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 by using a vibrating reed technique are reported. An extremely well expressed elastic anomaly at the superconducting phase transition has been discovered in some single crystals. This anomaly can be properly described in the framework of the Landau theory when the effects of Gaussian fluctuations are taken into account. The Landau discontinuity in the Young's modulus at the phase transition can be as large as $5 \cdot 10^2$ ppm.

In the present paper we report on new measurements of the Young's modulus (Y) of $YBa_2Cu_3O_7$ single-crystals in a wide temperature range employing a vibrating-reed technique.

A noticeable anomaly in the Young's modulus at the superconducting transition in $YBa_2Cu_3O_7$ has been observed in similar experiments [1-3] earlier. This anomaly can be interpreted as a smeared discontinuity in the Young's modulus with a magnitude about 100-200 ppm. However, as it appeared in the course of the present study among a number of $YBa_2Cu_3O_7$ single crystals, the quite unique samples can be found. Those samples reveal extremely well expressed anomalies, which as it is readily seen, include a slightly smeared discontinuity about twice as much as the highest value reported previously (see Fig. 1). As it is shown below, the anomaly of Y can be described in the framework of the Landau theory along with Gaussian fluctuation corrections. A magnitude of the Landau discontinuity can be as large as 500 ppm.

High quality $YBa_2Cu_3O_7$ crystals were grown from non-stoichiometric melt and annealed in flowing oxygen for several days [4]. The annealed crystals were heavily twinned and had the temperature of the superconducting transition T_c more than 90 K. The crystals under study with typical dimensions of $1,5 \times 0,5 \times 0,03$ mm were glued to the copper block by 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, corresponding to elongation in $a-b$ plane, as $\nu \sim (Y/\rho)^{1/2}$, where ρ is density. When necessary we used the values of density of $YBa_2Cu_3O_7$ from the thermal expansion data [5]. An accuracy of the frequency measurements was about 1-2 ppm, the temperature was measured with a thermocouple with an accuracy of 10^{-3} K. The experimental technique is described in more details elsewhere [6].

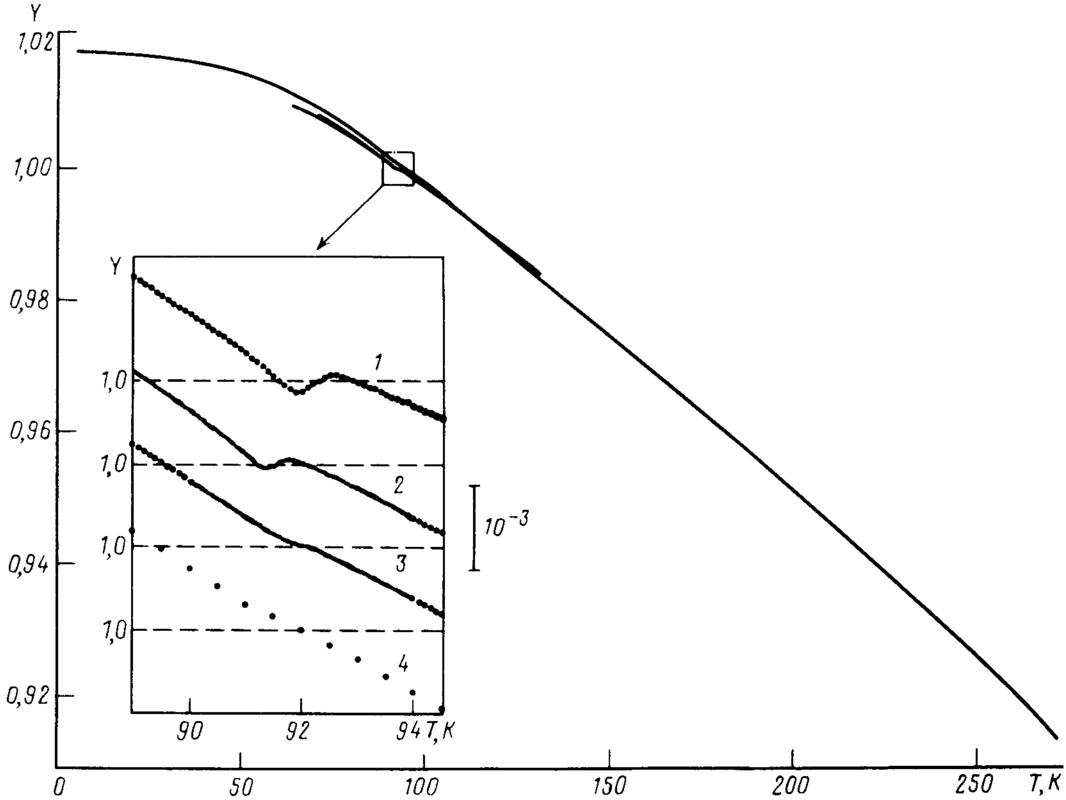

Fig. 1. Experimental data on the Young's modulus Y for several $YBa_2Cu_3O_7$ single crystals. The values of Y are reduced to $Y(T_c)$.

The experimental data are illustrated in Fig.1. As is seen the magnitude and the form of the anomaly vary from sample to sample, that is probably connected with various amount of the superconducting fraction and inhomogeneities in the samples. One may expect that the twin boundaries contribute somehow to the elastic moduli. But at present we are unable to make unambiguous estimations.

Before proceeding to discuss the experimental data let us 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 a second-order term, i.e.:

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

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

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

$$+[a_1^2(T_c - T) - 3a_1a_2(T_c - T)^2 + 2a_2^2(T_c - T)^3]\partial^2 T_c/\partial\sigma_i^2/2BV, \qquad (2)$$

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

As it is 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 $\partial^2 T_c/\partial\sigma_i^2$.

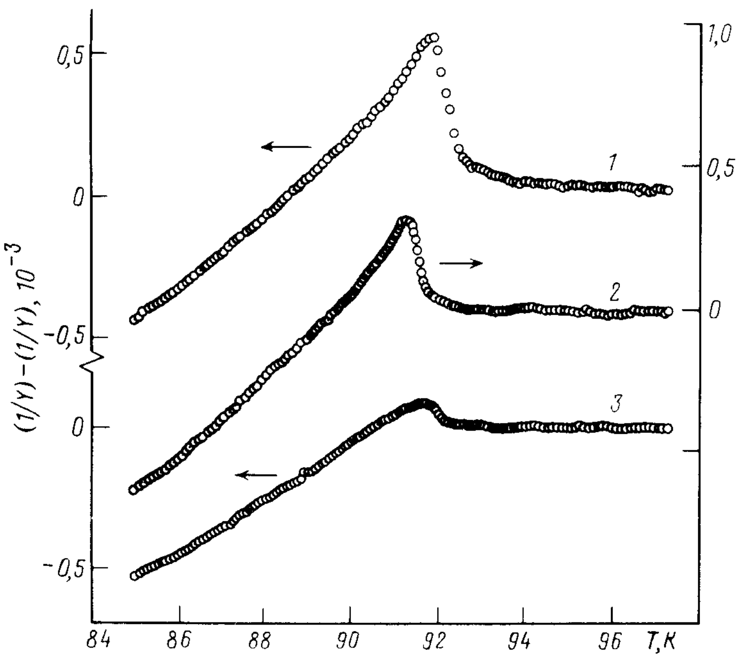

Fig. 2. The dependence of $\Delta\chi = (1/Y) - (1 - Y_0)$ on temperature near the superconducting transition for the samples 1-3. Explanations are given in the text.

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 range of interest ($T_c \approx$ 90 K) the thermodynamical quantities can be treated neither in high- nor in low-temperature approximation and simple solutions like a linear extrapolation of $\chi_0(T)$ to the range $T < T_c$ can not 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:

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

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

It has to be emphasized that the change of the slope in $\Delta\chi(T)$ is so significant that on temperature decreasing $\Delta\chi(T)$ changes the 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 the 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 the 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 magnitudes of the elastic moduli. The real contribution of the superconducting energy to the Young's modulus remains uncertain and we need more data to clear up the question.

Now we turn again to Fig. 2. Our numerous attempts to describe quantitatively the beavior of $\Delta\chi(T)$ in the temperature range near T_c using Eq. 2 were not quite successful, because of the fast increase of $\chi(T)$ near T_c. Under those circumstances it is natural to try to include into a description of the experimental data fluctuation terms in the form $C\tau^{-\alpha}$, where $\tau = \mid T_c - T \mid /T_c$ (see also [7]). The problems involved here are quite obvious. Should fluctuations contribute to $\chi(T)$, their contribution is very small (see Fig. 1). Futhermore, the background contribution χ_0 is not very well known. So the situation does not seem very favorable for reliable estimates of the corresponding exponents and amplitudes. As a result of the calculations we have to 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) up to 0 (log). Finally, we adopted the following way of 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, the exponent α was set equal to 1.5, 1 and 0.5 in correspondence with Gaussian fluctuation contributions for 1D-, 2D- and 3D-systems [10]. Then, using the calculated parameters, we subtracted background χ and the possible contribution of Gaussian fluctuations from the low-temperature part of $\chi(T)$ with the account of the ratio of the amplitudes C^-/C^+ assuming a two-component order parameter. The rest was analyzed with hope to understand which case was in better agreement with the Landau theory (see Eq. 2).

The results (Fig. 3) show that all three hypotheses (1D,2D and 3D) agree well with the experimental data, though certain advantage (in the sense of the standard deviation of approximation) has the hypothesis of 3D-character of fluctuations. But we should point out that at the present treatment of the experi-

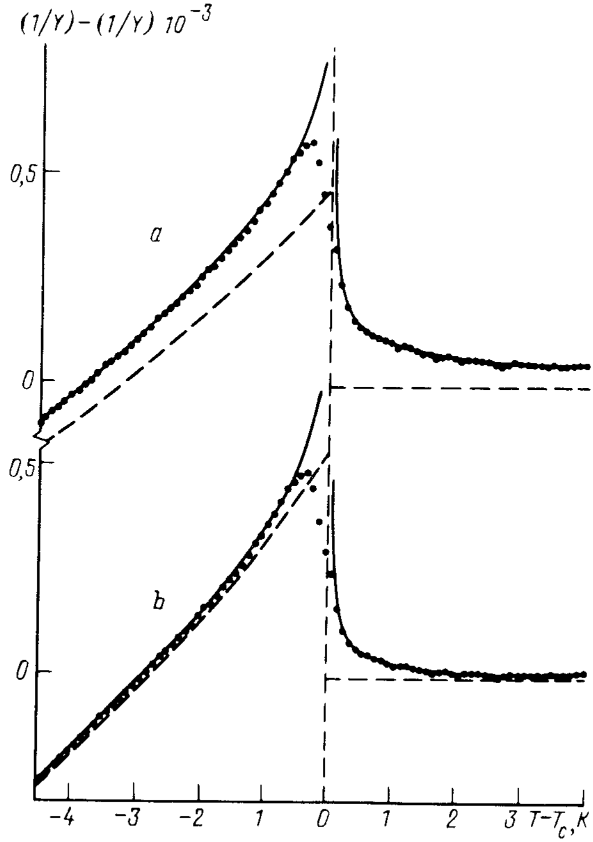

Fig. 3. The difference $\Delta\chi = (1/Y)-(1-Y_0)$ vs temperature for the sample 1. Dashed lines correspond to $\Delta\chi(T)$ with Gaussian fluctuation contributions subtracted. Gaussian fluctuation were taken into account in the form $C(|T-T_c|/T_c)^{-\alpha}$.
a: $a = 0.5$, $C^-/C^+ = 1.4$, $\Delta\chi \approx 4.8\cdot10^{-4}$;
b: $a = 1.0$, $C^-/C^+ = 1.0$, $\Delta\chi \approx 5.5\cdot10^{-4}$.

mental data decreasing the value of α makes to extend the seeming 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 3-D Gaussian case the fluctuation range seems to be too large when compared with other available data. Our unpublished results on the magnetic susceptibility of $YBa_2Cu_3O_7$ single crystals show that out of the temperature range $T-T_c \approx 3$ K fluctuations are certainly not three-dimensional. That might imply that within $\Delta T \approx 3$ K we encounter the 2D-3D crossover regime. One more thing is that the proper account of inhomogeneities could affect to some extent our conclusions (see, for instance, Ref. 11). Anyway, the magnitude of the jump $\Delta\chi$ at T_c is not very much sensitive to the fluctuation dimensionality (see Fig. 3) and makes up $\Delta Y/Y \approx 5\cdot10^{-4}$, that is about two times more 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 ones. 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.

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