dp} = \frac{2}{3} B^{-1}, \quad (5)$$

which appears to be an order of magnitude smaller as shown above. Thus, the much bigger pressure effect (PE) on $\xi(0)$ in comparison with the one on $\lambda(0)$ implies pressure dependence of the Ginzburg-Landau coefficient $\kappa(0)$.

Here we report studies of the effect of pressure on the Ginzburg-Landau coefficient $\kappa$ in YB$_6$ superconductor. It was found that with increasing pressure from 0 to 9.2 kbar $\kappa(0)$ decreases by an almost 8% [from 6.17(5) to 5.70(4)], implying that pressure drives YB$_6$ to the type-I direction. The pressure effects on two quantities entering $\kappa(0)$ [\(\xi(0)/\lambda(0)\) and $\xi(0)$] were studied separately. It was
obtained that the PE on $\kappa(0)$ arises mostly from the pressure dependence of the coherence length $\xi(0)$, while no PE on the magnetic penetration depth $\lambda(0)$ (within the experimental accuracy) was observed. It was also found that in BCS superconductors for which the absolute value of the pressure shift of $T_c$ is much bigger than $1/B$, the pressure shifts of the superconducting quantities such as $T_c$, $\kappa(0)$, $\xi(0)$, $H_{c2}(0)$, $dH_{c2}/dT|_{T=T_c}$ are related to each other.

Details on the sample preparation for YB$_6$ single crystal can be found elsewhere [7]. The sample was mixed with Fluorient FC77 (pressure transmitting medium). In both below described experiments the sample-to-liquid volume ratio was of approximately 1/6.

The field–cooled (FC) and zero-field cooled (ZFC) magnetization measurements were performed with a SQUID magnetometer in fields ranging from 0.5 mT to 0.3 T and at temperatures between 1.75 K and 10 K. Two sets of magnetization under pressure experiments were performed. In the first one, small parts of the main single crystal together with the small piece of In (pressure indicator) were added to the pressure cell. In these experiments the pressure dependences of the transition temperature $T_c$ and the upper critical field $H_{c2}$ were studied. In the second set, the part of the single crystal was grounded in mortar and then sieved via 10 µm sieve in order to obtain small grains needed for determination of $\lambda$ from magnetization measurements.

Figure 1 shows the temperature dependences of the low-field (0.5 mT FC) magnetization (a), upper critical field $H_{c2}$ (b) and magnetic penetration depth $\lambda$ (c) measured at different pressures. In the following we briefly discuss each dependence separately.

With increasing pressure magnetization curves shifts almost parallel to the lower temperatures implying the negative pressure effect on the transition temperature $T_c$ [see Fig. 1(a)]. The corresponding pressure dependence of $T_c$ is shown in the inset. $T_c$ was taken from the linearly extrapolated $M(T)$ curves in the vicinity of $T_c$ with the $M = 0$ line. The linear fit yields $dT_c/dp = -0.0547(4)$ K/kbar. Note that this value is in good agreement with $dT_c/dp \approx -0.053(8)$ K/kbar obtained indirectly by Lortz et al. [8] from thermal expansion measurements.

The values of the second critical field $H_{c2}(T)$ presented in Fig. 1(b) were extracted from the FC magnetization curves $M(T,H)$ measured in constant magnetic fields ranging from 0.5 mT to 0.3 T. For each particular field $H$ the corresponding transition temperature $T_c(H)$ was determined as described above [see Fig. 1(a)]. The value of the field $H$ was then attributed to be the upper critical field $H_{c2}$ at the temperature $T = T_c$. The solid lines represent fits of the WHH model [9] to the experimental data. The values of the upper critical field at $T = 0 \ [H_{c2}(0)]$ obtained from the fits are plotted in the inset as the function of pressure. The linear fit yields $\mu_0 dH_{c2}/dp = -4.84(20)$ mT/kbar. The values of $T_c$ and $H_{c2}(0)$ measured at various pressures are summarized in Table 1.

![Fig. 1](image_url)

**FIG. 1:** (Color online) Temperature dependences of the low-field (0.5 mT FC) magnetization (a), upper critical field $H_{c2}$ (b) and magnetic penetration depth $\lambda$ (c) measured at different pressures. Inserts show the corresponding pressure dependences of $T_c$ and the zero-temperature values of $H_{c2}(0)$ and $\lambda(0)$ (see text for an explanation).
The temperature dependences of $\lambda$ were calculated from the measured 0.5 mT ZFC magnetization by using the Shoenberg formula [3]:

$$\chi = -\frac{3}{2} \left( 1 - \frac{3\lambda}{R} \coth \frac{R}{\lambda} + \frac{3\lambda^2}{R^2} \right),$$  

(6)

where $\chi = M/HV$ is the volume susceptibility, $V$ is the volume of the sample and $R$ is the mean radius of the grains. The reducing of the grain size with pressure was taken into account in $\lambda(T)$ calculation [Eq. (6)] by using the bulk modulus value $B = 1900$ kbar [12]. Due to unknown $R$, the value of $\lambda$ at $T = 1.7$ K and $p = 0$ was normalized to $\lambda(1.7$ K$)=202$ nm obtained from muon-rotation experiments [10]. In order to obtain the zero temperature values of $\lambda$ the low temperature part of the data were fitted by the standard s-wave BCS model:

$$\frac{\Delta\lambda(T)}{\lambda(0)} = \sqrt{\frac{\pi\Delta(0)}{2k_BT}} \exp\left(-\frac{\Delta(0)}{k_BT}\right).$$  

(7)

In order to decrease the number of the fitting parameters it was assumed that $\Delta(0)$ scales with $T_c$ as $2\Delta(0) = 4.02k_BT_c$ [11]. Note that the independence of the ratio $2\Delta(0)/k_BT_c$ of pressure was recently confirmed for RbOs$_4$O$_6$ [13] and ZrB$_{12}$ [14] BCS superconductors. The resulting $\lambda(0)$ vs. $p$ dependence is shown in the inset of the Fig. (1c). The linear fit yields $d\lambda(0)/dp = 0.22(33)$ nm/kbar. This implies that within the accuracy of the experiment $\lambda(0)$ does not depend on pressure. The mean value of $\lambda(0)$ was found to be 199.4(1.5) nm.

Using the obtained values of $H_{c2}(0)$ (see Table I), the Ginzburg-Landau coherence length at $T=0$ K was calculated according to [1]:

$$\xi(0) = \sqrt{\frac{\Phi_0}{\pi H_{c2}(0)}},$$  

(8)

where $\Phi_0$ is the magnetic flux quantum. The values of $\kappa(0)$ were further calculated by using $\lambda(0) = 199.4(1.5)$ nm. It is seen (see Fig. 2) that $\kappa(0)$ decreases almost linearly from 6.17(5) at ambient pressure to 5.70(4) at $p = 9.18$ kbar. The decrease of $\kappa$ thus implies that pressure "softens" the YB$_6$ superconductor by driving it to the type-I direction.

One should note that the observation of a zero pressure effect on $\lambda(0)$, suggests that almost the whole PE on $\lambda(0)$ in YB$_6$ is determined by the pressure dependence of $\xi(0)$. The PE on $\xi(0)$ is twofold. First of all, by neglecting the first term at the right hand side of Eq. (4), one can easily see that the absolute value of the PE on $\xi(0)$ is expected to be the same as the one on $T_c$. Second, the absolute value of $\xi(0)$ was determined from the measured $H_{c2}(0)$ by means of Eq. (5) implying, that the PE on $H_{c2}(0)$ is twice as big as the PE on $\xi(0)$ and, as a consequence, twice as big as the PE on $T_c$. The value of $H_{c2}(0)$, however, is not uniquely determined by $T_c$. Various superconductors, having similar $T_c$-s, can have the upper critical fields values that are different by a few orders of magnitude. According to the WHH theory $H_{c2}(0) \propto T_c \cdot dH_{c2}/dT|_{T=T_c}$ so that the following relation holds

$$\frac{d\ln H_{c2}(0)}{dp} = \frac{d\ln [dH_{c2}/dT|_{T=T_c}]}{dp} + \frac{d\ln T_c}{dp} = -2\frac{d\ln \xi(0)}{dp}. $$  

(9)

This implies that in superconductors for which the absolute value of the pressure shift of $T_c$ is much bigger than $1/B$ the pressure shifts of the superconducting quantities such as $T_c$, $\kappa(0)$, $\xi(0)$, $H_{c2}(0)$, $dH_{c2}/dT|_{T=T_c}$ are not in-
experiments were performed for RbOs to check the validity of Eq. (10), similar pressure
κ and also analyzed the on the transition temperature
T
dependence for MgB
2
from 0.05%/kbar [12], the YB
6
superconductor and drives it in the type-I direction. It was also shown that in BCS superconductors for which the absolute value of the pressure shift of Tc is much bigger than 1/B, pressure induced shifts of the superconducting quantities such as Tc, κ(0), ξ(0), Hc2(0), dHc2/dT|T=Tc are related to each other.

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The pressure coefficients for the superconducting transition temperature Tc, for the second critical field Hc2(0) and for the coherence length ξ(0) turned out to be dTc/dp = −0.0547(4) K/kbar, μ0dHc2(0)/dp = −4.84(20) mT/kbar and dξ(0)/dp = 0.28(2) nm/kbar, respectively. No pressure effect on λ(0) = 199.4(1.5) was observed within the experimental accuracy. This implies that the Ginzburg-Landau parameter κ(0) = λ(0)/ξ(0) is pressure dependent, decreasing from 6.17(5) at ambient pressure to 5.70(4) at p = 9.2 kbar. Thus, pressure softens the YB6 superconductor and drives it in the type-I direction. It was also shown that in BCS superconductors for which the absolute value of the pressure shift of Tc is much bigger than 1/B, pressure induced shifts of the superconducting quantities such as Tc, κ(0), ξ(0), Hc2(0), dHc2/dT|T=Tc are related to each other.

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Table I: Summary of the pressure effect results (see text for details).

| p (kbar) | Tc (K) | p0Hc2(0) (mT) | p0dHc2/dTξ(0)Kstrom | κ(0) (nm) |
|---------|--------|---------------|----------------------|-----------|
| 0.0     | 6.589(3)| 315.0(1.7)    | 66.0(1.1)            | 32.32(17) |
| 2.77    | 6.450(3)| 301.0(1.7)    | 63.9(1.2)            | 32.07(19) |
| 4.16    | 6.360(3)| 292.9(1.3)    | 62.2(1.0)            | 33.52(15) |
| 7.63    | 6.186(3)| 278.7(1.7)    | 61.3(1.3)            | 34.37(21) |
| 9.92    | 6.100(2)| 272.2(1.6)    | 60.7(1.6)            | 34.77(20) |
| 9.18    | 6.087(3)| 268.5(1.8)    | 59.6(1.2)            | 35.01(21) |

To summarize, measurements of the pressure effect on the transition temperature Tc, the second critical field Hc2 and the magnetic penetration depth λ were performed on the YB6 superconductor. It was obtained that Tc, Hc2(0) and the coherence length ξ(0) ∝ Hc2(0)−1/2 change linearly with pressure. The pressure coefficients for the superconducting transition temperature Tc, for the second critical field Hc2(0) and for the coherence length ξ(0) turned out to be dTc/dp = −0.0547(4) K/kbar, μ0dHc2(0)/dp = −4.84(20) mT/kbar and dξ(0)/dp = 0.28(2) nm/kbar, respectively. No pressure effect on λ(0) = 199.4(1.5) was observed within the experimental accuracy. This implies that the Ginzburg-Landau parameter κ(0) = λ(0)/ξ(0) is pressure dependent, decreasing from 6.17(5) at ambient pressure to 5.70(4) at p = 9.2 kbar. Thus, pressure softens the YB6 superconductor and drives it in the type-I direction. It was also shown that in BCS superconductors for which the absolute value of the pressure shift of Tc is much bigger than 1/B, pressure induced shifts of the superconducting quantities such as Tc, κ(0), ξ(0), Hc2(0), dHc2/dT|T=Tc are related to each other.

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