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Investigation the positive moments on the M–T curve of YBCO films measured by using zero-field cooling*

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The superconducting transition of a YBCO film was measured by a MPMS-5 superconducting quantum interference device magnetometer, using a zero-field cooling process. The experimental results have shown that there are positive magnetic moment and positive peak on the M–T curve. We have proven that these anomalous behaviours are due to measurement error, but not phase transition. We have proposed a simple formula to explain and to calculate quantitatively these anomalous behaviours. It was found that, provided $\mathrm{d}H > 0.59H_\mathrm{p}$ ($\mathrm{d}H$ is the inhomogeneous field of the remnant field, H_p is the fully penetrated field of the measured sample), the experimental results will be positive, not negative. If $\mathrm{d}H \geq 2H_\mathrm{p}$, the experimental results will be symmetrical to their real negative values. From the M–T curve, which has positive moment and positive peak below T_c (superconducting transition temperature), we found a new possible method to obtain H_p of the measured sample.

Keywords: SQUID magnetometer, remnant field, superconducting M–T curve, flux pinning, positive moment, superconducting paramagnetic Meissner effect
PACC: 7420, 7460, 0755

1. Introduction

The superconducting quantum interference device (SQUID) magnetometer is very sensitive to very small magnetic signals. It is one of the best and the most advanced pieces of equipment for the measurement of magnetic properties, and is also a common tool for investigating superconducting properties.[1] However, on using this equipment an error may appear during the superconducting critical temperature measurement.[2] A superconducting positive magnetic moment has been observed by the SQUID magnetometer, and "the superconducting paramagnetic Meissner effect" has been reported and investigated.[3–6]

In this paper, we investigate the anomalous behaviours of positive moment and positive peak on the M–T curve. We point out that an inappropriate measurement will lead to these phenomena. We prove that these phenomena can be due to errors in the measurement. A simple formula is proposed to calculate these errors. We find the characteristics of the positive moment and positive peak, and the relations among the $\mathrm{d}H$ (the inhomogeneous field of the remnant field), H_p (the fully penetrated field of the measured sample), positive moment and positive peak. A possible new experimental method is then propose to obtain H_p.

2. Experimental details

A YBCO film sample was prepared by means of pulsed laser deposition. A 308nm XeCl excimer laser with a repetition rate of 6Hz was focused into the vacuum chamber to an energy density of $2\mathrm{J/cm}^2$ on the surface of the target. The distance from the target to the substrate was 3.5cm, and the substrate temperature held at 780°C was measured by an infrared pyrometer. During the deposition process the pressure of O_2 was 70Pa.[7]

The data were obtained by a MPMS-5 SQUID magnetometer using a 3cm scan length, with the applied field perpendicular to the ab plane of the sample. The scatter plot shown in Fig.1 was measured using the following process: 1, setting the field in the magnetometer to be 5T; 2, lowering the field to zero by using no overshoot mode; 3, zero-field cooling the YBCO film; 4, applying a field of 0.002T; 5, warming the sample and measuring the magnetic moment to obtain the M–T curve.

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The line plot shown in Fig.1 was measured using a procedure similar to the scatter plot in Fig.1, except for setting the zero field by using the reset mode instead of no overshoot mode.

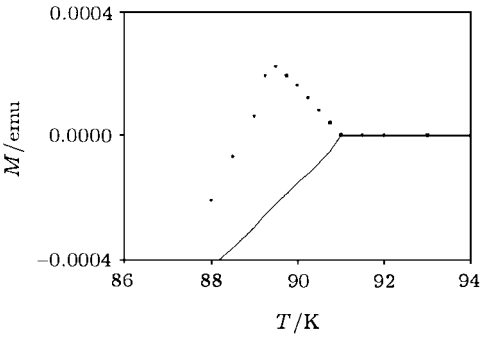


Fig.1. Superconducting transition curve of a YBCO film. The applied field for obtaining both the scatter plot and line plot is 0.002T.

3. Results and discussion

3.1. The positive magnetic moment is due to the errors made in the measurement

A common method for obtaining T_c is to find the temperature at which the measured magnetic moment changes from negative to positive. From Fig.1, the scatter plot shows that the appearance of positive magnetic moment is at 88.8K. However, the line plot shows that the appearance of positive magnetic moment is at 90.8K. There are two degrees of difference between the line plot and scatter plot.

In Fig.1 the scatter plot and line plot are obtained by using the same measuring system on the same sample. The only difference between the two measurements is the optional mode for setting the zero field. This indicates that the positive peak on the M–T curve is not the intrinsic property of the sample measured. The scatter plot in fact has a measurement error and does not mean a phase transition. The positive magnetic moment peak on the scatter plot in Fig.1 is caused by using no overshoot mode to set the zero field.

Why is there such a large error produced by using the no overshoot mode? What is the meaning of the positive peak? We discuss this in the following sections.

3.2. The remnant field in the measurement system

After the superconducting magnet has been charged to a field greater than about 0.02T, magnetic flux lines will become trapped in the windings of the superconducting magnet. When the field is decreased to zero by using no overshoot mode, the trapped field will stay in the superconducting magnet, i.e. there is a remnant field in the measuring system, which is not homogeneous. However, when the field is decreased to zero using a reset mode, the superconducting magnet will return to the normal state, and the trapped field in the superconducting magnet has gone, i.e. there is no remnant field in the measuring system.

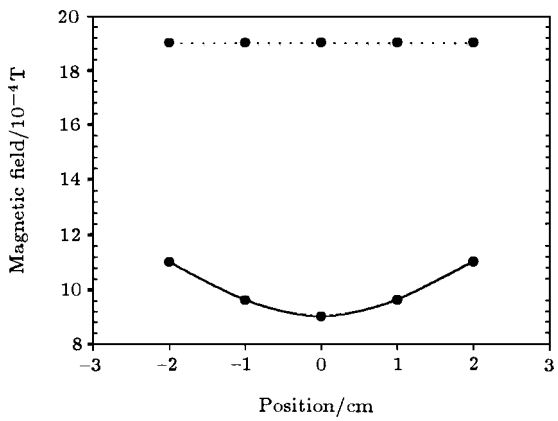


Fig.2. The profiles of the field, the field strength acting on the sample, and the effect of the two different decreasing field modes.

When the field is set to 5T and then reduced to zero by two different decreasing field modes (no overshoot mode and reset mode), and the applied field is set to be 0.002T. The real magnetic field strength, field profiles and the effect of the two different decreasing field modes are shown in Fig.2. These data were measured by a Gauss meter at 300K. The upper experimental data in Fig.2 are obtained using the reset mode. There is no remnant field in the system. The field profile is uniform and the field acting on the sample is equal to the applied field. For the overshoot mode, there is a negative remnant magnetic field retained in the measuring system, which is non-uniform. The lower experimental data in Fig.2 are obtained using the no overshoot mode.

During the measurement, the SQUID magnetometer is operated in a mode in which the sample must be translated through the pick-up coils. In this paper the measurement was performed by using 3cm of scan length. For the no overshoot mode, the field acting on the sample will decrease to about 120A/m.

3.3. Why are positive moment and positive peak produced by the inhomogeneous field?

At lower temperatures, the applied field (H_a) may be lower than H_{c1}, and the sample is in the Meissner state. When the temperature increases, H_a can be larger than H_{c1}, and the sample is in the mixed state. When the temperature further increases, the applied field H_a will be larger than H_p, and the flux lines reach the centre of the sample. According to Bean's model, the flux line distribution in the sample is shown in Fig.3 (the shaded area in Fig.3 represents the region of flux penetration under a field H_a).

From Fig.3, the magnetic induction (B) is proportional to the shaded areas, and the magnetic field strength H_a is proportional to the square area below H_a. The measured magnetization M is proportional to the difference of the above two areas. M is proportional to the area of the empty triangle in Fig.3. i.e. $M = (B - H)/4\pi$, which is negative.

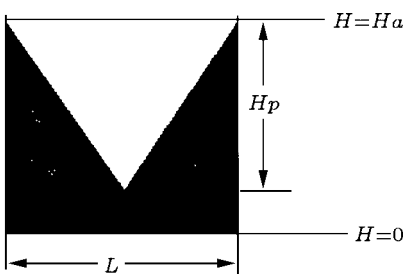


Fig.3. A plot showing a flux profile. The dark area shows the flux profile under an applied field (H_a). H_a is larger than H_p. L represents the size of the sample. The measured magnetization (M) is proportional to the area of the empty upside-down triangle, which is negative.

During the measurement, the field acting on the sample changes from H_a to H_a–dH. dH will largely affect the experimental results.[8]

The shaded area in Fig.4 shows the flux line distribution under the field H_a–dH. By comparing Fig.3 with Fig.4, we can see that the shapes of the flux profile under H_a and under H_a–dH are quite different. From Fig.4, the measured M under field H_a–dH is proportional to the area equal to the two grey-shaded triangles (A) minus the bottom small empty upside-down triangle (B). Consequently, M is strongly dependent on dH and H_p. It is easy to see (from Fig.4) that, as H_p decreases (because of increasing temperature), M can be changed from negative to positive. A detailed discussion is given in the next sections.

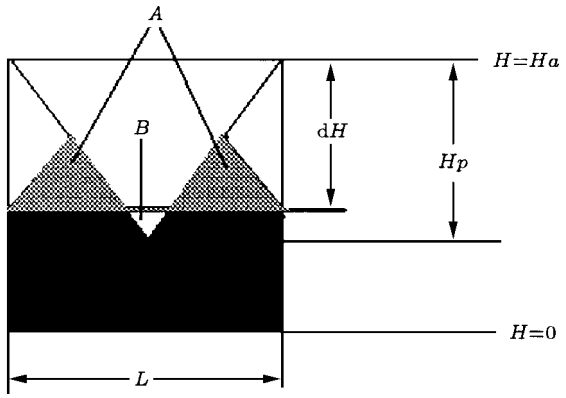


Fig.4. The flux profiles under the field H_a–dH. The measured magnetization M is proportional to the area of the two grey-shaded triangles (A) minus the bottom small upside-down empty triangle (B).

3.4. Relations among dH, H_p, positive moment and positive peak

From Fig.4, the area of A–B is proportional to the measured M. Calculating this area, we can obtain the following formula

$$
\begin{aligned}
&M \propto -1 && \text{(when } \mathrm{d}H = 0\text{)}\\
&M \propto -0.5(\mathrm{d}H/H_p)^2 && \\
&+2\mathrm{d}H/H_p - 1 && \text{(when } 0 < \mathrm{d}H < 2H_p\text{)}\\
&M \propto 1 && \text{(when } \mathrm{d}H(2H_p)
\end{aligned}
$$

If dH=0, M is always negative, since there is no measurement error produced by the field inhomogeneity, and M is the real value of the measured sample, which is proportional to the area of the empty triangle in Fig.3. We define the area of the empty triangle in Fig.3 as equal to -1.

If d$H \neq$0, from the above formula, the measured M will be different from its true value. The errors produced by the inhomogeneous field will appear. If $\mathrm{d}H = (2 - 2^{1/2})\ H_p$, the measured M is zero (true value is -1), and the error is 100%. If $\mathrm{d}H > (2 - 2^{1/2})\ H_p$, the measured M will be positive, and the errors are larger than 100%. If $\mathrm{d}H = H_p$, the error produced by the inhomogeneous field is 150%. If $\mathrm{d}H = 2H_p$, a positive peak will appear in the M–T curve, and the error is 200%. If $\mathrm{d}H > 2H_p$, the measured M is symmetric to its real value (when dH=0), and the error is 200%.

For a superconductor, if its pinning is weak (i.e. H_p is low), and dH in the measurement system is large, then $\mathrm{d}H > (2 - 2^{1/2})\ H_p$ can appear at temperatures much lower than T_c, and the positive peak

appears at temperatures much lower than T_c. The superconducting M–T curve will look like the superconducting paramagnetic Meissner effect.

The inhomogeneous field and the pinning property of the sample are the physical origin of the positive moment and positive peak on the M–T curve.

3.5. A possible method to obtain H_p from the M–T curve

From the experimental M–T curve which has a positive moment and a positive peak (the scatter plot in Fig.1), we propose a new possible method to obtain H_p. When the magnetic moment charges from negative to positive below the superconducting transition temperature, $dH = (2-2^{1/2})\, H_p$. When the magnetic positive peak appears in the M–T curve, $dH=2H_p$.

For the YBCO film used in this paper, the positive moment appears at 88.8K (see scatter plot in Fig.1), where $dH = (2 - 2^{1/2})\, H_p$. From Fig.2, dH is about 120A/m, thus at 88.8K, H_p is equal to 204A/m.

From Fig.1, the positive peak appears at a temperature of 89.5K, where $dH=2H_p$, and from Fig.2, dH is about 120A/m; thus at 89.5K, H_p is equal to 60A/m. In other words, when H_p is about 60A/m, the inhomogeneous field of 120A/m will cause the measurement signal to have a maximal positive value.

When the temperature is higher than 89.5K and lower than the real T_c 90.8K, the experimental results are not only positive, but are also symmetric to its real value. This is because the higher the temperature, the smaller H_p. Thus, at this temperature region, $dH > 2H_p$, the measurement error is 200%, and the measured values are symmetric to their real values.

4. Conclusions

The superconducting transition of a YBCO film was measured by a MPMS-5 SQUID magnetometer, using the zero-field cooling process. The positive magnetic moment and positive peak appeared at temperatures below T_c. We have proven that these anomalous behaviours are due to the measurement errors, not phase transition. We have proposed a formula to explain these phenomena, and to analyse the relations among the positive peak, the positive moment, dH and H_p. The physical origins of the positive moment and positive peak are the inhomogeneous remnant field and the superconducting flux pinning. We have found that the positive moment and positive peak have the following properties. If H_p=1.7dH, the measured M will be changed from negative to positive, and the measurement error will be 100%. If H_p=0.5dH, the measured M shows a positive peak, and the measurement error will be 200%. Provided $H_p < 0.5dH$, the measured M is symmetric to its real negative value. It is possible to obtain H_p from the M–T curve, if there are a positive moment and a positive peak on the M–T curve. The value of H_p of the YBCO film (used in this paper) is about 204A/m at 88.8K, and is about 60A/m at 89.5K. We believe that if the pinning of the measured sample is weak (i.e. H_p is low) and dH in the measurement system is large, the measured results will be symmetric to the true value at temperatures much lower than T_c. The measured results will not only appear as a very large error of T_c, but may also be investigated as the paramagnetic Meissner effect.

Acknowledgments

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