Magnetic remanence of Josephson junction arrays

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Abstract

In this work we study the magnetic remanence exhibited by Josephson junction arrays in response to an excitation with an AC magnetic field. The effect, predicted by numerical simulations to occur in a range of temperatures, is clearly seen in our tridimensional disordered arrays. We also discuss the influence of the critical current distribution on the temperature interval within which the array develops a magnetic remanence. This effect can be used to determine the critical current distribution of an array.

Keywords: Josephson junction arrays, Superconductivity, Magnetism

In 1997, Araujo-Moreira and coworkers conducted a systematic investigation on the AC magnetic susceptibility ($\chi_{AC}$) of Josephson junction arrays (JJAs) as a function of temperature (T) and excitation field (h). Relying on simulations, they have explained the dynamic reentrance (DR) displayed by $\chi_{AC}$(T). The authors have also demonstrated that JJAs may exhibit a paramagnetic response, offering thus a plausible explanation for the Wohlleben effect (WE) - also called Paramagnetic Meissner effect - which has been unsystematically observed in several samples of high (HTS) and low (LTS) temperature superconductors. Based on this interpretation, the WE behavior would be due to one or more JJAs being formed on those samples, depending on the strict conditions under which the specimens were prepared.
In a recent work\textsuperscript{2}, we have confirmed that WE is an inherent property of JJAs. In another front line\textsuperscript{3}, we have also demonstrated that tridimensional (3D) JJAs can be produced in a controlled manner. The 3D-JJAs exhibit both WE and DR. In their simulations using a single plaquette, Araujo-Moreira et al.\textsuperscript{1} have shown that this simple model accounts for the magnetic behavior of a JJA excited by AC magnetic fields. The magnetic induction versus applied field curve (B versus H) predicts that the array may exhibit a remanent moment upon excitation by a magnetic field.

This contribution reports a systematic study of the magnetic moment displayed by a JJA after excitation by an AC field of variable amplitude. The arrays were fabricated from LTS granular superconductors. The experimental results confirm those anticipated by simulations, including the fact that the remanence only appears for a limited range of temperatures.

We have selected a 3D-JJA from a batch of LTS granular samples fabricated following a standard procedure described elsewhere\textsuperscript{3}. In short, niobium powder is separated according to grain size, using a set of special sieves, with mesh gauges ranging from 38 to 44 $\mu$m. The powder is 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 (3D-DJJA) in which the junctions are weakly-coupled grains, i.e., weak-links formed by a sandwich between Nb grains and a Nb-oxide layer originally present on the grain surface. As a consequence of the uniaxial pressure, samples produced in this way are anisotropic. This anisotropy can be enhanced by applying higher uniaxial pressures or, in contrast, it can be decreased through submission of the pellet to an isostatic pressure. In fact, the critical currents ($J_c$) of the weak-links laying in planes perpendicular to the pressure axis are much less dispersed than those along that axis, as detected by measurements of the magnetic AC susceptibility. Further treatment under isostatic pressures tends to homogenize the critical currents and eliminate the anisotropy\textsuperscript{3}.

Before pelletizing, powder quality is monitored through several techniques as X-ray diffraction (XRD), scanning electron microscopy (SEM) imaging and magnetic measure-
ments ($\chi_{AC}$ and $M^Q$ versus $T$). Proper characterization of the grains certify that we have good-quality Nb without contaminants, probably with some interstitial gases, as the critical temperature ($T_c$) is 8.9 K. Also, size distribution of the grains is within the mesh range of the sieves, adequate for the purposes of the study.

To carry out the present work, we have selected an anisotropic 3D-JJA, so that we could not only study the magnetic remanence of the system, but also emphasize the role of $J_c$ dispersion and intensity on the observed effect. The sample exhibits all characteristic features of a genuine 3D-JJA. Two of these peculiarities are shown in Figure 1: the main picture is a low-field measurement of the reentrant magnetization (WE), for $H = 2$ Oe. The inset displays a Fraunhofer pattern for the real part of $\chi_{AC}$ which, as discussed in Ref. 5, is an indirect determination of the $J_c$.

The above mentioned prediction that JJAs may develop a magnetic remanence can be appreciated in Figure 2. It is a sketch of simulation results of the $B$ versus $H$ curves ($B = H + 4\pi M$), at temperatures $T_1 < T_2 < T_3 < T_c$, for a plaquette with four identical JJJs. For $T = T_2$ one can see that, if the applied field $H$ reaches a value larger than $H_0$ and then is turned off, the system will retain a magnetic moment for $H = 0$. On the contrary, there will be no remanence at temperatures $T_1$ and $T_3$, irrespective of the maximum value attained by $H$. It must be also noticed that the remanence predicted for $T = T_2$ does not depend on the time profile of the applied field, which could have, for example, a triangular shape (up and down) or be a sinusoidal excursion around zero, as long as its magnitude reaches the threshold value $H_0$ before returning to zero.

To verify the validity of these predictions, we performed a series of experiments, based on the following steps:

i. the sample is submitted to an AC field ($h$) consisting of a train of sinusoidal pulses, after what $h$ is kept null;

ii. with $h = 0$, the magnetic moment of the sample is measured.

Steps (i) and (ii) are the core of two experimental routines: the field scan routine (FS), for which the field is changed at a fixed temperature, and the temperature scan routine
Measurements following routines FS and TS were performed using a Quantum Design MPMS-5T SQUID magnetometer. Both routines were extensively explored, furnishing valuable results for the purposes of this work. In this short paper, however, we will present in more detail results derived from the FS routine, employed at several temperatures. As shown below, one can easily recognize the existing connections between these results and the prediction of a magnetized state, as pictured in Figure 2. Remaining parts of this study, including many other aspects of the problem, will be published elsewhere.

Using the FS routine we measured the remanent magnetization ($M_r$) 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-DJJA.

The inset of Figure 3 shows three examples of measurements performed using the FS routine. Notice that all curves originate at $h = 1$ mOe with the same value of $M_r$, but the evolution of each one depends strongly on $T$. The response is flat and reversible for low temperatures, but hysteretic in an interval of higher temperatures. For the sake of clarity, a logarithmic scale was used for the field $h$. Curves in the inset are ”as measured”, i.e., without subtraction of the powder response. The main frame of the figure displays curves for different values of the excitation field, constructed using the ascending branch (field up) of the FS routines. For each value of the field, $M_r$ is the remanence of the sample from which we subtracted the signal of the powder (not shown). It is evident that, as predicted, $M_r$ is confined to a window of temperature, being larger and more pronounced as the exciting field increases. There is some activity present at lower temperatures, most possibly related to the
unscreened DC field, of the order of 30 mOe during the experiments. In fact, the plaquettes probed by the experiment (families of 2D-JJAs perpendicular to the exciting field), are also penetrated by this additional flux, which induces screening currents that contribute to the magnetization of the whole sample. This contribution might be either positive or negative, depending on a delicate compromise involving many parameters of the system.

Another effective way of eliminating spurious contributions arising from pinning - either inside the grains or by the plaquettes - is to take the difference between measurements on the ascending and descending branches of the FS routine curves. The main illustration in Figure 4 shows the results of this procedure in two situations: the squares represent measurements taken with the field parallel ($h_{//}$) to the pressure axis, whereas the circles were taken with $h$ perpendicular ($h_{\bot}$) to that axis. Notice that each curve was normalized to its larger value, based on the "as measured" data presented in the inset of the figure. Not surprisingly, the $h_{//}$ curve resembles those shown in Figure 3 (all taken at the same relative orientation), including the non-zero constant response for lower temperatures. Most remarkably, however, is the fact that both curves coincide exactly above the maxima, being rather different in the temperature interval between 5 K to 7.5 K. This distinction is deeply related to the anisotropy of the uniaxially pressed sample, and disappears for isotropic specimens pressed isostatically. As a matter of fact, we have observed for this particular sample, using SEM imaging, that the pressure used was enough to deform, along the pressure axis, a significant portion of the grains. This caused the weak-links to become too much strong, practically soldering some neighbor grains and destroying part of the plaquettes laying in planes parallel to the pressure axis. On the other direction, however, the grains were not deformed and a much larger number of weak-links was preserved. Thus, one should expect a much more intense peak for the $h_{//}$ curve, since the intensity reflects the effective number of active plaquettes. The inset shows the absolute values, giving a peak ratio of the order of 4.5.

On the other hand, the window of temperatures for which a remanence is expected (represented by $T_2$ in Figure 3) is dependent on the $J_c$. Thus, the inhomogeneous soldering of the grains along the pressure axis should also have some influence, as it causes the critical
currents of the weak-links to be much more dispersed than in the perpendicular plane. As we see from Figure 4, the range of temperatures for which a remanence exists is much larger for the planes of arrays parallel to the pressure axis, a direct consequence of the critical current dispersion. We have, therefore, another important feature of remanence studied here: its measurement, when properly calibrated, might be taken as a figure of merit to qualify a JJA in terms of the $J_c$ distribution of its constituent elements.

In conclusion, we have measured the predicted magnetic remanence of JJAs, using a 3D-DJJA fabricated from granular Nb. The remanence occurs in a limited interval of temperatures, which extent depends on the excitation field. The profile of $M_r$ is sensitive to the critical current dispersion, as revealed by experiments with our anisotropic sample, thus constituting a prospective tool to determine the $J_c$ distribution.

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4. Throughout the paper, M is the volume magnetization, i.e., the magnetic moment of the samples.

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FIGURES

Fig. 1.  Magnetization curve of 3D-JJA showing WE. The inset shows a Fraunhofer pattern of this sample, taken by AC susceptibility measurements.

Fig. 2.  Numerical simulation of B versus H for a plaquette with four JJs [Ref. 1]. The simulation predicts the appearance of a remanence after application of a field $H \leq H_0$ in a range of temperatures (as $T = T_2$).

Fig. 3.  The main illustration shows $M_r - M_{powder}$ as a function of temperature for different magnitudes of the excitation field. The inset presents the "as measured" remanence as a function of h for different temperatures.

Fig. 4.  Sample anisotropy revealed by measurements of the remanence versus temperature for different orientations of the excitation field. Main graph: data normalized to peak values. Inset: "as measured" data.
$H = 2 \text{ Oe}$
$\Delta M_r / \Delta M_r^{\text{max}}$

$h = 0.01 \text{ Oe}$

$T_c (K)$

$T_c$