Universal Temperature Behavior of Remanent Magnetization Observed in Low-\(T_c\) and High-\(T_c\) Josephson Junction Arrays

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A comparative study of the magnetic remanence exhibited by tridimensional Josephson junction arrays in response to an excitation with an AC magnetic field is presented. The observed temperature behavior of the remanence curves for disordered arrays fabricated from three different materials (\(\text{Nb}, \text{YBa}_2\text{Cu}_3\text{O}_7-\delta\) and \(\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}\)) is found to follow the same universal law (based on the explicit temperature expressions for the activation energy and the inductance-dominated contribution to the magnetization of the array within the framework of the phase-slip model) regardless of the origin of the superconducting electrodes of the junctions which form the array.

PACS numbers: 74.50.+r; 74.25.Ha; 74.60.Jg

As it has been recently found \(^[1\, 3]\), tridimensional disordered Josephson junction arrays (JJAs) fabricated from either low-\(T_c\) (LTS) or high-\(T_c\) (HTS) superconductors may, upon excitation by a magnetic field, exhibit a temperature-dependent magnetic remanence, \(M_R(T)\). Typically \(^[1]\), the magnetized state occurs in a rather narrow window of temperatures, the extent of which depends on the critical current, \(I_c(T)\), of the junctions. Besides, there is a threshold value for the magnetic field in order to drive the JJA to the state where flux is retained after suppression of the field \(^[1]\).

In this Letter we present a comparative study of three different samples with a rather spectacular remanent behavior and suggest a possible interpretation of the observed temperature dependence of the remanent magnetization of both LTS and HTS tridimensional disordered JJAs. Our analysis shows that all the experimental data can be rather well fitted using the explicit temperature expressions for the activation energy and the inductance-dominated contribution to the magnetization of the array within the so-called phase-slip model \(^[1\, 3]\).

Three samples were prepared from selected material, respectively of \(\text{Nb}, \text{YBa}_2\text{Cu}_3\text{O}_7-\delta\) (YBCO) and \(\text{La}_{1.85}\text{Sr}_{0.15}\text{CuO}_{4-\delta}\) (LSCO). All three exhibit the predicted remanence and other characteristic features of Josephson arrays. Fabrication routes as well as the experimental routines employed for the magnetic measurements are described elsewhere \(^[1\, 3]\). In short, the corresponding (e.g., niobium) powder was separated according to grain size (using a set of special sieves, with mesh gauges ranging from 38 to 44\(\mu\)m), then uniaxially pressed in a mold to form a cylindrical pellet of 2.5\(mm\) radius by 2.0\(mm\) height. This pellet is a tridimensional disordered JJA in which the junctions are weakly-coupled grains, i.e., weak-links formed by a sandwich between (\(\text{Nb}\)) grains and a (\(\text{Nb-oxide}\)) layer originally present on the grain surface.

The measurements were made using a Quantum Design MPMS-5T SQUID magnetometer featuring the regular DC extraction magnetometer and an AC-susceptibility module. The remanence was obtained measuring the sample magnetization after application and removal of a train of sinusoidal pulses. Using the field scan routine we measured the remanent magnetization as a function of the excitation field. For an ordinary superconductor of any kind, from a single crystal to a totally disordered granular sample, the only possibility of a remanence after the application of the AC field would be a residual magnetization due to flux eventually pinned inside the specimen. This contribution, however, is expected to be small and practically independent of the excitation field. We have verified the above characteristics measuring \(M_R(h, T)\) for a variety of samples. In particular, the powder used to fabricate our arrays have the typical response of ordinary superconductors, so that the effects described below are entirely due to the formation of the 3D-JJA. The experimental results for all three samples (along with the model fits, see below) are summarized in Fig.1 which suggests that the observed behavior seems to follow a universal temperature pattern, irrespective of the type of superconductor of which the array is made.

Let us turn to a possible interpretation of the obtained results.

Since the observed remanent magnetization (RM) in our samples (JJAs) appears only below the so-called phase-locking temperature \(T_J\) (which marks the establishment of phase coherence between the adjacent grains...
in the array and always lies below a single grain superconducting temperature \( T_C \), it is quite reasonable to assume that origin of RM is related to thermal fluctuations of the phases of the superconducting order parameters across an array of Josephson junctions (the so-called phase-slip mechanism \( \pi \)). In the present approach we consider the sample as a single plaquette with four Josephson junctions (JJs), each of which is treated via an effective single junction approximation. Within this approximation, the phase-slip scenario yields then

\[
\Delta M_R(T) \equiv M(T) - M_R = M_0(T) I_0^{-2}[\gamma(T)/2] - M_R
\]

(1)

for the observed remanent magnetization. Here, \( M_0(T) \) is an inductance-induced contribution to the magnetization of the array (see below), \( \gamma(T) = U(T)/k_BT \) is the normalized barrier height for thermal phase slippage, \( I_0(x) \) is the modified Bessel function, and \( M_R = M(T_p) \) is a residual temperature-independent contribution (notice that, according to Eq.(1), \( \Delta M_R(T_J) = 0 \)).

For temperatures below \( T_J \) (where the main events take place, see Fig.1), the Bessel function can be approximated as \( I_0(x) \approx e^x/\sqrt{2\pi x} \) leading to a simplified version of Eq.(1):

\[
M(T) = 2\pi M_0(T)[U(T)/k_BT] \exp[-U(T)/k_BT]
\]

(2)

Figure 1 shows the temperature dependence (in reduced units, \( \tau = T/T_J \)) of the normalized remanent magnetization \( m_r(T) = \Delta M_R(T)/\Delta M_R(T_p) \), where \( T_p \) is the peak temperature and \( \Delta M_R(T) \) is defined via Eqs. (1) and (2). The data for YBCO- and Nb-based JJAs are found to be well fitted with the following explicit expression for the array magnetization:

\[
M(t) = A(1 - t^4)^{5/2} \exp[-\alpha(1 - t^4)]
\]

(3)

where \( t = T/T_C \). The best fits through all the data points (shown in Fig.1 by solid and dotted lines for YBCO- and Nb-based JJAs, respectively) using Eq.(3) and the known critical parameters

\[
YBCO : \quad T_C = 90K, \quad T_J = 82K, \quad T_P = 0.88T_J; \quad (4)
\]

\[
Nb : \quad T_C = 9.1K, \quad T_J = 8.2K, \quad T_P = 0.92T_J; \quad (5)
\]

yield the following estimates of the model parameters:

\( \alpha_{YBCO} = 7 \) and \( \alpha_{Nb} = 9 \).

At the same time, the data for the LSCO sample (which appears to have links weaker than the other two samples) are found to be better fitted using the following expression:

\[
M(t) = B(1 - t^2)^{3/2} \exp[-\beta(1 - t^2)^{3/2}],
\]

(6)

with

\[
LSCO : \quad T_C = 36.5K, \quad T_J = 19.87K, \quad T_P = 0.7T_J;
\]

yielding \( \beta_{LSCO} = 2 \).

To understand the observed behavior of the remanent magnetization, we need to specify the temperature dependencies of the activation energy \( U(T) \) and the inductance-dominated contribution \( M_0(T) \) to the magnetization of the array. Starting with the YBCO- and Nb-based arrays, it is reasonable to assume that

\[ U(T) = \Phi_0 I_C(T)/2\pi \] and \( M_0(T) = L I_C(T)/\mu_0 S \), where \( I_C(T) \) is an average value of the critical current, \( L \) is an average inductance of the Josephson network, \( S \) is an effective (in general, temperature-dependent, see below) projected area of the contact, \( \Phi_0 \) is the flux quantum, and \( \mu_0 \) is the vacuum permeability. In turn, the temperature dependence of the critical current is dictated by the corresponding dependence of the London penetration depth, namely \( \lambda \):

\[
I_C(T) = I_C(0)[\lambda_L(0)/\lambda_L(T)]^2
\]

(8)

where

\[
\lambda_L(T) = \lambda_L(0)[1 - (T/T_C)^2]^{-1/2}
\]

(9)

Finally, to arrive at the fitting expression given by Eq.(3), we have to assume that the projected area \( S \) is also temperature dependent (which is not unusual), viz. \( S(T) = \pi d(T)/l \) with \( d(T) \) and \( l \) being the thickness and the length of a SIS-type sandwich, respectively

\[ (d(T) = 2\lambda_L(T) + \xi) \]

\[ \lambda_L(T) = \lambda_L(0)[1 - (T/T_C)^2] \]

(10)

(Cf. Eq.(8)). Besides, in this particular case the projected area is temperature-independent, \( S = \pi l^2 \).

The above considerations bring about the following relationships between the fitting and the model parameters:

\[
A = \frac{\Phi_0 I_C(0)\alpha}{\mu_0 \lambda_L(0)l}, \quad B = \frac{2\Phi_0 I_C(0)\beta}{\mu_0 l^2}
\]

(10)

with \( \alpha = \Phi_0 I_C(0)/2\pi k_BT_C \) and \( \beta = U(0)/k_BT_C \).

In conclusion, to check the self-consistency of the model, we recall that within our scenario, the normalized remanent magnetization \( m_r(t) \) disappears for \( T \geq T_J \) (see Fig.1) where \( T_J \) is the phase-locking temperature of the Josephson network. At the same time, this temperature is usually defined via the equation \( U(T_J) = k_BT_J \) which results in the following two expressions (both valid near \( T_C \) relating the two critical temperatures \( T_C \) and \( T_J \)):
\[ t_J \equiv \frac{T_J}{T_C} = \frac{\alpha}{1 + \alpha} \]  

(11)

and

\[ (1 - t_J)^{3/2} = \frac{t_J}{\beta} \]  

(12)

for YBCO and Nb, and for LSCO based arrays, respectively. Using the above-mentioned values of the critical temperatures for the three samples and the experimentally found estimates for \( \alpha \) and \( \beta \) (see above), Eqs.(11) and (12) bring about the following reasonable estimates of the phase-locking temperatures (Cf. Eqs.(4), (5) and (7)) for the three arrays:

\[ T_{JYBCO} = (7/8)T_{CYBCO}, \quad T_{JLSCO} = (1/2)T_{CLSCO}, \quad \text{and} \quad T_{JNb} = (12/13)T_{CNb}. \]

In summary, by employing the so-called phase-slip mechanism in each element of a plaquette with four effective Josephson junctions, we have consistently derived expressions which lead to a reasonable description of the temperature behavior of magnetic remanence of disordered Josephson arrays. The values obtained for the two experimentally accessible parameters, the locking temperature, \( T_J \), and the superconducting critical temperature, \( T_C \), are in good agreement with the experimental data. The employed approach indicates that the temperature dependence of the magnetic remanence is universal, regardless of the origin of the superconducting electrodes of the junctions which form the array.

ACKNOWLEDGMENTS

Brazilian agencies FAPESP, CAPES, PRONEX and CNPq are acknowledged for partial financial support.

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FIG. 1. Temperature dependence of the normalized remanent magnetization \( m_r(T) \), showing the experimental data for three different samples and the corresponding fittings (see text).