Elastic properties of $YBa_2Cu_3O_7$ single crystals at the superconducting phase transition

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The results of new measurements of the elastic properties of $YBa_2Cu_3O_7$ single crystals using a vibrating-reed technique are reported. An extremely well expressed elastic anomaly at the superconducting phase transition has been observed in some single crystals. This anomaly can be correctly described by the Landau theory when the Gaussian fluctuations are taken into account. The Landau discontinuity in the Young's modulus at the phase transition can be as large as 5×10^2 ppm.

In the present paper we report the results of new measurements of the Young's modulus (Y) of $YBa_2Cu_3O_7$ single crystals in a wide temperature range, obtained by using the vibrating-reed method.

A noticeable anomaly in the Young's modulus at the superconducting transition in $YBa_2Cu_3O_7$ has been observed previously in similar experiments.[1–3] This anomaly can be interpreted as a smeared discontinuity in the Young's modulus with a magnitude about 100–200 ppm. As was observed in the course of the present study of a number of $YBa_2Cu_3O_7$ single crystals, however, unique samples could be obtained.

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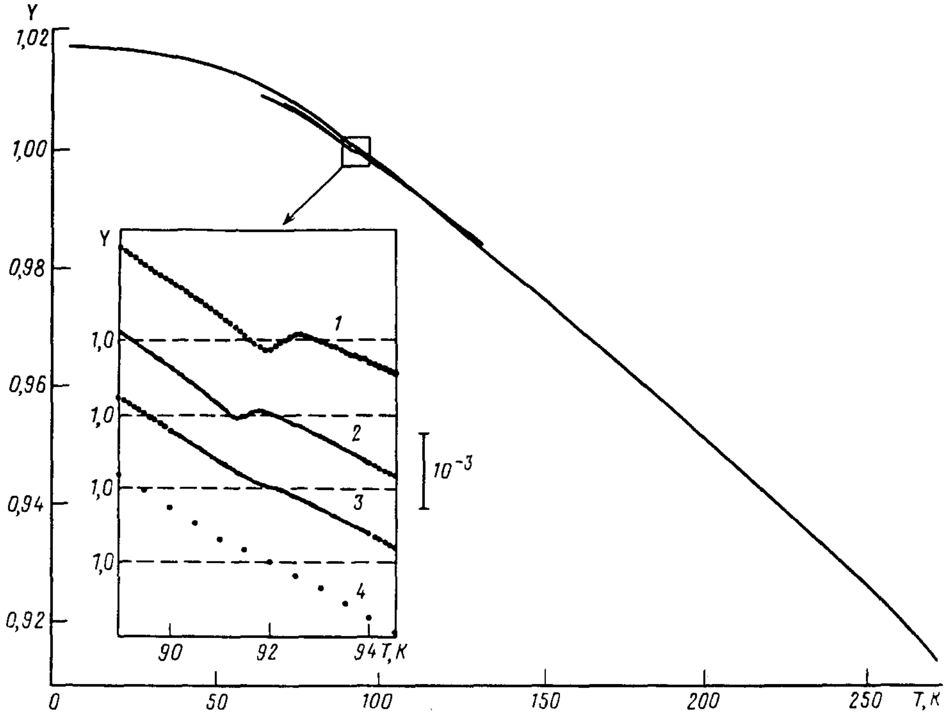

FIG. 1. Experimental data on the Young's modulus Y for several $YBa_2Cu_3O_7$ single crystals. The values of Y are reduced to $Y(T_c)$.

Those samples reveal extremely well expressed anomalies, which include a slightly smeared discontinuity, about twice as large as the highest value reported previously (see Fig. 1). As will be shown below, the anomaly of Y can be described by the Landau theory, along with Gaussian fluctuation corrections. The Landau discontinuity can be as large as 500 ppm.

High quality $YBa_2Cu_3O_7$ crystals were grown from nonstoichiometric melt and annealed in flowing oxygen for several days.[4] The annealed crystals were heavily twinned and the temperature of the superconducting transition T_c was above 90 K. The crystals under study with typical dimensions of $1.5\times0.5\times0.03$ mm were attached to the copper block at one end. The flexural vibrations were induced in the crystals by using electrostatic technique. The resonant frequency ν, measured in the experiment, is proportional to the effective Young's modulus which corresponds to the elongation in the ab plane, as $\nu\sim(Y/\rho)^{1/2}$, where ρ is the density. When necessary, we used the values of the density of $YBa_2Cu_3O_7$ from the thermal expansion data.[5] The accuracy of the frequency measurements was about 1–2 ppm; the temperature was measured with a thermocouple within 10^{-3} K. The experimental technique is described in more detail elsewhere.[6]

The experimental data are shown in Fig. 1. We see that the magnitude and form of the anomaly vary from sample to sample, probably because of the different amounts of the superconducting fraction, and because of the inhomogeneity of the samples. It is likely that the twin boundaries contribute to the elastic moduli. But at present it cannot be determined unambiguously.

Before proceeding to discuss the experimental data, we will obtain an expression for the inverse Young's modulus, $\chi = 1/Y$, in the vicinity of the phase transition, in the terms of the Landau approach. We use the standard form of the Landau expansion $F = F_0 + A\eta^2 + B\eta^4$, but in the expression for $A(T)$ we take into account the second-order term, i.e.,

$$A = a_1(T - T_c) + a_2(T - T_c)^2. \tag{1}$$

The necessity of the second-order term in the expansion of $A(T)$ follows from the experimental data,[7,8] where the changes of the slope on the $\alpha(T)$ and $C_p(T)$ curves are clearly observed. Finally, we obtain for the inverse Young's modulus

$$\chi = \chi_0 + [a_1^2 - 6a_1a_2(T_c - T) + 6a_2(T_c - T)^2](\partial T_c/\partial \sigma_i)^2/2BV$$
$$+[a_1^2(T_c - T) - 3a_1a_2(T_c - T)^2 + 2a_2^2(T_c - T)^3]\partial^2 T_c/\partial \sigma_i^2/2BV, \tag{2}$$

where V is volume, and σ_i is the corresponding component of the stress.

As can be seen from Eq. 2, the quantity $\chi(T) = 1/Y$ has a discontinuity at $T = T_c$, which is proportional to $(\partial T_c/\partial \sigma_i)^2$. The slope of the temperature dependence of χ is also discontinuous at T_c, with a jump defined by the terms containing $(\partial T_c/\partial \sigma_i)^2$ and $\partial^2 T_c/\partial \sigma_i^2$.

Unfortunately, our analysis of the experimental data, using Eq. 2, is complicated by the problem of finding the "right" expression for the temperature dependence of χ_0. The point is that in the temperature region of interest ($T_c \approx 90$ K) the thermodynamical quantities cannot be used either in the in high- or in the low-temperature approximation and simple solutions like a linear extrapolation of $\chi_0(T)$ to the region $T < T_c$ cannot be justified.

In the present paper we use so-called quasiharmonic approximation for Y, assuming that the temperature dependence of Y arises only from the volume change. Thus, in the linear approximation and using the Einstein formula for the thermal energy we obtain

$$1/Y_0 = \chi_0 \approx c + d\theta/(e^{\theta/T} - 1), \tag{3}$$

where θ is the Einstein temperature. Using Eq. 3, it is easy to calculate the values of c and d and, consequently to determine the values of $\Delta\chi = (1/Y) - (1/Y_0)$ in the corresponding temperature region. The results of those calculations are shown in Fig. 2. As one can see, the behavior of $\Delta\chi$ near T_c agrees qualitatively with the Landau theory (see Eq. 2). We see a jump and a change of the slope on the $\chi(T)$ curve at T_c. Note that the Young's modulus softens at the transition to the superconducting phase, in accordance with Eq. 2.

It should be emphasized that the change of the slope on the $\Delta\chi(T)$ curve is so significant that as the temperature is lowered, $\Delta\chi(T)$ changes sign not so far away from T_c. Finally, we expect that the Young's modulus of the superconducting phase would exceed that of the normal phase at $T = 0$. Reasonable extrapolation of χ and χ_0 to zero temperature for samples 1 and 2 leads to the conclusion that $(Y - Y_0)/Y_0 \approx 0.003$ at $T = 0$. It is worth noting that in the case of many ordinary superconductors the corresponding changes of the elastic moduli are opposite in sign and at least an order of magnitude smaller.[9] Earlier, these facts have been used as a basis to claim unusual elastic properties of the high-T_c superconductors. But, in reality, the only conclusion which can be made is that the contribution of the superconducting energy shifts the equilibrium volume of the system to a smaller value with the corresponding increase of the elastic moduli. The actual contribution of the superconducting energy to the Young's modulus remains uncertain and we need more data to clear up the question.

Let us again examine Fig. 2. Our numerous attempts to describe quantitatively the behavior of $\Delta\chi(T)$ in the temperature region near T_c, using Eq. 2, were not successful because of the fast increase of $\chi(T)$ near T_c. Under those circumstances it is natural to include in the description of the experimental data fluctuation terms in the form $C\tau^{-\alpha}$, where $\tau = |T_c - T|/T_c$ (see also Ref. 7). The problems involved here are quite obvious. Should fluctuations contribute to $\chi(T)$; their contribution is very small (see Fig. 1). Furthermore, the background contribution χ_0 is not very well known. So

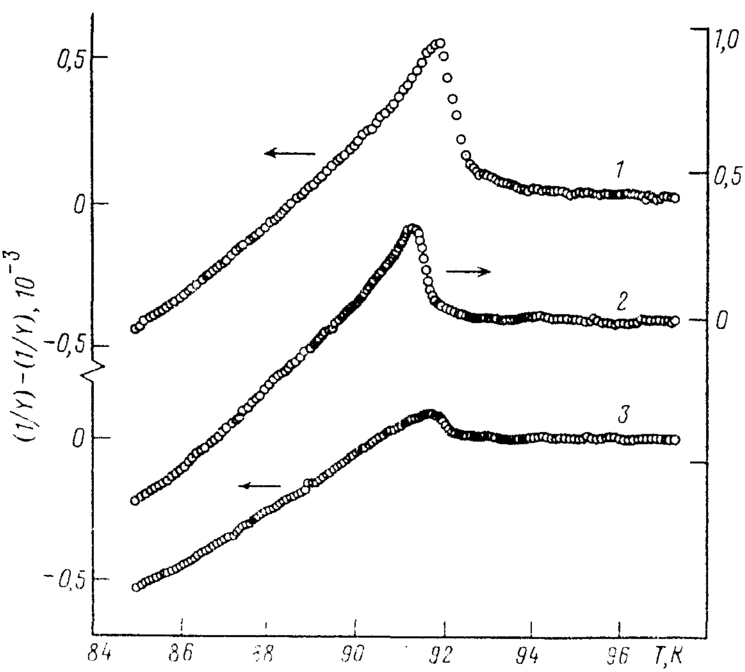

FIG. 2. Dependence of $\Delta\chi = (1/Y) - (1 - Y_0)$ on the temperature near the superconducting transition for the samples 1–3. Explanation is given in the text.

the situation does not seem favorable for reliable estimates of the corresponding exponents and amplitudes. As a result of the calculations, we must conclude that the quality of the approximation of the experimental data is not sensitive enough to the value of α. In other words, a satisfactory description of the data can be reached at the values of α from 1.5 (1D-Gaussian fluctuation) to 0 (log). Finally, we adopted the following treatment of the data. The high-temperature part of $\chi(T)$ at $T > T_c$ was approximated by the expression $c + d\theta(e^{\theta/T} - 1) + C\tau^{-\alpha}$. Here c, d, θ, and C are adjustable parameters, and the exponent α was set equal to 1.5, 1, and 0.5, in correspondence with the Gaussian fluctuation contributions to 1D, 2D, and 3D systems.[10] Using the calculated parameters, we subtracted the background χ and the possible contribution of the Gaussian fluctuations from the low-temperature part of $\chi(T)$, with allowance for the ratio of the amplitudes C^-/C^+, assuming a two-component order parameter. The rest was analyzed with the hope of understanding which case was in better agreement with the Landau theory (see Eq. 2).

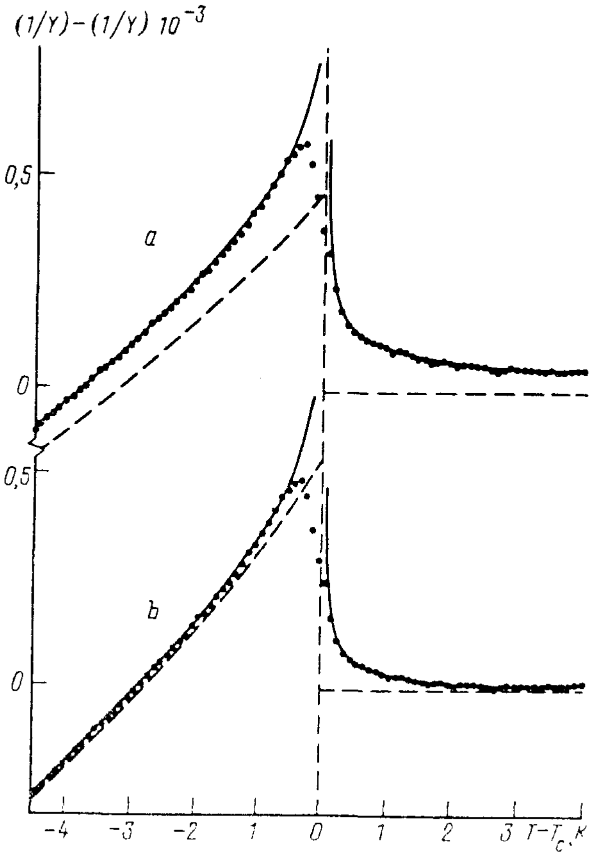

FIG. 3. The difference $\Delta\chi = (1/Y) - (1 - Y_0)$ vs the temperature for sample 1. Dashed lines correspond to $\Delta\chi(T)$ with the Gaussian fluctuation contributions subtracted. Gaussian fluctuations were taken into account in the form $C(|T - T_c|/T_c)^{-\alpha}$. a: $\alpha = 0.5$, $C^-/C^+ = 1.4$, $\Delta\chi \approx 4.8 \times 10^{-4}$; b: $\alpha = 1.0$, $C^-/C^+ = 1.0$, $\Delta\chi \approx 5.5 \times 10^{-4}$.

The results (Fig. 3) show that all three hypotheses ($1D$, $2D$, and $3D$) agree well with the experimental data, although the hypothesis of $3D$ character of fluctuations has a certain advantage (in the sense of the standard deviation of the approximation). But we should point out that with the present treatment of the experimental data, decreasing the value of α makes it possible to extend the fluctuation range. For that reason, our attempts to describe the data with the small exponents typical of the scaling regime lead to unrealistic fluctuation range. Even for the $3D$ Gaussian case the fluctuation range seems to be too large as compared with other available data. Our unpublished results for the magnetic susceptibility of $YBa_2Cu_3O_7$ single crystals show that outside the temperature region $T - T_c \approx 3$ K the fluctuations are definitely not three-dimensional. This might imply that within $\Delta T \approx 3$ K we encounter the $2D$–$3D$ crossover regime. Additionally, the proper account of inhomogeneities could affect to some extent our conclusions (see, for instance, Ref. 11). In any case, the magnitude of the jump $\Delta\chi$ at T_c is not very sensitive to the fluctuation dimensionality (see Fig. 3) and amounts to $\Delta Y/Y \approx 5 \times 10^{-4}$, which is about a factor of two greater than the maximum estimate obtained earlier.[1-3]

In conclusion we emphasize that elastic effects at T_c in the novel superconductors are expressed more clearly compared with the ordinary effects. That is another reason to believe that the contribution of the superconducting energy to the total energy of the high-T_c materials is much higher than in the conventional superconductors.

[1] S. Hoen, L. C. Bourne, *et al.*, Phys. Rev. B **38**, 11949 (1988).
[2] X. D. Shi, R. C. Yu *et al.*, Phys. Rev. B **39**, 827 (1989).
[3] V. A. Melik-Shakhnazarov, I. I. Mirzoeva, T. Sh. Kvirikashvili *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **50**, 72 (1989) [JETP Lett. **50**, 81 (1989)].
[4] A. B. Bykov, L. N. Demyanets, I. P. Zibrov *et al.*, J. Cryst. Growth **91**, 302 (1988).
[5] I. V. Aleksandrov, I. P. Zibrov, and S. M. Stishov, JETP Lett. **52**, 5, 920 (1990).
[6] V. A. Melik-Shakhnazarov and I. A. Naskidashvili, Prib. Tekh. Eksp. **1**, 181 (1967).
[7] S. E. Inderhees, M. B. Salamon *et al.*, Phys. Rev. Lett. **60**, 1178 (1988).
[8] C. Meingast, B. Blank, *et al.*, Phys. Rev. B **41**, 11299 (1990).
[9] G. A. Alers and D. L. Waldord, Phys. Rev. Lett. **6**, 677 (1961).
[10] S. K. Ma, *Modern Theory of Critical Phenomena*, Benjamin, New York, 1976.
[11] A. V. Gurevich and A. L. Takhmanov, Fiz. Tverd. Tela **31**, 255 (1989) [Sov. Phys. Solid State **31**, 1244 (1989)].