# Expression describing the field dependence of the critical current in ceramic high-$T_c$ superconductors over broad field and temperature ranges

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(Submitted 1 February 1991)
Pis'ma Zh. Eksp. Teor. Fiz. **53**, No. 5, 246–249 (10 March 1991)

The critical current $I_c$ has been studied as a function of the magnetic field in a 1-2-3 ceramic with $T_c = 89$ K over the temperature range from 4.2 K up to $T_c$. The results can be described well by the expression $I_c(H) = I_i \exp[(H_0/H)^a]$. The exponent has a value $a = 0.49 \pm 0.06$ and is independent of the temperature. The temperature dependence of the parameters $I_i$ and $H_0$ has been determined.

A study has been made of the field dependence of the critical current $I_c$ in a ceramic 1-2-3 sample. The transition temperature of this sample was $T_c = 89$ K, and the width of the superconducting transition was less than 1 K. The grain size in the ceramic was on the order of 5 $\mu$m. The sample had the shape of a rectangular parallelepiped with dimensions of $0.15 \times 0.15 \times 0.8$ cm. Measurements were carried out by the four-contact method, with the current contacts applied to the ends of the sample. The distance between the potential contacts was 0.5 cm. Current-voltage characteristics of the sample were recorded; they had the shape typical of high-$T_c$ superconductors.[1,2] We assumed $I_c$ to be the value of the current at which the voltage across the potential contacts reached 0.5 $\mu$V.

A magnetic field $H$ up to 3 kOe was produced by a superconducting solenoid. The "frozen field" of the solenoid was less than 1 Oe. The magnetic field was directed perpendicular to the current flow in the sample.

The sample was placed in a "warm-field" channel. Its temperature was regulated within $\pm$ 1.5 K and monitored within $\pm$ 0.5 K by a thermocouple.

Before a given field dependence was recorded, the sample was heated to 120 K to remove the "frozen" field.

Over the temperature range 4.2–80 K the dependence $I_c(H)$ can be described well by the empirical expression

$$I_c(H) = I_i \exp\left[\left(\frac{H_0}{H}\right)^a\right], \tag{1}$$

where $a$, $I_i$, and $H_0$ are positive constants at the given temperature.

For each temperature, the most probable values of $a$, $I_i$, and $H_0$ were found by fitting expression (1) to the experimental points. These values were determined within about $\pm$ 15%. Over the temperature range 4.2–77 K, the exponent $a$ is in the interval $0.49 \pm 0.06$. At $T = 80$ K its value is $0.1 \pm 0.07$. At higher temperatures, the thresh-

  

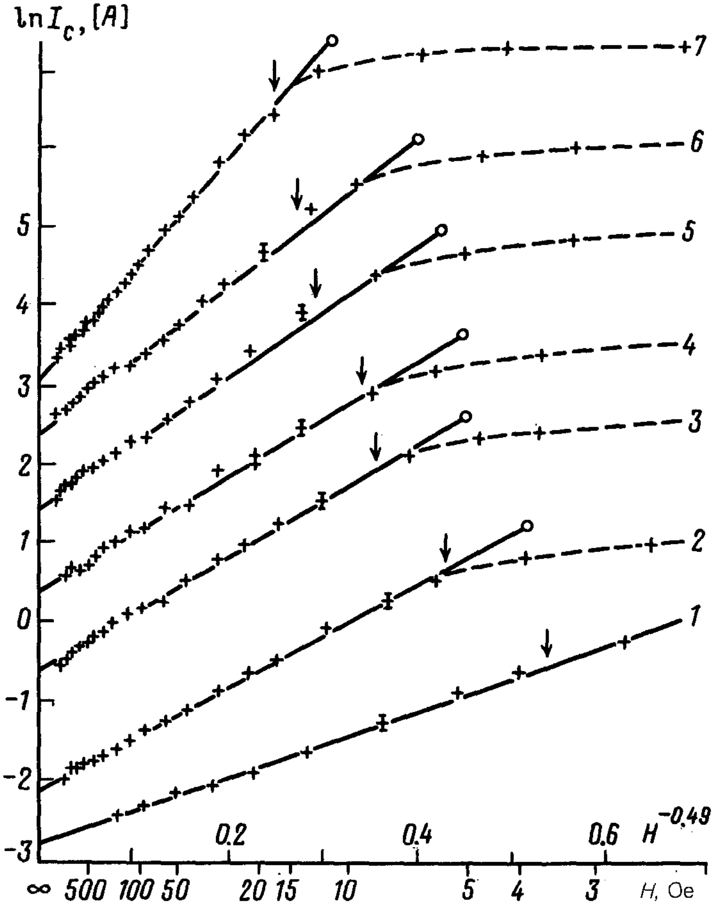


FIG. 1. Field dependence of the critical current $I_c$ at several temperatures. 1—77; 2—67; 3—55; 4—45; 5—35; 6—17; 7—4.2 K. Curve *3* has been shifted upward by 1 unit, curve *4* by 2, *5* by 3, *6* by 4, and *7* by 5 units. The open circles on the lines show $I_c(H=0)$; the arrows show $H_I^0$.

old on the current-voltage characteristics is greatly rounded, even in fields of tens of oersteds, and $I_c$ can no longer be determined.

We have reached the conclusion that the exponent $a$ is independent of the temperature in the temperature range 0–77 K, where it has a value of 0.49. Figure 1 shows a family of $I_c(H)$ curves for various temperatures in the rectifying coordinates $\ln(I_c)$, $H^{-0.49}$. We see a good agreement in strong fields (on this plot, near the origin). In weak fields, in contrast, the experimental data on $I_c(H)$ show a saturation. [The open circles on the lines show the values of $I_c(0)$.]

The reason for the saturation, we believe, is that the external field $H$ becomes weaker than the self-field of the current, $H_I$, and thus ceases to influence $I_c$. At $H=0$ the critical current $I_c^0$ should then be determined by the magnetic field which itself produces, $H_I^0$. For our sample, the average value (along the cross section) of the magnetic field produced by the current flowing through the sample, $I_c^0$, is about $H_I^0 = (1.7\ \mathrm{Oe/A})\cdot I_c^0$ (we are assuming that the current is uniform along the cross section). The corresponding field values are shown by the arrows in Fig. 1. We see that expression (1) breaks down when the external field $H$ becomes comparable to $H_I^0$.

In summary, no deviations from (1) are observed over the field range from a few oersteds up to 3 kOe.

Figure 2 shows the temperature dependence of the parameters $I_i$, $I_c^0$, and $H_0$.

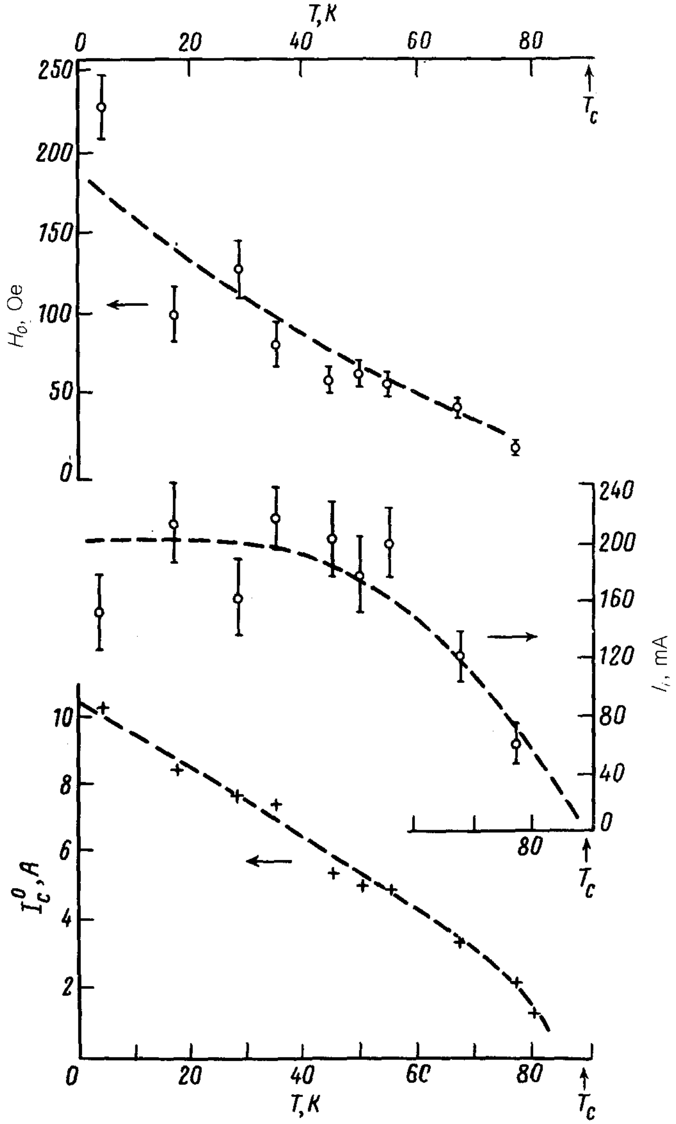


FIG. 2. Temperature dependence of the critical current $I_c^0$ and of the parameters $I_i$ and $H_0$.

The parameter $I_i$ behaves in the manner of the critical current of an SIS Josephson junction[3] (the dashed lines). At low temperatures $T$, the quantities $H_0$ and $I_c^0$ are roughly linear functions of the temperature. The values of $I_i$ and $H_0$ have not been determined accurately enough to support definitive conclusions.

Our calculations on the behavior $I_c(H)$ for corresponding objects from Refs. 1 and 2 show that expression (1) also holds for them. For $T = 77$ K, we found the value $a = 0.63 \pm 0.13$ from Ref. 1., i.e., a value close to that which we found for our own sample. For the data of Ref. 2, where the magnetic field was parallel to the current in the sample, the value $a = 0.35 \pm 0.09$ was found (at 4.2 K).

It thus appears that one can hope that expression (1) has a fairly wide range of applicability and holds for more than this particular sample.

The fact that the exponent $a$ does not vary over a wide temperature range suggests that expression (1) has a physical meaning. Since the superconductivity in the high-$T_c$ ceramics is of a percolation nature, in agreement with the form of expression (1), the exponent $a$ might be determined exclusively by the geometry of a superconducting cluster and would therefore be independent of the temperature.

If one assumes, as usual, that a high-$T_c$ ceramic is a conglomerate of superconducting grains connected by Josephson junctions, then $H_0$ would apparently be comparable in magnitude to the critical field $H_{c1}$ of the current-carrying junctions. At such fields the critical current becomes much lower than that at $H = 0$. The fact that it does not actually vanish even at $H \gg H_0$ and instead reaches a constant value can apparently be attributed to the pronounced nonuniformity of the junctions.[3]

We can estimate the characteristic areas: $s \propto \Phi_0/H_0$. At 4.2 K we thus find $s \propto 10^{-9}$ cm$^2$. This result is much lower in order of magnitude than the grain size (a few microns) of the ceramic, but it is close to the characteristic dimensions of the Josephson junctions (for the high-$T_c$ superconductors, the quantity $\lambda\delta_J$—the product of the penetration depth and the Josephson length, and a measure of the influence of the magnetic field on the properties of the junction—may be of this order of magnitude[4]).

Vinokur and Koshelev[4] have derived a theory for the field dependence of the critical current in a "long" nonuniform Josephson junction (which was assumed to serve as a model of a high-$T_c$ ceramic). For strong fields they found $I_c \propto \exp(H_1/H)$, where $H_1$ is on the order of the critical field $H_{c1}$ of the junction. The shape of this curve is close to the experimental shape (1). It may be that the appearance of the exponent $a$ in the experimental dependence is a consequence of specifically the percolation nature of the superconductivity in high-$T_c$ ceramics—a point which was not considered in Ref. 4.

In summary, the expression which we are proposing (1), is capable of describing the field dependence of the critical current of a high-$T_c$ superconducting ceramic within better than 10% over the temperature range from 0 to $0.9T_c$ and over the field range at least from 3 Oe to 3 kOe. Among the parameters $a$, $H_0$, and $I_i$, the parameter $a$ is on the order of unity and independent of the temperature, while $H_0$ and $I_i$ depend on $T$ in the regular way, falling off with increasing temperature and approaching zero near $T_c$.

I wish to thank D. A. Komarkov for furnishing the sample and for assistance in the experiments. I also wish to thank V. F. Gantmakher and A. E. Koshelev for useful discussions.

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Translated by D. Parsons