Effect of Pressure on the Ginzburg-Landau Parameter $\kappa = \lambda/\xi$ in YB_6

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Measurements of the transition temperature T_c , the upper critical field H_{c2} , and the magnetic penetration depth λ under hydrostatic pressure (up to ≈ 9.2 kbar) in the YB_6 superconductor were carried out. A pronounced and negative pressure effect (PE) on T_c and H_{c2} with $dT_c/dp = -0.0547(4)$ K/kbar and $\mu_0 dH_{c2}(0)/dp = -4.84(20)$ 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 $\kappa = \lambda/\xi$ (λ is the magnetic penetration depth and ξ is the coherence length) is one of the fundamental parameters for superconductors. The parameter κ establishes the border between type-I ($\kappa < 1/\sqrt{2}$) and type-II ($\kappa > 1/\sqrt{2}$) superconductors by determining the point where the surface energy, associated with the domain wall between the superconducting and the normal state areas, changes its sign from “plus” to “minus.” Remarkably, two physical quantities entering κ (λ and ξ) depend on different properties of the superconducting material. Indeed, for BCS superconductors the zero-temperature coherence length obeys the relation [1]

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

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 [2,3]

$$\frac{1}{\lambda^2(0)} = \frac{e^2}{\pi^2 \hbar c^2} \oint_{S_F} ds |\mathbf{v}_F(s)|, \quad (2)$$

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

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

A quick glance at Eqs. (1) and (3) reveals 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 were able to affect only the superconducting (normal) state properties, the Ginzburg-Landau parameter κ would 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 $S_F \propto v_F^2 \propto V^{-2/3}$ (V is the unit cell volume). For Sn, In, Pb, and Al, values of the bulk modulus B lie in the range 400–800 kbar [4] leading to $|d \ln S_F / dp| = 2 |d \ln v_F / dp| = 2/3 B^{-1} \approx 0.08\% - 0.17\%/\text{kbar}$. Note that this effect is almost 1 order of magnitude smaller than the corresponding pressure effect on T_c : Sn ($d \ln T_c / dp = -1.30\%/\text{kbar}$), In ($-1.12\%/\text{kbar}$), Pb ($-0.51\%/\text{kbar}$), and Al ($-2.47\%/\text{kbar}$) [5]. 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 :

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

On 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

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

which appears to be an order of magnitude smaller as shown above. Thus, the large positive pressure effect (PE) on $\xi(0)$ together with the small positive effect on $\lambda(0)$ implies a strong negative pressure dependence of the Ginzburg-Landau coefficient $\kappa(0)$.

Here we report studies of the effect of pressure on the Ginzburg-Landau coefficient κ in the single-band, isotropic BCS YB_6 superconductor [6]. It was found that with increasing pressure from 0 to 9.18 kbar, $\kappa(0)$ decreases by an almost 8% [from 6.16(5) to 5.68(4)]. The pressure effects on the two quantities entering $\kappa(0)$ [$\lambda(0)$ 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 relative pressure shift of T_c is much bigger than $1/B$, the pressure shifts of the superconducting quantities such as T_c , $\kappa(0)$, $\xi(0)$, $H_{c2}(0)$, and $dH_{c2}/dT|_{T=T_c}$ are related to each other.

Details on the sample preparation for YB₆ single crystal can be found elsewhere [6]. The hydrostatic pressure was generated in a copper-beryllium piston cylinder clamp especially designed for magnetization measurements under pressure [7]. The sample was mixed with Fluorinert FC77 (pressure transmitting medium). In both experiments described below, 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 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 ground in mortar and then sieved via a 10 μm sieve in order to obtain small grains needed for the determination of λ from magnetization measurements. The grain size distribution was determined by analyzing the scanning electron microscope photographs.

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 λ (c) measured at different pressures. In the following we briefly discuss each dependence separately.

With increasing pressure the magnetization curves shift 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.* [6] from thermal expansion measurements.

The values of the upper 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 Werthamer-Helfand-Hohenberg (WHH) model

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 λ (c) measured at (from the right to the left) 0.0, 4.16, and 9.18 kbar [panels (a) and (b)] and 0.60, 5.15, and 9.15 kbar [panel (c)]. The solid lines in (b) and (c) correspond to the fit of the WHH (Ref. [8]) and the low-temperature s -wave BCS [Eq. (7)] models to the experimental data, respectively. Insets 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).

[8] 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 $\mu_0 dH_{c2}(0)/dp = -4.84(20)$ mT/kbar. The values of T_c and $H_{c2}(0)$ measured at various pressures are summarized in Table I.

The temperature dependence of λ was calculated from the measured ZFC magnetization curves ($\mu_0 H = 5$ mT) by using the Shoenberg formula [9], modified for the known grain size distribution $N(R)$ [10]:

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

p (kbar)	T_{c0} (K)	$\mu_0 H_{c2}(0)$ (mT)	$\mu_0 dH_{c2}/dT$ (mT/K)	$\xi(0)$ (nm)	$\kappa(0)$
0.0	6.589(3)	315.0(1.7)	66.0(1.1)	32.32(17)	6.16(5)
2.77	6.456(3)	301.0(1.7)	63.9(1.2)	33.07(19)	6.02(5)
4.16	6.369(3)	292.9(1.3)	63.2(1.0)	33.52(15)	5.94(4)
7.63	6.186(3)	278.7(1.7)	61.3(1.3)	34.37(21)	5.79(5)
8.92	6.100(2)	272.2(1.6)	60.7(1.6)	34.77(20)	5.72(4)
9.18	6.087(3)	268.5(1.8)	59.6(1.2)	35.01(21)	5.68(4)

$$\chi = -\frac{3}{2} \int_0^\infty \left(1 - \frac{3\lambda}{R} \coth \frac{R}{\lambda} + \frac{3\lambda^2}{R^2} \right) N(R) R^3 dR \Big/ \int_0^\infty N(R) R^3 dR, \quad (6)$$

where $\chi = M/HV$ is the volume susceptibility and V is the volume of the sample. The reducing of the grain size with pressure was taken into account in the $\lambda(T)$ calculation [Eq. (6)] by assuming $R \propto B^{-1/3}$. The value of the bulk modulus $B = 1900$ kbar was estimated from the Fig. 2 of Ref. [11]. In order to obtain the zero-temperature values of λ the low-temperature part of the data was fitted by the standard s -wave BCS model:

$$\frac{\Delta\lambda(T)}{\lambda(0)} = \sqrt{\frac{\pi\Delta(0)}{2k_B T}} \exp\left(-\frac{\Delta(0)}{k_B T}\right). \quad (7)$$

In order to decrease the number of the fitting parameters it was assumed that $\Delta(0)$ scales with T_c as $2\Delta(0) = 4.02k_B T_c$ [12]. Note that the independence of the ratio $2\Delta(0)/k_B T_c$ on pressure was recently confirmed for RbOs_2O_6 [13] and ZrB_{12} [14] BCS superconductors. The resulting $\lambda(0)$ vs p dependence is shown in the inset of the Fig. 1(c). The linear fit yields $d\lambda(0)/dp = 0.33(44)$ 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 199.0(1.9) nm. Note that according to Eq. (5) we expect an increase in the penetration depth with pressure of the order of 0.3% at $p \approx 10$ kbar. However, such a small change of the penetration depth is well within the range of error of the present experiment [15].

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]

$$\xi(0) = \sqrt{\frac{\Phi_0}{2\pi H_{c2}(0)}}, \quad (8)$$

where Φ_0 is the magnetic flux quantum. The values of $\kappa(0)$ were further calculated by using $\lambda(0) = 199.0$ nm. It is seen (see Fig. 2) that $\kappa(0)$ decreases almost linearly from 6.16(5) at ambient pressure to 5.68(4) at $p = 9.18$ kbar. The linear fit yields $d\kappa(0)/dp = -0.049(5)$ kbar $^{-1}$. The decrease of κ 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 $\kappa(0)$ in YB_6 is determined by the pressure dependence of $\xi(0)$. The

PE on $\xi(0)$ is twofold. First, by neglecting the first term on 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. (8), implying that the PE on $H_{c2}(0)$ is twice as big as the PE on

FIG. 2 (color online). Pressure dependences of $\kappa(0)$ (a), and the relative pressure shifts $\Delta T_c/T_c$, $\Delta\kappa(0)/\kappa(0)$, $\Delta\xi(0)/\xi(0)$, $1/2\Delta H_{c2}(0)/H_{c2}(0)$, and $\Delta(dH_{c2}/dT|_{T=T_c})/(dH_{c2}/dT|_{T=T_c})$ (b). The solid line in (a) is a linear fit with the parameters shown in the Figure.

$\xi(0)$ 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 transition temperatures, can have upper critical fields values that are different by a few orders of magnitude. According to the WHH theory, $H_{c2}(0) \propto T_c dH_{c2}/dT|_{T=T_c}$ so that the following relation holds:

$$\begin{aligned} \frac{d \ln H_{c2}(0)}{dp} &= \frac{d \ln(dH_{c2}/dT|_{T=T_c})}{dp} + \frac{d \ln T_c}{dp} \\ &= -2 \frac{d \ln \xi(0)}{dp}. \end{aligned} \quad (9)$$

This implies that in superconductors for which $d \ln T_c / dp \gg 1/B$ the relative pressure shifts of the superconducting quantities such as T_c , $\kappa(0)$, $\xi(0)$, $H_{c2}(0)$, and $dH_{c2}/dT|_{T=T_c}$ are not independent but related to each other in accordance with

$$\begin{aligned} \frac{d \ln T_c}{dp} &\simeq \frac{d \ln \kappa(0)}{dp} \simeq -\frac{d \ln \xi(0)}{dp} \simeq \frac{1}{2} \frac{d \ln H_{c2}(0)}{dp} \\ &\simeq \frac{d \ln(dH_{c2}/dT|_{T=T_c})}{dp}. \end{aligned} \quad (10)$$

The YB₆ superconductor [$1/B = 1/1900$ kbar $\simeq 0.05\%/kbar$ (see above), $d \ln T_c / dp = -0.83(1)\%/kbar$ (see inset in Fig. 1(a) and Table I)] fulfills the above mentioned criteria. This implies that for YB₆ relation (10) is expected to be correct. A quick glance at Fig. 2(b) and Table I reveals that this is exactly the case. All the quantities entering Eq. (10) are almost equal to each other within the accuracy of the experiment. Equation (10) also implies that for extreme type-II superconductors ($\kappa \gg 1$) the transition from type-II to type-I superconductivity occurs at the *same pressure* where T_c vanishes [16]. Further investigations are needed to clarify this point.

Good agreement of the experimental data with the simple above presented approach suggests that in the BCS superconductors, where the condition $d \ln T_c / dp \gg 1/B$ holds, one needs to measure the pressure effect on T_c only. The pressure dependences of $H_{c2}(0)$, $dH_{c2}/dT|_{T=T_c}$, $\xi(0)$, and $\kappa(0)$ can then be obtained by using Eq. (10). In order to check the validity of Eq. (10), similar pressure experiments were performed for RbOs₂O₆ [17]. We have also analyzed the H_{c2} vs p dependence for MgB₂ from Ref. [18]. In both cases good agreement between the experimental data and Eq. (10) was observed.

To summarize, measurements of the pressure effect on the transition temperature T_c , the upper critical field H_{c2} , and the magnetic penetration depth λ were performed on the YB₆ superconductor. It was obtained that T_c , $H_{c2}(0)$, and the coherence length $\xi(0) \propto H_{c2}(0)^{-1/2}$ change linearly with pressure. The pressure coefficients for the superconducting transition temperature T_c , for the upper critical field $H_{c2}(0)$, and for the coherence length $\xi(0)$ turned out to be $dT_c/dp = -0.0547(4)$ K/kbar, $\mu_0 dH_{c2}(0)/dp =$

$-4.84(20)$ mT/kbar, and $d\xi(0)/dp = 0.28(2)$ nm/kbar, respectively. No pressure effect on $\lambda(0) = 199.0(1.9)$ nm was observed within the experimental accuracy. This implies that the Ginzburg-Landau parameter $\kappa(0) = \lambda(0)/\xi(0)$ is pressure dependent, decreasing from 6.16(5) at ambient pressure to 5.68(4) at $p = 9.18$ 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 relative pressure shift of T_c is much bigger than $1/B$, pressure induced shifts of the superconducting quantities such as T_c , $\kappa(0)$, $\xi(0)$, $H_{c2}(0)$, and $dH_{c2}/dT|_{T=T_c}$ are related to each other.

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