Pressure-dependent measurements in Superconductors

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Abstract. To evaluate the performance of a home-built miniature non-magnetic piston clamp cell we have carried out extensive low-temperature (1.5 to 10 K) measurements of the critical field, \(H_c\), for the element Pb up to a pressure of \(P = 1.2\) GPa. Surprisingly, such data has not previously been reported above 0.3 GPa. From this data the electronic entropy, specific heat, thermal expansion coefficient and compressibility is calculated as a function of temperature, pressure and magnetic field. The zero-field data is consistent with direct thermodynamic measurements and the \(P\)-dependence of \(T_c\) and specific heat coefficient, \(\gamma(T, P)\), allows the determination of the \(P\)-dependence of the pairing interaction. Using Pb as a manometer we investigated the pressure dependence of oxygen isotope effect on \(T_c\) for \(YBa_2Cu_4O_8\).

1. Introduction

The thermodynamic and superconducting properties of the metal Pb have been extensively studied, including specific heat[1, 2], isotope effect[3, 4], critical field[5] and thermal expansion[6]. In addition the effects of pressure on its superconducting properties have also been well studied[7, 8, 9]. Subsequently, the use of the pressure-dependent superconducting transition temperature \(T_c(P)\) for Pb as a low-temperature manometer has also been proposed[10]-[12]. The above quoted references are only the early ones and one would assume that the thermodynamic properties of this material have been comprehensively investigated.

In the course of investigations into the pressure dependence of the oxygen isotope effect on \(T_c\) for the high-

\(T_c\) superconductor \(YBa_2Cu_4O_8(Y124)[13]\) we used the metal Pb as an internal pressure calibrant. Using a clamp cell in a SQUID magnetometer we tracked the pressure using the reported pressure dependence of \(T_c\) for Pb[11]. Despite the many above-noted early studies on Pb we discovered that the pressure, \(P\), and temperature dependence of the critical field, \(H_c\), for Pb has not been reported except at very low pressures (\(\leq 0.3\) GPa)[7]. We therefore carried out a study of \(H_c(T, P)\) from 1.5 to 10 K and up to 1.2 GPa from which we have derived a full set of thermodynamic parameters. This paper presents a summary of these measurements and the deduced values of the \(T\)- and \(P\)- dependence of the electronic entropy, \(S(T, P)\), electronic specific heat coefficient, \(\gamma(T, P)\), thermal expansion coefficient, \(\alpha(T, P)\) and electronic compressibility, \(\kappa(T, P)\).

The electron-phonon interactions play an important role in the physics of high \(T_c\) superconductors and especially in the pairing interactions between carriers. The experimental situation remains ambiguous. A marked anomaly in both \(T_c[14, 15]\) and superfluid density
\( \rho_0 \) [15] has been observed due to isotope substitution in \( La_{2-x}Sr_xCuO_4 \) at a hole concentration of \( p = 0.125 \). The underdoped cuprates exhibit a remarkably large pressure dependence of \( T_c \) that is yet to be fully understood [16]. Y124 lies close to, but just above the 1/\( 8^{th} \) doping point where \( La_{2-x}Sr_xCuO_4 \) displays this marked anomaly in isotope effect. It also has a large \( dT_c/dP \) coefficient of \( \approx 5.5K/GPa \) [17, 16] and \( T_c \) rises to a maximum of 108K [18] between 9 and 12 GPa before falling at higher pressure. However, bond valence sums to characterize bond stresses leads to the conclusion that \( T_{c,max} \) has a negative (in-plane) pressure coefficient [19, 20]. There are thus anomalous pressure effects and anomalous isotope effects in underdoped cuprates. In the second part of this present work we bring these issues together to examine the pressure dependence of the oxygen isotope effect in Y124.

2. Lead

2.1. Experimental

The sample used was a bar of dimensions 1.1 \times 0.93mm cross section and 5.58mm long, shaped from Puratronic 99.9985%, 2 mm diameter Pb wire from Johnson Matthey. Using the formulae of Osborn the demagnetization factor [21] was calculated as 0.97 and this value was used throughout. The Pb sample was annealed in vacuum at 300 C for 8 hours to reduce magnetic hysteresis [5]. This was loaded in a 2.67 mm diameter 9 mm long Teflon capsule along with Fluorinert FC70 and FC77 mixed in 1:1 ratio as a cryogenic hydrostatic pressure medium. The sample capsule was then placed in a miniature home-built non-magnetic Be-Cu (Mico Metal 97.75% Cu, 2% Be) piston clamp cell (8.8mm diameter, 65mm length, with cobalt-free tungsten-carbide pistons (RoctecTM). The pistons of this cell are lightly tapered using electric-discharge machining [22]. To apply pressure the cell was preloaded before clamping at room temperature using a laboratory press with calibrated digital pressure gauge (Ashcroft Model 2089, 0.05% accuracy). The magnetization measurements were carried out in a Quantum Design MPMS SQUID magnetometer. The pressure in the sample was measured from the reported shift in \( T_c \) of Pb at zero field [11]. For in-field measurements the cell was always zero-field cooled to avoid hysteresis error.

2.2. Results

Fig. 1 shows the measured \( T \)-dependence of the magnetic moment, \( M \), up to a field of 700 G and at pressures of 0 GPa (1 bar), 0.5, 0.9 and 1.15 GPa. \( T_c \) was determined by the extrapolation to zero of the steepest slope of \( M(T) \). This gives \( T_c(H) \) which is re-plotted in Fig. 2 as \( H_c(T, P) \) versus \( T \). The data shows a progressive decline in both \( T_c \) and \( H_c(T) \) with increasing pressure. We will see that the combination of these two pressure effects allows access to the pressure dependence of the density of states, \( N(E_F) \), at the Fermi level, \( E_F \) and of the pairing interaction.

To fit this data we expand \( H_c(T) \) as a power series in \( T \). The first-order term must be zero otherwise \( S_s \neq 0 \) at \( T = 0 \) and the third-order term must also be zero to avoid a negative \( \gamma \) at low \( T \). It is usual, therefore, to adopt an even polynomial of the form [5]

\[
H_c(T, P) = H_{c0}(P) + H_{c1}(P) \times T^2 + H_{c2}(P) \times T^4
\]  

(1)

where, as indicated, the coefficients are each an independent function of pressure. It turns out that the coefficients are not independent and it is common to adopt the “similitude principle” which separates the \( P \)- and \( T \)-dependent terms as follows [7]

\[
H_c(T, P) = H_{c0}(P) \times f(t)
\]

\[
= H_{c0}(P) \times \{1 - \alpha \times t^2 - (1 - \alpha) \times t^4\}
\]  

(2)
where $t = T/T_c$. A free fit of eq. (1) to the data consistently yielded $H_{c2}/H_{c0}$ very close in value to $1 - H_{c1}/H_{c0}$, consistent with eq. (2). We therefore proceeded to fit the data with eq. (2) for all subsequent analysis. The fits are shown by the four curves through the data shown in Fig. 2. We obtain $H_{c0}$ values of 804.08, 770.88, 739.99 and 729.01 Gauss for $P = 0, 0.5, 0.9$ and 1.15 GPa, respectively. A linear fit yields

$$H_{c0}(P) = (803.72 - 67.028P) \ G$$

(3)

This now allows the scaling of all the data by plotting $H_c(T, P)/H_{c0}(P)$ versus $t^2$ as shown in Fig. 3. The small departure from linearity in Fig. 3 reflects the small quartic term ($\alpha = 0.95475$; $1 - \alpha = 0.04525$) and the scaled data in Fig. 3 allows a global fit to determine $\alpha$ that provides an overall consistency in the data fits that is necessary when second derivatives of $H_c(T, P)$ are used to determine the electronic specific heat coefficient, thermal expansion coefficient or compressibility.

These parameters may be determined as follows. We restrict our thermodynamic parameters to the electronic contribution, thus ignoring the lattice contribution to the specific heat or thermal expansion. The difference in free energy between the normal and superconducting states at the same $T$ and $P$ is given by

$$G_s(T, P) = G_n(T, P) - \frac{1}{2} \mu_o H_c(T, P)^2 \times V_M$$

(4)

where $\mu_o$ is the permeability of free space and $V_M$ is the molar volume. As shown by Shoenberg[23] the thermodynamic parameters entropy, specific heat coefficient, molar volume, thermal expansion coefficient and compressibility, in the superconducting state, in that order are obtained by differentiating equation (4) with respect to $T$ and $P$, giving

$$S_s(T, P) = S_n(T, P) + \mu_o H_c V_M (\partial H_c/\partial T)_P$$

$$\gamma_s = \gamma_n + \mu_o V_M (\partial H_c/\partial T)_P - \mu_o H_c V_M (\partial^2 H_c/\partial T^2)_P$$
The pressure dependence of $\gamma$ in the inset to Fig. 3. The value at ambient pressure, this is considerably stronger than the value for the free electron gas.

Including lattice and electronic terms, and similarly for $\kappa$.

The entropy in both states $S_s(T, P)$, and dividing through by $T$ we note the requirement that $S_s/T \to 0$ as $T \to 0$ due to the opening of a full superconducting gap in the DOS. At the same time if $\gamma_n$ is constant then $S_n/T$ is just $\gamma_n$. This then imposes a relationship between $\gamma_n$ and the quadratic term in $H_c(T)$. In particular,

$$\gamma_n = \lim_{T \to 0} -\mu_o T^{-1} H_c V_M (\partial H_c / \partial P)_T$$

In this way $\gamma_n$ is calculated from the fits in Fig. 3 and its pressure dependence value is plotted in the inset to Fig. 3. The value at ambient pressure, $\gamma_n = 3.47$ mJ/(mol K$^2$) compares favorably with the value $\gamma_n = 3.13$ mJ/(mol K$^2$) determined from direct specific heat measurements[1].

The pressure dependence of $\gamma_n$ shown in the inset reveals a dimensionless volume dependence given by $\partial \ln \gamma_n / \partial \ln V = 3.26 \pm 0.27$ (where we assume a total compressibility of $24\%$ $\kappa_0 = 0.0205$ GPa$^{-1}$). There have been various estimates of this dimensionless parameter ranging from 1.7 + 0.5 from thermal expansion measurements[25], 1.8 + 0.5 from volume expansion at $T_c[26]$, 6.0 based on pressure dependence of $H_c[7]$ and 3.1 + 0.8 in good agreement with our present value based on more recent measurements of volume change at $T_c$ by Ott[27]. Note that this is considerably stronger than the value for the free electron gas $\partial \ln \gamma_n / \partial \ln V = 2/3$.

With these relations in place we proceed to calculate the entropy as shown in Fig. 4(a). The linear slope in the normal state is just the above-determined $\gamma_n(P)$. The entropy in both states must vanish at $T = 0$. A more rigorous test of the polynomial fits to the data is whether $S_s/T$ also vanishes as $T \to 0$ and whether the data preserves monotonic systematics in this region. The $T$-dependence of $S/T$ is plotted in Fig. 4(b) and this indeed shows a quadratic behavior at low $T$ which is perfectly systematic with increasing pressure and extrapolates to zero as $T \to 0$.

In a finite external field the same entropy curves are retraced up to the reduced $T_c(H)$ value and
then the entropy jumps discontinuously to the normal-state value, consistent with a first-order phase transition in magnetic field and second-order when $H = 0$. The condensation energy, $U_o$ is determined from

$$U_o = \int_0^{T_c} [S_n(T,P) - S_s(T,P)]dT$$ \hspace{1cm} (7)

from which we obtain the following values: $U_o = 47, 43.2, 39.8$ nd $38.6 \text{ mJ/mol}$ for $P = 0, 0.5, 0.9$ and $1.15 \text{ GPa}$, respectively. The condensation energy reduces with pressure due to the twin effects of reduced $T_c$ and reduced $\gamma_n$.

Turning to the specific heat coefficient, this is calculated using the second equation in eqs. (4) and is shown in Fig. 5 for both the normal and superconducting states. The entropy balance is evident from the equal areas above and below the temperature where $\gamma_s = \gamma_n$, and is confirmed by the fact shown in Fig. 4(b) that $S_s/T = \gamma_n$ at $T_c$. The calculated values for the jump in $\gamma(T, P)$ at $T_c$ are shown in Table 1. There is a weak pressure dependence here in this ratio that is not expected with a simple BCS picture where $\Delta \gamma_c/\gamma_n = 1.55$. Direct specific heat measurements at ambient pressure have reported values for $\Delta \gamma_c$ and these are shown for comparison in Table 1 are in good agreement with our ambient result. Combining with the measurement by Horowitz et al[1] of $\gamma_n = 3.13 \text{ mJ/(mol K}^2\text{)}$ gives $\Delta \gamma_c/\gamma_n = 2.34, 2.54$ and $2.60$, again in good agreement with our present ambient-pressure result. We note that for the purely parabolic form $H_c = H^0_c\{1 - t^2\}$ then $\Delta \gamma_c/\gamma_n = 2$ exactly, and so the experimentally observed excess of $\Delta \gamma_c/\gamma_n$ is a direct indication of the presence of a higher order (quartic) term in the $T$-dependent critical field.
Table 1. Specific heat coefficients calculated at different pressures for Pb

| P (GPa) | $\Delta \gamma_c$ (mJ/molK$^2$) | $\Delta \gamma_c/\gamma_n$ mJ/(mol K$^2$) | $\Delta \gamma_c$ comparison with other reports (all at $P=0$) |
|---------|---------------------------------|------------------------------------------|----------------------------------------------------------|
| 0       | 7.85                            | 2.33                                     | 7.33±0.3 Clement and Quinnell[28]                         |
| 0.5     | 7.51                            | 2.28                                     | 7.96±0.08 Shiffman et al.[29]                            |
| 0.9     | 7.05                            | 2.18                                     | 8.13±0.13 Neighbor et al.[30]                            |
| 1.15    | 7.17                            | 2.24                                     |                                                          |

Figure 6. (a) The $T$-dependence of the difference in volume thermal expansion coefficient between the superconducting and normal states for pressures of 0, 0.5, 0.9 and 1.15 GPa. (b) the difference in molar volume for the same pressures.

Fig. 6(a) shows the calculated difference in volume thermal expansion coefficient between the superconducting and normal states at each pressure and Fig. 6(b) shows the difference in molar volume. Given that the absolute molar volume at $T = 0$ K is 18.26 cm$^3$/mol these changes in volume seem extremely small but they are readily measurable. The jumps in thermal expansion coefficient at $T_c$ in zero field are shown in Table 2. We omit the calculations of the electronic compressibility because these involve double derivatives with respect to pressure and here the errors begin to accumulate markedly. Nonetheless the discontinuous jumps in isothermal compressibility may be calculated from the Ehrenfest equation for a second order transition:

$$dT_c/dP = \Delta \kappa/\Delta \alpha$$  \hspace{1cm} (8)

Empirically we find that

$$T_c(P) = 7.1863 - 0.3847P + 0.01769P^2$$  \hspace{1cm} (9)
so that the absolute jumps in isothermal compressibility at $T_c$ in zero field are shown in Table 2.

Direct measurements [31] of the ambient-pressure elastic moduli for Pb in the superconducting state yield $\Delta \kappa / \kappa_0 = -4.0 \text{ ppm}$, again in excellent agreement with our analysis for $P = 0 \text{ GPa}$.

We consider the following results in the light of the BCS model [32]. The condensation energy is

$$\frac{1}{2} \mu_0 H_c(P) = \frac{1}{2} N(0) N_A \Delta_0^2 = (47.11 - 7.75P) \text{ mJ/mol} \quad (10)$$

where $P$ is in GPa. The jump in specific heat is given by

$$\gamma_s - \gamma_n = 10.2 k_B^2 N(0) N_A = (7.85 - 0.68P) \text{ mJ/(molK}^2) \quad (11)$$

Therefore, we obtain

$$N(0) = \left(1.07 - 0.093P\right) \text{ states/atom/eV} \quad (12)$$

$$\Delta_0 = \left(11.1 - 0.432P\right) \text{ K,} \quad (13)$$

$$2\Delta_0 / k_B T_c = 3.09 + 0.037P \quad (14)$$

This should be compared with the BCS result $2\Delta_0 / k_B T_c = 3.53$ and the value of $\Delta_0 = 15.76 \pm 0.05 \text{ K}$ observed from tunneling [33] giving $2\Delta_0 / k_B T_c = 4.37$.

If, on the other hand, we determine the DOS from the nearly-free electron expression [32]

$$\gamma_n = (2/3) \pi^2 k_B^2 N(0) N_A = (3.47 - 0.232P) \text{ mJ/(molK}^2) \quad (15)$$

Then we obtain

$$N(0) = \left(0.736 - 0.0492P\right) \text{ states/atom/eV} \quad (16)$$

$$\Delta_0 = \left(13.7 - 0.653P\right) \text{ K,} \quad (17)$$

$$2\Delta_0 / k_B T_c = 3.72 + 0.007P \quad (18)$$

and the ratio $2\Delta_0 / k_B T_c$ is more or less pressure independent. Finally, using the BCS expression [32] for $T_c$

$$T_c = 0.85 \Theta_D \exp\left(-\frac{1}{N(0)W}\right) \quad (19)$$

where $\Theta_D$ is the Debye temperature (= 96 K for Pb [32]) and $W$ is the pairing interaction, then, using eq. (12)

$$W = \left(0.343 + 0.0167P\right) eV \quad (20)$$

or using eq. (16)

$$W = \left(0.499 + 0.0143P\right) eV \quad (21)$$

Here we have used the Gruneisen coefficient $\gamma_G = -2.6$ for Pb [34].

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**Table 2.** $T_c$, Thermal expansion coefficient, Compressibility and its relative jumps for Pb

| $P$ (GPa) | $T_c$ (K) | $\Delta\alpha$ $\times 10^{-7}$ K$^{-1}$ | $\Delta\kappa$ $\times 10^{-8}$ (GPa$^{-1}$) | $\Delta\kappa / \kappa_0$ (ppm) |
|-----------|----------|-------------------------------------|----------------------------------|-------------------------------|
| 0         | 7.18     | 1.91                               | -7.3                             | -3.56                         |
| 0.5       | 6.99     | 1.63                               | -6.0                             | -2.93                         |
| 0.9       | 6.86     | 1.42                               | -5.0                             | -2.44                         |
| 1.15      | 6.76     | 1.29                               | -4.4                             | -2.15                         |
3. \textit{YBa}_2\textit{Cu}_4\textit{O}_8

Exploring the pressure dependence of the oxygen isotope effect in \textit{Y124} is motivated by the facts that (i) \textit{Y124} lies very close to \(1/8\)th doping with an estimated hole concentration of \(p=0.13\). It is therefore likely to be influenced by stripe or checkerboard fluctuations; (ii) \textit{Y124} lies in the underdoped region where the pressure dependence of \(T_c\) is unusually high (iii) it is sufficiently underdoped that the pseudogap plays a very important role in governing its thermodynamic and transport properties; (iv) it is rigidly oxygen stoichiometric; and (v) this material is one of the most defect free HTS materials known.

Samples were prepared by standard solid state reaction at 945 K at 60 bar oxygen pressure as described elsewhere\[35\]. A 12 mm diameter pellet was cut in half and one half was annealed in 98\% \(^{18}\text{O}\) and the other half in pure \(^{16}\text{O}\) in gold baskets placed in adjacent narrow fused quartz tube furnace at 760 \(^\circ\text{C}\) for 6 hours at 0.95 bar pressure. The anneal was repeated twice resulting in a mass change in \(^{18}\text{O}\) sample consistent with 95\% oxygen exchange. The nearly complete isotope exchange was confirmed by shift in oxygen vibrational modes determined from Raman spectroscopy\[35\]. For each sample zero-field cooled temperature sweeps were made at 25 Gauss to measure diamagnetic magnetization and hence the onset of the superconductivity. The transition temperature, \(T_c\), was determined as a function of pressure using Pb as pressure marker in the pressure cell detailed above. Fig. 7 displays the pressure dependence of \(T_c\) for \textit{Y124} with \(^{16}\text{O}\) and \(^{18}\text{O}\) oxygen isotope exchange. The increase in \(T_c\) is essentially linear with \(T_c = 80.847 + 4.947P\) for \(^{18}\text{O}\) sample and \(T_c = 81.506 + 5.265P\) for \(^{16}\text{O}\) sample. The value of \(dT_c/dP = 5.27\text{K/GPa}\) for \(^{18}\text{O}\) is similar to previous reports\[16, 17, 18\]. The value of isotope exponent \(\alpha = -dlnT_c/dlnM\) at \(P=0\) deduced from the linear fits of \(^{16}\text{O}\) and \(^{18}\text{O}\), 0.069 is also comparable to the previous report\[35\]. The inset in Fig. 7 shows the steady increase in \(\alpha\) with increasing pressure and evidently by 2 GPa the isotope exponent is projected to double.

\textbf{Figure 7.} Figure 7. The pressure dependence of \(T_c\) for \textit{YBa}_2\textit{Cu}_4\textit{O}_8\) with isotope exchange. The inset shows the pressure dependence of isotope exponent \(\alpha(T_c) = -\frac{M\times\Delta T_c}{\Delta M\times T_c}\).

This result is surprising. The effect of pressure is generally to transfer holes onto the \(\text{CuO}_2\) planes. In the light of the fact that the isotope effect is generally observed to decrease with increasing doping one might expect the isotope effect to decrease with pressure. An additional outcome may be that the increase in doping moves the sample further away from the \(1/8\)th doping and hence away from any anomaly associated with stripe instability. This also would tend to decrease the magnitude of the isotope effect. So it is reasonable to conclude the increase is not a simple doping effect. It is possible, rather, that the tendency to stripe formation is enhanced under pressure in \textit{Y124}. It would be valuable to determine the pressure dependence...
of the isotope effect in superfluid density $\rho_s$ to see if this is a strong positive effect indicating the enhancement of stripe formation [15].

4. Summary
In summary, we have measured the pressure dependence of the superconducting critical field in Pb to 1.15 GPa using a clamp cell in a SQUID magnetometer. By using thermodynamic identities we have determined the electronic free energy, entropy, specific heat coefficient, thermal expansion coefficient and compressibility, including the jumps in these properties at $T_c$. The calculated results match rather well the experimentally observed ambient pressure data, where it is available. The present results allow calculation of the these parameters as pressure-dependent quantities and an estimation of the pressure dependence of the density of states, superconducting energy gap and the pairing interaction.

We find a strong pressure-induced increase in oxygen isotope effect in Y124 which we find surprising in the light of pressure-induced charge transfer. We conclude that the effect of pressure may be to enhance the exchange interaction and hence the tendency to stripe (or checkerboard) formation. Some tests of this hypothesis are proposed.

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References
[1] M Horowitz, A A Silvidi, S F Malaker and J G Daunt 1952 Phys. Rev. 88 1182
[2] H V Culbert, D E Farrell and B S Chandrasekhar 1971 Phys. Rev. B 3 794
[3] R R Hake, D E Mapother and D L Decker 1958 Phys. Rev. 112 1522
[4] R W Shaw D E Mapother and D C Hopkins 1961 Phys. Rev. 121 86
[5] D L Decker D E Mapother and R W Shaw 1958 Phys. Rev. 112 1888
[6] K Andres, J L Olsen and H Rohrer 1962 IBM J. Res. Dev. 6 84
[7] S Alterovitz and D E Mapother 1975 Phys. Rev. B 11 139
[8] N B Brandt and N I Ginzburg 1965 Sov. Phys. Uspekhi 8 202
[9] H H Hansen R L Pompei and T M Wu 1973 Phys. Rev. B 8 1042
[10] J Wittig Zeitschrift fur Physik 1966 195 228
[11] A Eiling and J S Schilling 1981 J. Phys. F: Metal Phys. 11 623
[12] J Thomasson C Ayache Y L Spain, and M Villedieu 1990 J. Appl. Phys. 68 5933
[13] N Suresh and J L Tallon 2007 Phys. Rev. B 75 174502
[14] M K Crawford, M N Kunchur W E Fahnest, E M McCarro III, S J Poon 2005 Phys. Rev. B 41 282
[15] J L Tallon, R S Islam, J Storey G V M Williams and J R Cooper 2005 Phys. Rev. Lett. 94 237002
[16] J L Tallon and J Lusk 1990 Physica C 167 236
[17] B Bucher J Karpinski E Kaldis P Watche 1989 Physica C 157 478
[18] E N Van Eenige, R Griessen R J Wijngaarden, J Karpinski et al 1990 Physica C 168 482
[19] A Mawdsley J L Tallon and M R Presland 1992 Physica C 190 437
[20] G V M Williams and J L Tallon 1996 Physica C 258 41
[21] J A Osborn Phys Rev 1945 67 351
[22] I R Walker 1999 Rev. Sci. Instrum. 70 3402
[23] D Shoeben 1952 Superconductivity (CUP, Cambridge) p. 56
[24] D L Waldorf and G A Alers 1962 J. Appl. Phys. 33 3266
[25] G K White 1962 Phil. Mag. 7 271
[26] J L Olsen and H Rohrer 1957 Helv. Phys. Acta 30 49
[27] H R Ott 1972 J. Low Temp. Phys. 9 331
[28] J R. Clement and E.H. Quinnell 1952 Phys. Rev. 85 502
[29] C A Shiffman, J F Cochran and M Garber 1963 J. Phys. Chem. Solids 24 1369
[30] J E Neighbor, J F Cochran and C A Shiffman 1967 Phys. Rev. 155 384
[31] G A Alers and D L Waldorf 1961 Phys. Rev. Lett. 6 677
[32] R Reservey and B B Schwartz 1969 Superconductivity Vol 1 ed R D Parks (Dekker, New York) p 117
[33] W L McMillan and J M Rowell 1965 Phys. Rev. Lett. 14 109
[34] M Hasegawa 1980 J. Phys. F - Metal Phys. 10 225
[35] G V M Williams J L Tallon J Quilty H J Trodahl and N E Flower 1998 Phys. Rev. Lett. 80 377