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Relationship between the magnetic field distribution and attractive force of single-domain YBCO bulk under different field cooling processes*

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The levitation forces under different field cooling states were measured at 77K by changing the field cooling distance $Z_{\rm fc}$ between a YBCO bulk and a permanent magnet. It is found that the relationship between the absolute maximum attractive force ($F_{\rm maf}$) and the corresponding gap distance ($Z_{\rm maf}$) to $F_{\rm maf}$ can be well described by exponential laws as a function of $Z_{\rm fc}$, which allow us to predict these values according to $Z_{\rm fc}$. It is also found that the distance between the $Z_{\rm 0fa}$ (gap distance corresponding to the zero force) and $Z_{\rm maf}$ in the ascending process is a constant value, which is closely related to the constant reduction factor of the axial component of flux density along the axial line of the magnet if $Z_{\rm maf} - Z_{\rm 0fa}$ is a constant value. These results are very interesting for fundamental research and helpful in practical designing and applications.

Keywords: single-domain YBCO bulk, levitation and attractive force, field cooling process
PACC: 7640, 7640M, 7490

1. Introduction

A magnet can be stably levitated over or suspended below a superconductor; this is one of the most impressive phenomena revealing the unique properties of superconductor.[1] The levitation force depends mainly on the properties of the superconductor and the magnetic field distribution of the magnet. For a single-domain YBCO bulk superconductor, the levitation force is closely related to many parameters, such as the critical current density and grain radius,[2] grain-orientation,[3−6] thickness of the sample,[7,8] and the temperature.[9] For a magnet, the levitation force is closely related to the magnetic flux density[10] and magnetic field distribution,[11−13] etc. For a given pair of YBCO bulk and permanent magnet, it is known that the same levitation force can be obtained at different gap distances between the superconductor and the magnet, due to the magnetization history of the superconductor by a mechanical descending and ascending process of the magnet during the levitation force measurement. Most of the levitation forces have been measured in the zero field cooling (ZFC) state, few works have been done in the field cooling (FC) state. In the ZFC case, the sample is cooled when the distance Z between the superconductor and magnet is kept large enough to avoid any magnetic field being trapped in the superconductor before the levitation force measurement. But for the FC state, the sample is generally cooled when the sample is very near to the magnet.[12,14] It is known that higher levitation (or repulsive) force can be obtained by the ZFC process, and larger attractive force can be obtained in the FC process. However, ZFC and FC processes are two limiting cases for the levitation force measurements, which cannot give any detailed information of levitation force or attractive force when the sample is cooled in a case between the ZFC and FC states.

The effect of different field cooling processes on the repulsive force has been clearly revealed.[15] We report here the relationship between the magnetic field

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distribution and the attractive force of a single domain YBCO bulk under different FC states. Based on the results, we can predict the attractive force in different FC states, because they obey the same laws. It is also found that there are some special interaction properties between a superconductor and a magnet.

2. Experiment

X-ray pure $YBa_2Cu_3O_y$, 4N purity Y_2O_3 and PtO_2 powders were weighed and mixed in the weight ratio of 90.5:8.5:1. The well-mixed powders were uniaxially pressed into pellets of ø35mm×14mm in a steel mould. The $Nd_{1+x}Ba_{2-x}Cu_3O_y$ single crystals were prepared in air[16] and used as seeds in this study. The pellets with seed were put into a furnace with 1–4°C/cm temperature gradient in the vertical direction. The samples were heated up to 1040–1060°C at a rate of 120°C/h, and held for 1–5h for homogeneous melting. After that, the samples were cooled to about 1020°C at a rate of 10–30°C/h, and further cooled to 960–940°C at a rate less than 1°C/h, then the samples were cooled to room temperature at a rate of 120°C/h. The as-grown single-domain YBCO samples (ø30mm×12mm) were annealed at 400–550°C in flowing O_2 for a week to turn them into the superconducting state.

The levitation forces were measured at liquid nitrogen temperature by a home-made device.[12,13] The YBCO bulk superconductor (SC) and a permanent magnet (PM) for levitation force measurements were axisymmetrically fixed in their coaxial line in the vertical direction, so that the PM (or the SC) could be moved only along the coaxial line; the SC was located in the lower part in this experimental configuration. The magnet is of ø30mm×30mm size with surface field of 0.5T. The axial component of flux density (B_z) distribution along the axis line of the PM is shown in Fig.1. In order to obtain the levitation force between the SC and PM in different FC processes, the SC was cooled to liquid nitrogen temperature while the FC gap distance (Z_{fc}) between the SC and PM was fixed before the levitation force measurement. Z_{fc} was taken to be 0.1, 0.8, 1.3, 2.0, 2.5, 3.4, 4.6, 5.2 and 7cm in this experiment. Then the PM was moved in a descending–ascending procedure, so that we can have a set of force–distance (F–Z) curves under different FC states. The maximum levitation force in this experiment was measured at the smallest gap (0.1cm) between the two nearest surfaces of the sample and the magnet.

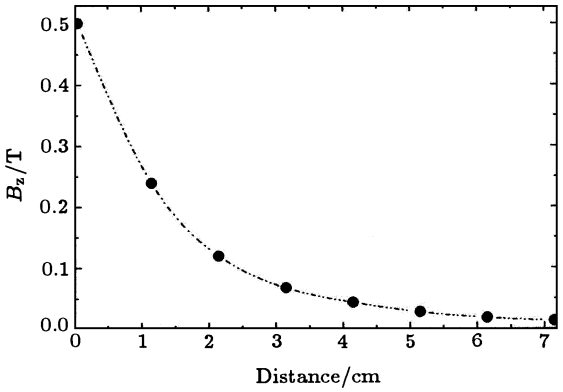


Fig.1. Axial component flux density B_z distribution along the axial line of the PM.

3. Results and discussion

The levitation force between an SC and a PM always shows a F–Z hysteresis loop during the descending and ascending process. This corresponds to the magnetization of the SC by mechanically moving the PM (or SC) to and from the SC (or PM). The repulsive force can be observed during both the descending and ascending processes. It is impossible to observe the attractive force in the descending process, but it is possible to observe the attractive force in the ascending process, which means that the levitation force is composed of repulsive and attractive forces. The F–Z curves measured under different FC states are shown in Fig.2, from which can see that the maximum levitation force decreases with the increase of the trapped magnetic field density.[15] It is clear that the levitation force curve shifts to the left side and changes from a curved line to a straight line in the upper part, where the interaction force is greater than zero; in the meantime, the slope of the curves increases from the right to the left side with the decrease of Z_{fc}. The results indicate that the stiffness of the levitation system between the SC and PM increases with the increase of trapped magnetic flux density in the SC.

As we can see from Fig.2, the same levitation force can be obtained by FC processes with different gap distances. For the same levitation force with different Z_{fc}, the gap distance decreases with the decrease of Z_{fc}, but the stiffness increases with the increase of Z_{fc}; for the same levitation force at a given Z_{fc}, the gap distance in the descending process is larger than that of the ascending process, but the stiffness in the latter is larger than that in the former. A larger suspension distance can be obtained by using a relatively larger Z_{fc}, but with decrement of attractive

force. This means that we can have the same levitation force at a relatively larger gap distance but with a smaller stiffness in the descending process, or at a relatively smaller gap distance but with a larger stiffness in the ascending process for a given Z_{fc}.

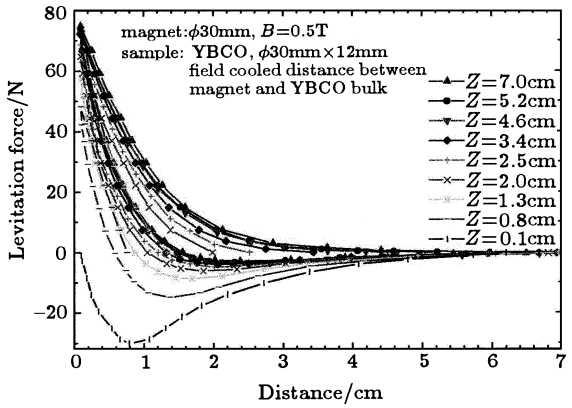


Fig.2. Levitation force versus distance (F–Z) curves different field cooling distances Z_{fc} between the SC and PM at 77K.

Figure 2 shows that the attractive force is very different for the samples in different FC states. The absolute maximum attractive force (F_{maf}) increases from 2.96N to more than 30.6N with the decrease of Z_{fc} from 7cm to 0.1cm, and the corresponding curve shape changes from flat to sharp, especially in the gap distance range where the maximum attractive force appears. At the same time, we can see that the gap distance (Z_{maf}) corresponding to F_{maf} decreases from 2.34cm to 0.8cm with the decrease of Z_{fc} from 7cm to 0.1cm. This indicates that a larger attractive force between an SC and a PM can be achieved with a smaller Z_{fc}, but accompanied by a decrement in the space between SC and PM and vice versa. It should be noted that the F_{maf}, different from the levitation force F_{mlf}, does not appear in the smallest gap between the SC and PM, but occurs at a relatively larger distance Z_{maf} for each FC state. For example, the largest F_{maf} of 30.6N appears at Z_{maf}=0.8cm but not at 0.1cm.

The absolute maximum attractive force F_{maf} at different Z_{fc} is measured and shown in Fig.3. As we can see from Fig.3, the F_{maf} value increases with the decrease of Z_{fc}, which can be well fitted by the following formula:

$$F_{maf} = 2.96 + 31.15e^{-\frac{Z_{fc}}{0.82}}. \quad (1)$$

The dotted curve going through the solid triangle data is calculated using formula (1). It is in good agreement with the experimental data. This indicates that the F_{maf} increases exponentially with the decrease of Z_{fc}. The exponential equation (1) is closely related to the exponential decay of the magnetic field density along the axis of the PM. According to Eq.(1), we can predict the F_{maf} values for a given Z_{fc}, and vice versa. These results are very important for practical applications, especially for the design and manufacture of superconducting devices.

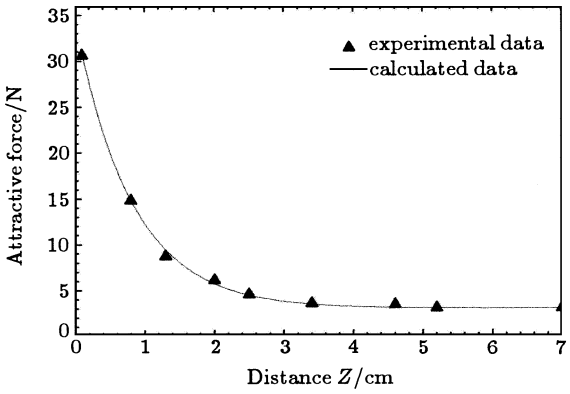


Fig.3. Absolute maximum attractive force F_{maf} versus the field cooling distance Z_{fc}.

In Fig.2, the Z_{maf}, corresponding to the distance where F_{maf} appears, is very different for different Z_{fc} values. At the same time, the gap distance Z_{0fa}, corresponding to the distance where zero force (F_{0fa}) appears in the ascending process, varies also as a function of Z_{fc}. The relationships of Z_{maf} versus Z_{fc} and the Z_{0fa} versus Z_{fc} are shown in Fig.4. This figure shows that both Z_{maf} and Z_{0fa} decrease with the decrease of Z_{fc}; the two curves are similar but different in magnitude. The solid line passing though the filled circle data of Z_{maf} versus Z_{fc} is calculated by the following formula:

$$Z_{maf} = 2.35 - 1.65e^{-\frac{Z_{fc}}{1.57}}. \quad (2)$$

As we can see from this figure, the calculated curve is in good agreement with the experimental data. This phenomenon can be well explained by the Bean model,[2,9] which is closely related with the trapped magnetic flux in the sample, produced by the magnet with different cooling distances (z) between the sample and the magnet. The smaller the z value, the stronger the trapped magnetic field in the sample and the larger the attractive force between the sample and the magnet. For the Z_{0fa}–Z_{fc} curve, it can be well described by the following equation:

$$Z_{0fa} = 1.46 - 1.5e^{\frac{Z_{fc}}{1.62}}. \quad (3)$$

The dashed line going through the filled triangle data is calculated using Eq.(3), which is in good agreement with the experimental results.

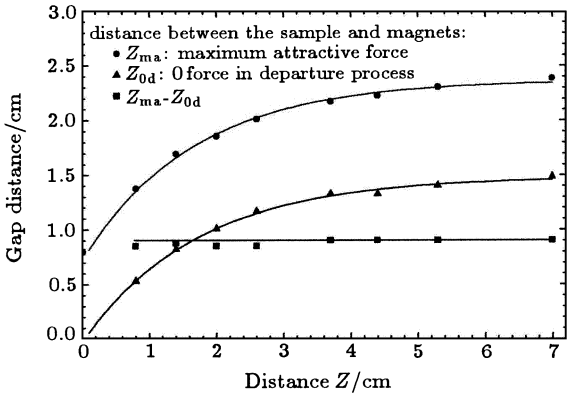


Fig.4. Gap distances of Z_{maf} and Z_{0fa}, and the difference $Z_{maf} - Z_{0fa}$ versus Z_{fc}.

It is very interesting to note that the difference of distances between Z_{maf} and Z_{0fa} is approximately a constant value of 0.8cm for different Z_{fc} within the experimental error. As we can see from Fig.4, the filled square data are the differences between Z_{maf} and Z_{0fa}, which form nearly a line with a constant value. This is a new discovery of the physical properties for a SC and PM system, which is related to the intrinsic characteristics of the material and the PM.

It is necessary to make clear why $Z_{maf} - Z_{0fa}$ is a constant value. In our experiments, the parameters of SC and PM are fixed, the levitation force is produced by the interaction between the external magnetic field and the induced current in the SC. However, the current contributing to the interaction force between the SC and PM is induced from the axial component of the external field, so we should make clear the relationship between the magnetic field distribution and the parameters related to the attractive force. According to Fig.1, we calculate the axial component of magnetic flux density B_z at distances of Z_{maf} and Z_{0fa} along the axis line of the PM for each Z_{fc}, as shown in Fig.5.

As we can see from Fig.5, the magnetic flux density B_{z0fa} at a distance $Z = Z_{0fa}$ is larger than that of B_{zmaf} at $Z = Z_{maf}$. Both B_{z0fa} and B_{zmaf} decrease with the increase of Z_{fc}. The difference between B_{z0fa} and B_{zmaf}, and the reduced ratio of $(B_{z0fa} - B_{zmaf})/B_{z0fa}$ have been calculated and are also shown in Fig.5. It is very interesting to note that the reduction rate of the magnetic flux density from B_{z0fa} to B_{zmaf} is nearly a constant value around 42%. This just corresponds to the constant value of Z_{maf}-Z_{0fa}. So it is clear that, for a given set of SC and PM, the interaction force from zero to F_{maf} in the ascending process corresponds to around 42% reduction of the magnetic field in the axial component. These values are constant but may be different for different set of SC and PM system, due to the different physical properties of SC and different field distribution of PM.

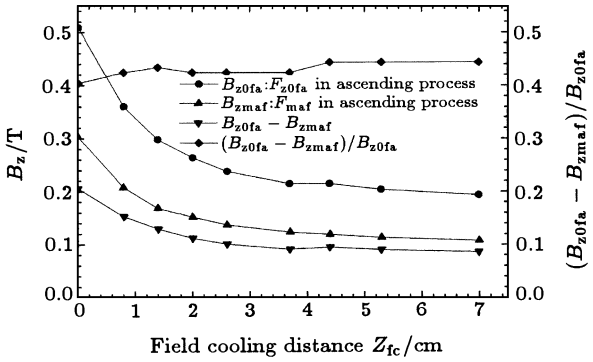


Fig.5. Axial component of magnetic flux density B_{z0fa} at Z_{0fa} and B_{zmaf} at Z_{maf} for different Z_{fc}, and the decrement of B_{0fa}-B_{maf} and the reduction rate of $(B_{z0fa} - B_{zmaf})/B_{z0fa}$ under different Z_{fc}.

For a given constant difference of distances along the axis of a cylindrical PM, the reduction rate of magnetic field density is a constant. Generally, the axial component of flux density (B_z) of the PM can be formulated as

$$B_z = B_0 e^{-AZ}, \tag{4}$$

where A is a constant value for the PM, B_0 is the axial component of magnetic flux density at the surface centre of the PM, and Z is the distance from the top surface of the PM along the axial line. If Z changes from Z_1 to Z_2, it is easy to deduce the following equation:

$$\frac{B_{Z_1} - B_{Z_2}}{B_{Z_1}} = 1 - e^{-A(Z_2 - Z_1)}. \tag{5}$$

This formula indicates that for a given difference of distance $Z_2 - Z_1$, the reduction rate of magnetic flux density is also a constant, which is in good agreement with and can well interpret the experimental results in Figs.4 and 5.

4. Conclusion

In summary, the effects of different FC processes on the attractive force of single-domain YBCO bulk have been investigated. It is found that F_{maf} increases from 2.96N to 30.6N with the decrease of Z_{fc} from 7cm to 0.1cm. This obeys the first decreasing exponential law. The stiffness between the YBCO and magnet increases with the decrease of Z_{fc}. It is also found that the distances of Z_{maf} and Z_{0fa}, corresponding to the distances of F_{maf} and F_{0fa}, respectively, decrease

according to an exponential law with the decrease of Z_{fc}. The results can help to predict the values of F_{maf} and Z_{maf} at different Z_{fc}. The same difference of distances between Z_{maf} and Z_{0fa}, corresponding to F_{maf} and F_{0fa} of different Z_{fc}, is related to the constant reduction rate of flux density of the PM from B_{0fa} and B_{maf}. The results are very useful for practical design and other applications.

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