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# Vortex avalanches in a Pb-porous glass nanocomposite

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Magnetic properties of a superconducting lead-porous glass composite were studied. The glass pore size was 7 nm. The onset of superconductivity was observed at 7.22 K with complete diamagnetic screening at lower temperatures. Strong magnetic instabilities were found on the magnetization-versus-field loops in the temperature range from 1.8 to 5.5 K at a sweep rate of 20 Oe/s. The shape of the hysteresis loops above 2.5 K was typical for other types of hard type-II superconductors in the adiabatic limit, the field of the first jump on the virgin magnetization being maximal at 3.5 K. Below 2.5 K the hysteresis loops become complex, showing different behavior at lower and higher fields. The nature of such a loop was discussed. The smooth hysteresis loops just below the superconducting transition had fishtails that completely disappeared down to 6 K. The evolution of magnetization instabilities until complete smoothing away the hysteresis loops with increasing or decreasing the sweep rate was observed at 1.8 or 5 K, respectively.

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## I. INTRODUCTION

Magnetic instabilities or flux jumps observed in some type-II superconductors are of great interest for applied and fundamental physics, and therefore they were extensively studied for more than 40 years (see the reviews in Refs. 1 and 2). Flux jumps were first found in metallic low-temperature superconducting materials and later in high-temperature and other unconventional superconductors. The most studied bulk superconductors with magnetic instabilities are the conventional low-temperature superconducting Nb and its alloys (see Refs. 1 and 3–6 and references therein), YBaCuO and some other high-$T_c$ superconductors (see Refs. 7 and 8 and references therein), and $MgB_2$ (see Refs. 9 and 10 and references therein), which have a rather low heat capacity and the possibility to transport high enough $J_c$. It is generally assumed that the occurrence of magnetic instabilities is caused by abrupt redistribution of Abrikosov vortices triggered by thermomagnetic fluctuations.[4,11] When type-II superconductors are submitted to an external magnetic field that is higher than the lower critical field $H_{c1}$, flux-bearing vortices enter inward through the sample borders until they are captured by pinning centers. This process results in inhomogeneous flux distribution over the sample volume. The spatial variation of the magnetic field gives rise to supercurrents in the sample that were accommodated to be exactly the critical current $J_c$. The achieved self-organized state is called the critical state. Under small perturbations, such as, for instance, local temperature fluctuations, vortices move to adjust a new critical current relevant to the altered temperature. The energy dissipation produced by moving flux lines leads to a local increase in temperature. If the latter is smaller than the initial fluctuation, the critical state remains stable. Otherwise, the positive feedback gives rise to vortex avalanches and pronounced flux jumps. The flux avalanche patterns depend also on the sample geometry (see Ref. 12 and references therein). In particular, recent studies of magnetic instabilities in thin superconducting films revealed dendrite and branched fingerlike patterns as well as feather-shaped flux fronts.[2,12–15]

The flux jumps in type-II superconductors are often observed experimentally by measuring the magnetization at sweeping external magnetic field $H_e$.[7,8,10,16] In this case, the initial rise in the local temperature emerges owing to small flux changes provoked by increasing or decreasing $H_e$. On hysteresis loops $M(H_e)$, the flux jumps, when they occur, are seen as abrupt decreases in magnetization followed by gradual recovering. Depending on ambient conditions and particular superconductor features, the magnetization jumps can be minuscule and hardly recognized or enormous. Basic concepts on superconductivity and model theories predict a strong dependence of magnetic instability on temperature, which agrees with known experimental results.[1,4,5,11] For many superconductors, magnetization jumps can be observed only within some temperature and field ranges in the superconducting state.[1,16,17] A drastic influence of the field sweep rate on magnetization jumps is also expected, but only few experimental observations were reported until recently.[8,18–21]

Here we present results of experimental observations of magnetic instability variations with the field sweep rate and temperature for a lead-porous glass nanocomposite. The flux jumps are detected by magnetization measurements upon sweeping the external magnetic field. At present, composites with nanosized metallic inclusions[22] attract increased attention because of their perspective technological applications in superconducting devices and other nanodevices. As far as we know, no studies of magnetic instabilities were carried out for a nanocomposite consisting of lead nanoparticles embedded into porous glass, and they were never seen in granular or textured lead, while dendrite flux avalanches were observed in thin Pb films.[23] Small magnetization jumps were reported for a Pb film with a square antidote array,[24] and weak flux jumps were found in a lead inverse opal.[25]

 

## II. SAMPLES AND EXPERIMENT

The porous glass sample was made from phase-separated soda borosilicate glass with the pore structure produced by acid leaching. After acid leaching, an interconnected network of fine pores was formed with an average pore diameter of 7 nm, as determined by mercury intrusion porosimetry, which showed also that 80% of pore volume corresponded to a size range from 6.8 to 7.4 nm. The volume fraction of pores was ∼24%. The liquid lead was embedded into the porous glass under high pressure of up to 10 kbar. The filling of the total pore volume near 85% was evaluated by weighing the sample. The specimen for magnetization measurements had the form of a slab with dimensions of 1.4 × 2.1 × 3.7 mm. The surface of this specimen was thoroughly cleaned to remove traces of bulk lead.

Magnetic properties were studied using a Quantum Design superconducting quantum interference device (SQUID) magnetometer with a 7-T solenoid in the temperature range 1.7–20 K. The temperature during measurements was stabilized within 0.01 K. The zero-field-cooled (ZFC) and field-cooled (FC) magnetizations were measured by using the conventional procedure of cooling the sample at zero field down to minimal temperature, switching on the magnetic field, warming up to 20 K, and subsequent cooling at a constant applied field. The hysteresis loops were monitored upon sweeping the external field with a sweep rate ranging from 0.25 to 700 Oe/s. The resistance was measured by a four-probe method by using a Quantum Design physical property measurement system (PPMS) at zero magnetic field upon cooling.

## III. EXPERIMENTAL RESULTS

The temperature dependences of the ZFC and FC magnetization obtained for the sample under study at a magnetic field of 1 Oe and ZFC magnetization at 10 Oe are shown in Fig. 1. The magnetization was calculated without taking into account the demagnetizing factor. The onset of diamagnetism is seen at 7.22 K with near complete diamagnetic shielding at lower temperatures. As can be seen from Fig. 1, the FC magnetization is weak compared to the ZFC magnetization at low temperature. The dependence of resistance on temperature is shown in the inset to Fig. 1. The resistive transition is very sharp with a transition temperature that is quite similar to that in bulk lead [7.19 K (Ref. 26)].

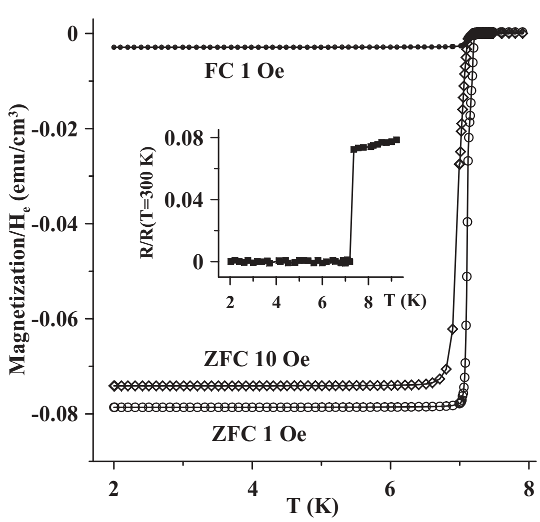


FIG. 1. Temperature dependences of the magnetization divided by field. Open symbols show the ZFC magnetization observed at fields of 1 Oe (circles) and 10 Oe (diamonds); closed symbols show the FC magnetization at 1 Oe. The inset shows the temperature dependence of the sample resistance at zero field.

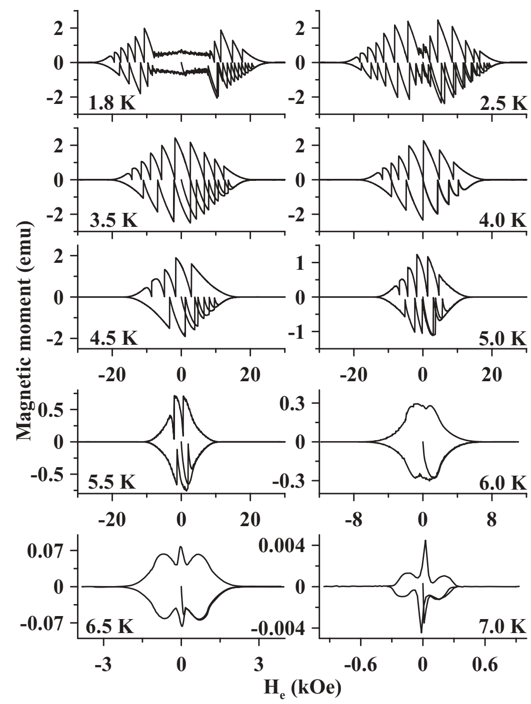


FIG. 2. Magnetization-vs-field hysteresis loops at different temperatures obtained at a sweep rate of 20 Oe/s.

The magnetization-versus-field loops obtained at different temperatures upon the same sweep rate, 20 Oe/s, are shown in Fig. 2. Pronounced magnetic instabilities are seen only below 6 K. At 6 K some tiny flux jumps can be still observed, but at 6.5 K and above the hysteresis loops do not show any signs of instabilities. Note that at a temperature of 6.5 K and higher temperatures up to the superconducting transition, the hysteresis loops feature the distinct fishtail shape. Below 5.5 K and up to 3 K, the magnetization jumps are full or almost near full. The number of magnetization jumps decreases with increasing temperature, and they are concentrated closer to the center of the loops. At 5.5 K no jump event is seen on the virgin magnetization curve, while a jump is observed in every quadrant for the secondary magnetization. Generally, the $M(H_e)$ loops in the temperature range from 5.5 to 3 K are rather similar to instability patterns often seen for typical type-II superconductors of different natures.[3,7,10,11,16,19,20] At 2.5 K one can see alterations in the vortex behavior: Incomplete and frequent jumps occur at low fields in the central part of the hysteresis loop. This trend develops to lower temperatures, leading to a complex loop at 1.8 K.

Magnetization pattern variations with a sweep rate were studied here at two temperatures, 1.8 and 5.0 K. Figure 3 shows some examples of the hysteresis loops at 5 K. Magnetic instabilities gradually disappear when the sweep rate decreases

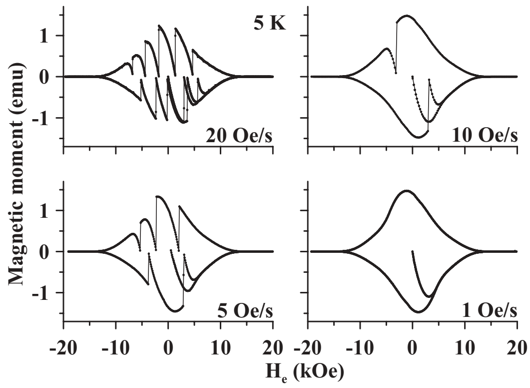


FIG. 3. Magnetization-vs-field hysteresis loops at 5 K observed at different sweep rates below 20 Oe/s.

from 20 to 1 Oe/s, with flux jumps remaining full at any sweep rate. However, the number of magnetization jumps reduces with a decreasing sweep rate in a nonmonotonic way, as can be seen from patterns obtained at 10 and 5 Oe/s. At a rate of 1 Oe/s, the magnetization-versus-field loop becomes stable and remains unchanged when the sweep rate was equal to 0.5 and 0.25 Oe/s.

The case of the magnetization pattern alterations with increasing the sweep rate at 1.8 K is presented in Fig. 4. By starting from a rate of 50 Oe/s, some jumps on the higher field parts of the hysteresis loops become incomplete and the amplitude of the magnetization jumps decreases. Such trends become pronounced at 200 Oe/s. At a rate of 300 Oe/s, one can observe only individual incomplete jumps, which smeared eventually at higher sweep rates. The hysteresis loop at 700 Oe/s corresponds to the averaged central part of loops at lower sweep rates.

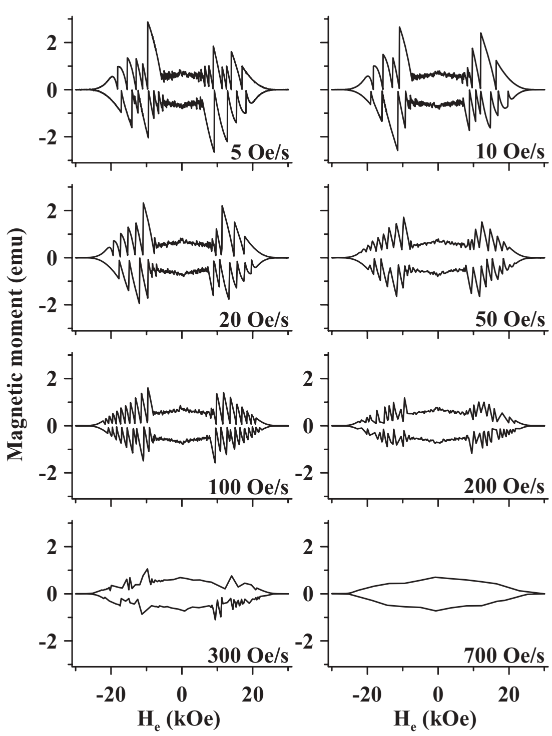


FIG. 4. Magnetization-vs-field hysteresis loops at 1.8 K observed at different sweep rates above 20 Oe/s.

According to Figs. 2–4, the magnetic instability patterns in the first and third quadrants as well as the second and fourth quadrants on the hysteresis loops are quite symmetric in pairs, but they are somewhat less symmetric with respect to the field axis. Such binary symmetry was also seen in measurements performed with high-temperature superconducting materials.[7,9,10,27]

## IV. DISCUSSION

The temperature dependences of ZFC and FC magnetization (Fig. 1) show behavior typical for dirty type-II superconductors. The onset of weak diamagnetism is seen to be slightly higher than the superconducting temperature for bulk Pb. However, the maximal derivative of ZFC with temperature at 1 Oe is observed at 7.15 K. Note that in earlier studies of synthetic lead composites, a slight reduction of the superconducting transition temperature was reported,[28,29] which agrees with the shift of the derivative maximum. The near-complete diamagnetic shielding at temperatures lower than 6.6 K confirms that the whole composite sample is screened by supercurrents. The superconducting transition is quite sharp, in agreement with the complete shielding. These results evidence that the behavior of the sample is in accordance with the models developed in Refs. 28–30, where the metal-glass composite was conceived as a type-II granular superconductor, whose behavior is dominated by strong Josephson links. It was suggested in Refs. 28 and 29 that spatial inhomogeneities of the pore network provoke inhomogeneities in metal distribution over the sample volume, leading to a hierarchy of interparticle Josephson links. Several strongly coupled neighbor nanoparticles within pores form granules that are also linked with each other. In the case when weak Josephson links between granules play an important role, one should expect a two-step superconducting transition with incomplete diamagnetic shielding at low temperature.[31–35] Because in the lead-porous glass nanocomposite under study the superconducting transition is sharp and the whole sample was screened from an external field, one can conclude that the intergranular coupling is dominated by strong links.[28–30],[33] A big difference between the ZFC and FC magnetizations seen in Fig. 1 reveals strong pinning in the sample.

In agreement with these results, the temperature and sweep rate variations of the magnetization-versus-field hysteresis loops shown in Figs. 2–4 can be understood by using general concepts developed for magnetic instabilities in type-II superconductors. The first ideas on the theoretical description of magnetic instabilities were suggested in Refs. 4, 11, 36, and 37 on the basis of the critical state model. Because the conditions after a temperature fluctuation depend on two processes of heat dissipation and critical current adjustment, the so-called adiabatic approximation, corresponding to the limit when the thermal diffusivity is much slower than the magnetic one, was assumed in Ref. 11. Then the critical current after a flux jump just follows a change in temperature, which is defined by the emerged heat. For the Bean model of critical current, which is independent of magnetic field, the following analytical formula was obtained[11] for the field $H_{\text{fj}}$ at which the first jump on the virgin magnetization is seen:

$$H_{\text{fj}} = \sqrt{\pi^3 c J_c/(-dJ_c/dT)}, \qquad (1)$$

where $c$ is the specific heat and $J_c$ is the critical current density. The theory of magnetic instabilities within the adiabatic approximation was further developed for various field dependences assumed for the critical current (see Refs. 7 and 38 and references therein), but in most of those cases the field of the first jump can be evaluated only numerically. A theoretical analysis within the framework of the adiabatic approximation predicts that the field of the first flux jump does not depend on the sweep rate.

A competition between thermal and magnetic diffusion was also considered (see Ref. 1 and references therein). An approximation corresponding to the opposite limit of slow magnetic diffusivity was suggested in which the temperature rise in the superconductor was neglected. Under some additional assumptions, including that on the field dependence of the critical current, an analytical formula for $H_{\text{fj}}$ was derived in Ref. 39, which predicted that magnetic instabilities can be always observed at high enough sweep rates.

Both approaches were generalized in a recent analysis[40] on the basis of the coupled magnetic and heat diffusion equations. Numerical results showed that the occurrence of flux jumps depends crucially on the sweep rate as well as on temperature. At a very slow rate of sweeping field, the hysteresis loops are free from jumps. When the sweep rate increases, the magnetization-versus-field curves at a given temperature show regular magnetization jumps, which become more often with increasing the rate of changing field. At further increasing the sweep rate, the flux jumps become very rapid and gradually smooth away, with the magnetization being much smaller than at slow sweeping. Similar trends were obtained for variations of hysteresis loops with temperature. The results of the numerical analysis[40] agree well with experimental studies of magnetic instabilities carried out for textured $Bi_2Sr_2CaCu_2O_{8+\delta}$ in Ref. 19, where the disappearance of flux jumps was observed above some boundary temperature and below a threshold sweep rate.

The behavior generally similar to that predicted in Ref. 40 but with some remarkable peculiarities is seen in Figs. 2–4. Figure 2 shows that at temperatures close to the superconducting transition, the magnetization jumps at a particular sweep rate are no longer observed. At 5.5 K the jumps are seen on the secondary magnetization, but still do not occur on the virgin magnetization, in agreement with the predictions of Ref. 40. Such a difference between the experimental virgin and secondary magnetizations was not reported in Ref. 19. Below 5.0 K and up to 2.5 K, the flux jumps show thermally activated behavior that is typical for type-II superconductors, which is consistent with the adiabatic theory mentioned previously.[7,11] The field $H_{\text{fj}}$ of the first jump on the virgin magnetization increases and then decreases with decreasing temperature, as shown in Fig. 5. Note that for 2.5 K the field of first full jump was shown in Fig. 5, while at lower fields there are still incomplete jumps. The field corresponding to the first incomplete jump is also depicted in Fig. 5, and is marked with an open symbol. $H_{\text{fj}}$ achieves

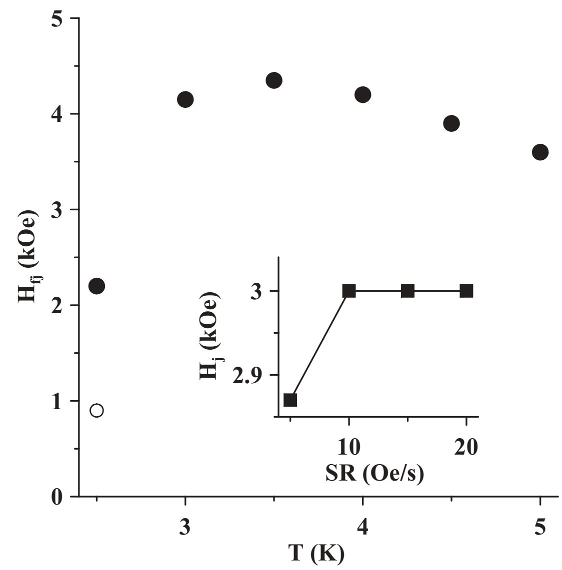


FIG. 5. Temperature variations of the field $H_{fj}$ of the first full jump on the virgin magnetization at a sweep rate of 20 Oe/s (closed symbols). An open symbol shows the field of the first incomplete jump at 2.5 K. The inset shows variations of the field $H_j$ of the first jump on the secondary magnetization by changing the sweep rate SR at 5 K.

its maximal value at ~3.5 K. The existence of maximal $H_{\text{fj}}$ at an intermediate temperature agrees with predictions of Eq. (1) if the usual assumptions on the temperature dependences of the specific heat and critical current are made: $c \propto T^3$ and $J_c \propto (1 - T/T_c)$. However, according to relationship shown in Eq. (1) the $H_{\text{fj}}$ maximum should be observed at $T = 0.75T_c$, while in our experiments it is seen near $T = 0.5T_c$, which evidences some deviations from the Bean assumption for the critical current. Thus, one can assume that in this temperature range the thermal diffusivity is actually smaller than the magnetic one. However, at a temperature of 1.8 K, the magnetic jumps differ remarkably from those predicted in Ref. 40. Very small, incomplete, and rapid jumps such as noise are seen only in the central part of the hysteresis loop, while at higher fields the flux jumps remain full with a much lower periodicity. The highest magnetization level in this field range is remarkably smaller than at the higher field. It means that the sample temperature fluctuates near an average temperature, which is higher than the bath one. However, at higher fields the temperature settled after a flux jump is close to or exceeds the superconducting transition temperature and restores to the bath one. As far as we know, such types of magnetic instabilities as were seen at 1.8 K were not observed for other superconductors. The coexistence of minuscule rapid magnetization jumps typical for slower magnetic diffusion at the central part of the hysteresis loop with full jumps associated with faster magnetic diffusion at a higher field could be understood if we imply that the vortex mobility depends crucially on the magnetic field and rises strongly above a threshold field. The influence of the relation between the thermal and magnetic diffusivities on the avalanche pattern and dynamics was recently discussed in Ref. 12.

The magnetic instability patterns observed in the lead-loaded porous glass (Fig. 2) differ remarkably from magnetization jumps found in a Pb thin film with a square antidote array.[24] It was suggested in Ref. 24 that the antidote array leads to the emergence of the terraced critical state, and the movement of terraces induces the jumps of magnetization, while the general behavior and structure of the lead-porous glass nanocomposite agrees with the model of it as a granular type-II superconductor,[28–30] where the thermomagnetic instabilities are expected. The boundaries between effective granules serve as the most probable vortex pins.[30,33] Such types of pins are general for any granular superconductors of a different nature.

The fishtail or peak effect on the magnetization-versus-field curves just below the superconducting transition (Fig. 2) evidences a nonmonotonic dependence of the critical current on the applied field, in contrast to a linear decrease of the critical current with increasing magnetic field reported in earlier works on synthetic superconductors with lead.[28] It is interesting that the fishtail effect for the lead-porous glass nanocomposite has a strong temperature dependence and can be seen only near the superconducting transition. The fishtail hysteresis loops were also observed for a porous glass impregnated with Ga (Ref. 33) but in a much larger temperature range. The existence of fishtails on the magnetization loops is consistent with theories for Josephson junctions arrays,[41,42] which model the behavior of granular superconductors.

The magnetization-versus-field hysteresis loops shown in Figs. 3 and 4 reveal a strong dependence of magnetization jumps on the sweep rate. The gradual disappearance of jumps with decreasing sweep rate is seen in Fig. 3. At a rate of 1 Oe/s, the vortex creep stabilizes completely the magnetization at 5 K. While such a result at low sweep rate is expected from a general consideration of the phenomenon of magnetic instability, there are only few experimental observations of this effect.[18–20] The magnetization jump disappearance with slowing the field sweep was reported recently for superconducting $MgB_2$.[18] However, the jumps seen in Ref. 18 at higher sweep rates were very small, resembling noise. The vanish of full jumps on the virgin magnetization was observed at $T/T_c \approx 0.046$ for the textured $Bi_2Sr_2CaCu_2O_{8+\delta}$ in Ref. 19, at a rate of 1 Oe/s. No data were reported for magnetization jumps versus sweep rate in other quadrants. In Ref. 20 the smoothed virgin magnetization curves were observed for a textured $(Nd_{0.33}Eu_{0.33}Gd_{0.33})Ba_2Cu_3O_{7-\delta}$ bulk superconductor with Gd-211 doping particles at $T/T_c \approx 0.03$, when the sweep rate was equal to or lower than 100 Oe/s, while full flux jumps still remained in the third quadrant. In our studies jumps on the virgin magnetization are seen only when the sweep rate exceeds 10 Oe/s at $T/T_c = 0.7$. Jumps on the secondary magnetization are seen at slower sweep rates up to 1 Oe/s. The field $H_j$ of the first jump on the secondary magnetization curve in the first quadrant is shown in the inset of Fig. 5. $H_j$ practically does not depend on the sweep rate, which corresponds to the assumption of adiabatic conditions. Note that the vertical size of the hysteresis loops in Fig. 3 remains the same for the sweep rate range from 1 to 10 Oe/s. It shows that the magnetization completely recovers after a jump when it occurs, and the sample achieves the thermal equilibrium with the bath. Therefore, the thermal conductivity of the composite is high enough despite its heterogeneous structure, in agreement with zero resistance below the superconducting transition.

The gradual smoothing away of magnetization jumps with increasing sweep rate is shown in Fig. 4. The full jumps on the hysteresis loop wings become more rapid, starting from a rate of 50 Oe/s and the final temperature after each jump decreases. At 200 Oe/s and to a higher sweep rate of up to 400 Oe/s, only small jumps can be observed on the loop wings. In contrast to the magnetization on the wings, the central part of the hysteresis loop remains almost undisturbed until the minuscule jumps disappear at a rate of 300 Oe/s. At the rate 700 Oe/s the magnetization-versus-field curve is smooth, with the magnetization level corresponding to that in the central part upon a slower sweeping field. By comparing the results obtained with the numerical predictions of Ref. 40, one can see good agreement of the calculations with the behavior of the jumps on the loop wings, which follows the general ideas about the evolution of magnetic instabilities that, when the adiabatic approximation is no longer valid, the system is characterized with an average temperature that different from the bath temperature, and some kind of dynamic equilibrium is established between the heat removed to the bath and that produced in the sample by moving vortices. The shape of the smooth experimental hysteresis loop at low fields does not match with the numerically obtained ones, in particular, it does not show a peak near zero field accompanied with a single flux jump. This again shows a specificity of magnetic instabilities at low temperatures and low magnetic fields in the lead composite under study.

In conclusion, magnetic instabilities were found in the temperature range from 1.8 to 6.0 K for a lead-porous glass nanocomposite with a superconductivity onset temperature 7.22 K. The ZFC and FC magnetization and resistivity behavior was consistent with the model of the composite as a granular superconductor dominated by strong links. In agreement with this, in the range from 2.5 to 5.5 K the magnetic instabilities on the magnetization-versus-field curves at the sweep rate of 20 Oe/s were typical for other kinds of hard type-II superconductors in the adiabatic limit. The field of the first jump on the virgin magnetization achieved a maximum at 3.5 K, which corresponds to $T/T_c \approx 0.5$. It was shown that the magnetization jumps at 5 K gradually disappear with decreasing the sweep rate, with jumps on the secondary magnetization surviving at a slower sweeping rate compared to those on the virgin magnetization, which is consistent with predictions of numerical analysis in Ref. 40. At 1.8 K the magnetic instabilities change remarkably, and show quite different behavior at a low magnetic field in the central part of the hysteresis loop and at a higher field on the hysteresis loop wings. Studies of the evolution of hysteresis loops at 1.8 K with increasing sweep rate confirmed the specificity of magnetization at this temperature. The magnetization jumps at high enough sweep rate were shown to be smoothed away, with magnetization settled on a level corresponding to the central part of the hysteresis loops at a slower sweeping rate. It was suggested that the complex shape of the hysteresis loop at 1.8 rises owing to a field dependence of the magnetic diffusivity. In addition, fishtail loops without flux jumps were observed above 6.5 K, with the fishtail effect completely vanishing at 6 K.

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