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Negative dynamic creep in the peak-effect regime in type-II superconductors

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We report the observation of a negative dynamic creep rate, i.e., increasing irreversibility in the magnetic hysteresis loop for decreasing sweep rate of the magnetic field, in both $YBa_2Cu_3O_{7-\delta}$ and 2H-$NbSe_2$ single crystals. This phenomenon is found to appear on the increasing branch of the peak effect that corresponds to a state which is intermediate between the dislocation-free Bragg glass and a highly disordered vortex phase. The origin of this anomalous creep is shown to be connected to a negative differential resistance resulting from the *N*-like shape of the current-voltage characteristics.

One of the most important features of type-II superconductors is the existence of thermally activated flux creep.[1] This phenomenon is manifested at finite temperatures either for a fixed magnetic field through the time decay of the current flowing in the superconductor or with the dependence of the magnetic moment on the rate with which the magnetic field is swept.[2] The latter regime, with varying magnetic field, is often called a dynamic creep. The flux creep phenomenon can be connected to the current-voltage characteristics of the superconductor. In the dynamic case the magnetic moment is related to the shielding current, and the sweep rate of the magnetic field to the value of the electric field.[3] Then, according to the usual behavior of the current-voltage characteristics, one expects an enhancement of the irreversible magnetic moment as the magnetic-field sweep rate is increased. However, an anomalous negative creep behavior was recently reported for a twinned $YBa_2Cu_3O_{7-\delta}$ single crystal in a tilted magnetic field.[4] The nature of the anomaly, and whether this phenomenon exists in other superconductors as well, remain unclear. In this paper, we show that the negative creep anomaly is a general phenomenon and is a precursor to the peak effect (PE) in superconductors with weak pinning. Two different superconductors were studied: a pure twin-free $YBa_2Cu_3O_{7-\delta}$ and a 2H-$NbSe_2$ single crystal. Previous investigations had found that 2H-$NbSe_2$ has a very sharp peak effect and suggested that the onset of the peak corresponds to the disruption of the ordered state.[5] Recently we showed[6] that in $YBa_2Cu_3O_{7-\delta}$ the situation is qualitatively the same. Thus, in accordance with the theory,[7] the onset of the peak effect marks the disruption of the dislocation-free Bragg glass phase, and the proliferation of dislocations.[5–8] In this paper we show that for both systems, a negative creep occurs in a rather narrow field interval between the onset of the increase and maximum of the current, i.e., the ubiquitous PE. We propose that this phenomenon develops in the intermediate region between the dislocation-free Bragg glass and a highly disordered vortex phase. We also demonstrate the existence of the *N*-type shape of the current-voltage characteristics for this case.

We report results acquired on a detwinned $YBa_2Cu_3O_{7-\delta}$ single crystal (DT3) with dimensions $1.29\times1.25\times0.08\,\mathrm{mm}^3$, grown by a conventional self-flux method using yttria-stabilized zirconia crucibles.[9] The sample was initially annealed at 500 °C for 6 d in a 1 bar O_2 atmosphere resulting[10] in $7-\delta=6.934$. Detwinning was achieved by applying a uniaxial pressure of ~50 MPa at 550 °C in air for 15 min. The crystal was then reoxygenated for 7 d at 450 °C in 1 bar O_2, which should give an oxygen content of $7-\delta=6.970$. The superconducting transition occurs at 91.7 K, with a width of $\Delta T_c<0.3\,\mathrm{K}$. The 2H-$NbSe_2$ single crystal (NBS) was prepared as described in Ref. 11, and contained 200 ppm of Fe impurities. The sample had dimensions $1.70\times2.12\times0.10\,\mathrm{mm}^3$ and the diamagnetic onset of the superconducting transition occurred at $T_c=6.0\,\mathrm{K}$ with a width of $\Delta T_c<0.3\,\mathrm{K}$. Magnetic hysteresis measurements were performed using a vibrating sample magnetometer for applied fields up to 12 T.

For the relaxation studies we do not use a normalized relaxation rate that presumes normalization by the irreversible magnetization. The normalization factor cannot be unambiguously determined due to a significant difference between the magnetic moments in the ascending and descending branches of the magnetization loop, which as shown in Ref. 6, is due to history effects in superconductors with weak pinning. Rather, we use the relaxation rate *R*, determined from the dependence of the magnetization on the sweep rate of the applied magnetic field ($\beta=dB/dt$): $R=\pm dM/d\log\beta$ with "+" and "−" for the descending and ascending branch of the magnetization loop, respectively. Such determination reflects the opposite direction of the shielding currents for the increase and decrease of the magnetic field, and gives a positive sign for the conventional creep. In our experiment *R* was calculated from the linear slope of the *M* vs $\log\beta$ dependence. For a fixed β, the differential resistivity $\rho_d=dE/dJ$ determines the behavior of $R\propto dJ/d\log E=E/\rho_d$.

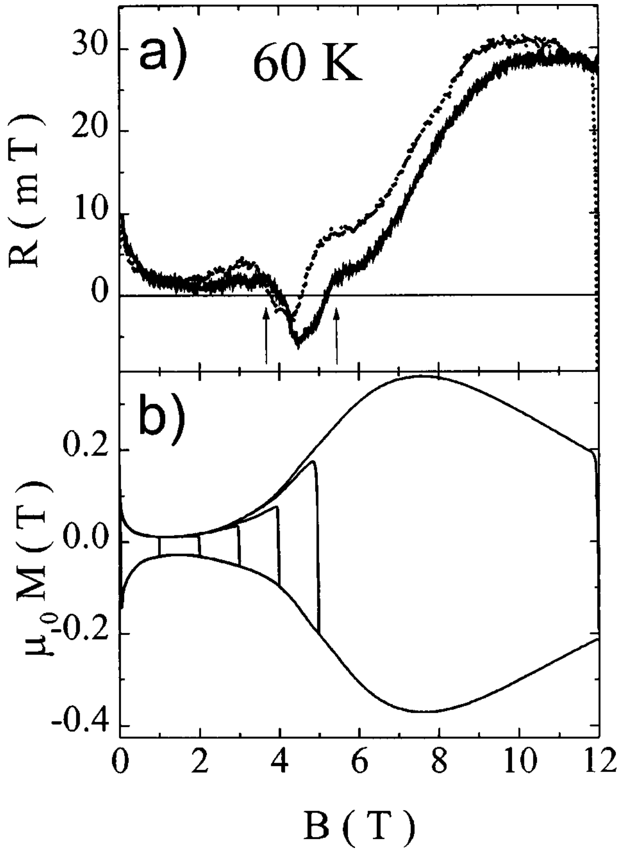

FIG. 1. (a) The magnetic-field dependence of the relaxation rate R for the ascending (full line) and descending (dashed line) branches of the magnetization curves in $YBa_2Cu_3O_{7-\delta}$ single crystal at $T=60$ K for $B\|c$. Arrows mark the region where the anomaly resulting in the negative creep exists for the ascending branch of the magnetization loop. (b) The magnetization loop together with the partial loops demonstrate the appearance of the history effects at the onset of the peak effect (Ref. 6).

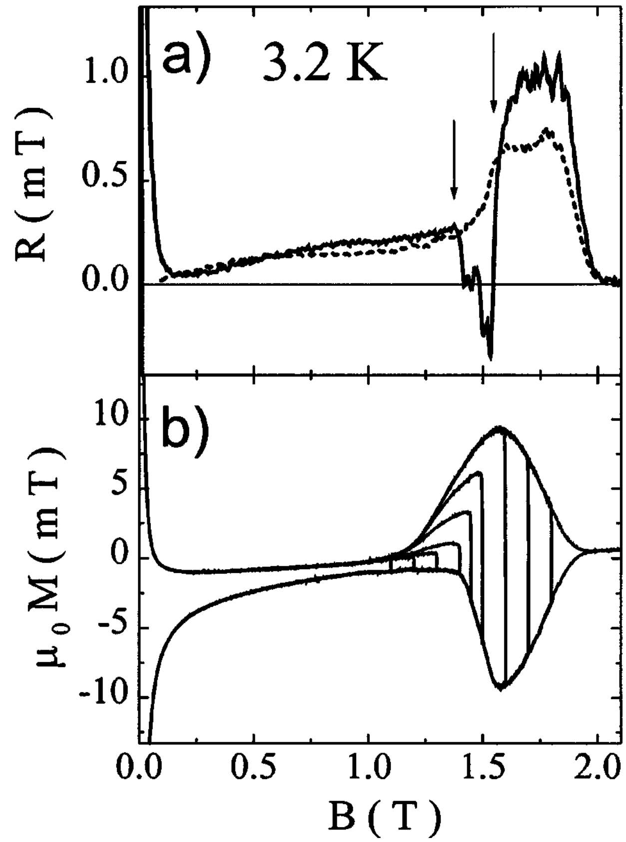

FIG. 2. (a) The magnetic-field dependence of the relaxation rate R for the ascending (full line) and descending (dashed line) branches of the magnetization curves in 2H-$NbSe_2$ single crystal at $T=3.2$ K. (b) The magnetization loop together with the partial loops demonstrate the appearance of the history effects at the onset of the peak effect (Ref. 13).

Figures 1(a) and 2(a) show the magnetic-field dependence of the relaxation rate for DT3 and NBS. As expected, for most of the magnetic-field range, R is positive. However, in a narrow interval slightly above the onset of the increase in the current (henceforth we will refer to this latter point as the onset of the peak effect B_{on}) R changes sign demonstrating a negative creep, i.e., increasing irreversibility for a decreasing sweep rate of the magnetic field. More detailed inspection shows that the anomaly starts as a fast decrease of the relaxation rate from a weakly field dependent $R(B)$. There is also a significant asymmetry between the ascending and descending legs that can be related to the history dependent concentration of dislocations in the vortex system.[6] This asymmetry is strongly pronounced in the NBS sample where the negative creep disappears completely for the return leg of the magnetic field.

Using a technique based on partial magnetization loops[6,12,13] for both samples, the appearance of history effects is seen above a critical-field B_{pl}. At low fields the partial loops follow each other, but above B_{pl} they start to deviate significantly and the magnetization attains much higher values [Figs. 1(b) and 2(b)]. This behavior was recently related to the destruction of the dislocation-free Bragg glass and the proliferation of dislocations in the vortex system.[6] In both samples B_{pl} is close to the onset of the peak effect B_{on}. As can be seen from Fig. 3, the negative creep anomaly is connected with the onset of the peak effect and the history effects. This is most clear for 2H-$NbSe_2$ where the negative creep exists in a very broad temperature range ($T\leqslant 5.3$ K). Moreover, the range of the magnetic fields where this anomaly exists corresponds very closely to the width of the increasing branch of the peak effect. This behavior is less pronounced in DT3 where the negative creep appears in a relatively narrow field interval and a small temperature region. However, in this case as well, the anomaly arises soon after the onset of the peak effect and corresponds to the increasing branch of the current. From the sweep rate dependence of M (Fig. 4), one can obtain the current-voltage characteristics. The magnetic moment and the sweep rate of the magnetic field are proportional to the current and voltage, respectively.[3] The negative creep implies that the slope of the current-voltage characteristics should change sign [Fig. 4(a)]. This presumes the appearance of a negative differential resistivity, which means that the shape of the $J(E)$ curve should be either N- or S-like.[4] Near the transition point we were indeed able to observe the double change in the sign of dJ/dE within our experimental E window and found it to be an N-like $J(E)$ anomaly [Fig. 4(b)]. We found similar changes in the slope of the current-voltage characteristics for 2H-$NbSe_2$. However, in this case our experimental E win-

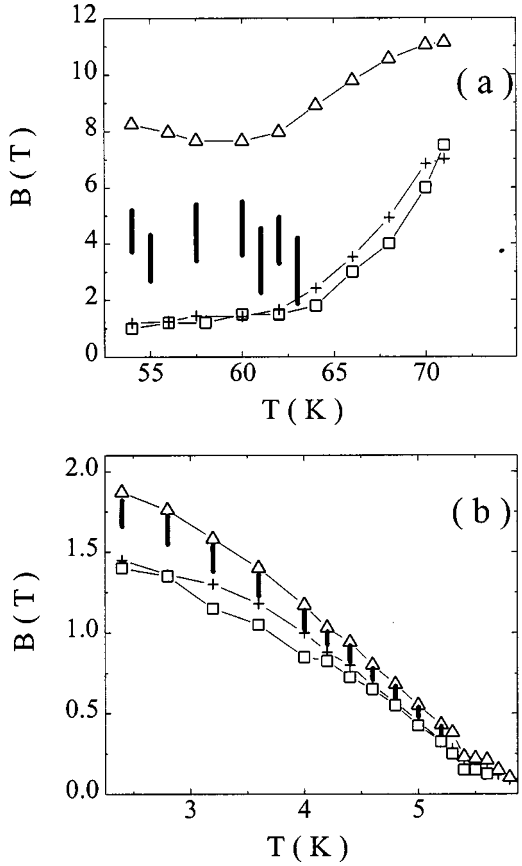

FIG. 3. The temperature dependence of the magnetic-field values for the appearance of the history effects (squares) and for the onset B_{on} (crosses) and maximum B_p (triangles) of the peak effect in (a) $YBa_2Cu_3O_{7-\delta}$ and (b) 2H-$NbSe_2$. The bars show the range where the negative creep anomaly exists.

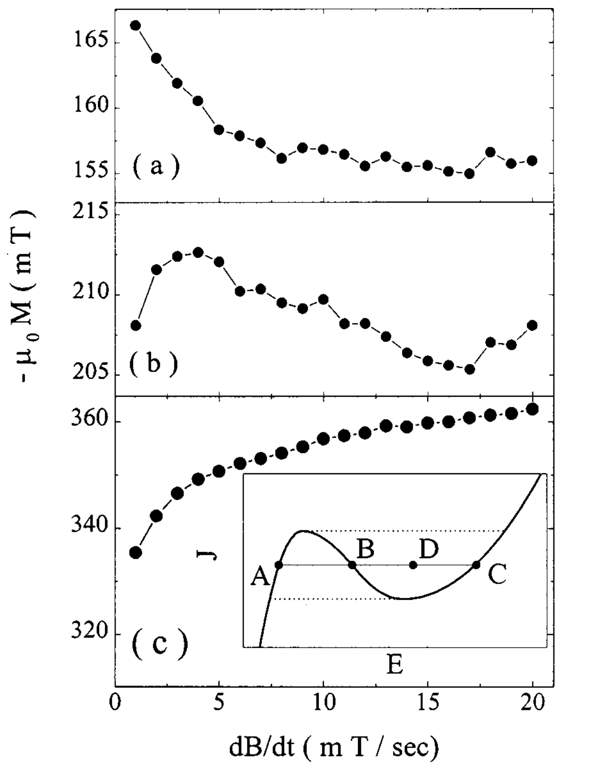

FIG. 4. The dependence of the magnetic moment on the sweep rate of the magnetic field in YBCO single crystals at different magnetic fields B: (a) 4.6 T, (b) 5 T, and (c) 6.6 T for the ascending branch of the $M(B)$ loop at 60 K. It represents the behavior of the J-E characteristics with $-M$ and dB/dt proportional to J and E, respectively. The inset demonstrates the existence of instabilities within the region marked by the dashed lines.

dow appeared too narrow to cover the whole N-type shape, as in Fig. 4(b).

We should stress that for $YBa_2Cu_3O_{7-\delta}$, negative creep can be observed only for clean samples. In twinned pure samples it exists only in a tilted magnetic field when the influence of twin boundaries (TB) is significantly suppressed.[4] Similarly to history effects this phenomenon vanishes for large concentrations of point defects.[14] Then the peak also broadens significantly and transforms to a common fishtail. On the other hand, in the 2H-$NbSe_2$ system, even for a Fe-doped sample, we observe a sharp peak effect, strong history effects, and a large negative creep. This observation suggests a much smaller influence of point disorder in 2H-$NbSe_2$.

Recent structural neutron-scattering studies[15] in Nb revealed the existence of the following sequence of vortex phases through the peak effect. At the onset of the peak an ordered phase (Bragg glass) is followed by an intermediate phase that is characterized by the disappearance of positional order in the vortex lattice, but the orientational order is still preserved. Above the peak a completely disordered phase (vortex glass or pinned vortex liquid) is realized. Our data seem consistent with this transformation. The N-shaped $j(E)$ characteristics could then be considered as a fingerprint of this intermediate state.

To understand the origin of the N-type anomaly we need to analyze the nature of this intermediate state. The simplest possible scenario could be a macroscopic domain structure consisting of regions with ordered Bragg glass and disordered vortex states. This situation is expected to arise when the energy of the phase boundary between ordered and disordered phases has a negative sign. Then macroscopic phase inhomogeneities could induce an N-like shape of the current-voltage characteristics as shown recently within nonlinear electrodynamics of randomly inhomogeneous superconductors.[16]

Another possible scenario could be related to a macroscopically homogeneous intermediate phase produced by ordering of dislocations.[17] With the Lorentz force applied one would expect a correlation in the movement of dislocations. In the dynamic approach[18] a driven smectic vortex phase may be realized. In this case periodicity exists only in the direction transverse to the vortex movement, which takes place in quasiperiodic amorphous channels.[19] Because the disordered phase should have a significantly reduced correlation volume, it should be more strongly pinned and hence be associated with a significantly larger current for the same voltage. Then with increasing sweep rate β the improvement of the vortex order and suppression of the channels can induce a decrease of the current. Using a simple approach of linear behavior of the energy barrier U for creation of channels, the concentration of vortices moving in channels may be estimated by $n = n_0 \exp[-(U_0 + \gamma E)/k_B T]$, with $n_0 = B/\Phi_0$, $U_0 = U(0)$ and γ determining the increase of U with the electric field E. Then assuming that the elementary pinning forces $f_B(E)$ and $f_{CH}(E)$ resist the vortex movement in the bulk and channels, respectively, we can evaluate the resulting dependence $J(E) \sim f_B(E)(n_0 - n) + f_{CH}(E)n$. For large enough γ one can easily find the appearance of a negative sign in dJ/dE that could account for the observed effect. The creation and suppression of channels should be very sensitive to the prehistory. This can explain a significant difference in R for increasing and decreasing magnetic field. The resulting state is expected to be spatially inhomogeneous and, therefore, description by nonlinear electrodynamics[16] might be appropriate even in this case.

As is well known for semiconductors[20] an N-type shape of the current-voltage characteristics can be a source of macroscopic instabilities in the current flow inside the sample. It is immediately clear that in the regime of fixed current that is usually realized in transport measurements, three different voltages (E_A, E_B, and E_C — see inset of Fig. 4) correspond to the same j value in the region of the N-type anomaly. The point B is usually unstable. Any point with the electric field E_D can be realized via domains with two stable E_A and E_C values when their length ratio along the direction of electric field corresponds to $L_C/L_A = (E_D - E_A)/(E_C - E_D)$. As a result one should expect the existence of electric field domains spreading through the sample with a pronounced dependence on the parameters and prehistory in the region marked by the dashed lines. Therefore the macroscopically measured current-voltage curve is significantly different from the microscopic characteristics and the negative $J(E)$ slope is not realized in transport measurements. As a rule, the appearance of moving domains results in voltage jumps and oscillations, particularly such as the well-known Gunn oscillations.

It is difficult to directly map the theory developed for semiconductors where E is determined by electron scattering, while for superconductors, E originates from vortex movement. However, our observation of the N-type anomaly in the region of the intermediate state correlates very well with the existence of voltage hysteresis,[21] instabilities,[22] and oscillations,[23] which have been reported in transport measurements for a similar B and T regime.

Finally we should stress the advantage of our magnetization approach for the study of this N-type anomaly. When the influence of the self-field is small, then constant β induces a fixed E value. In this case one can realize stable current-voltage characteristics that become single-valued functions in contrast to the fixed J regime usually realized in the transport studies.

In summary, we have observed the negative creep rate in $YBa_2Cu_3O_{7-\delta}$ and 2H-$NbSe_2$ single crystals, suggesting this is a general phenomenon for superconductors with weak pinning. This anomaly develops near the onset of the peak effect. It exists in the intermediate region between the dislocation-free Bragg glass and a highly disordered vortex phase and is a precursor to the peak. We observe an N-type shape of the current-voltage characteristics which can be understood in terms of both a macroscopically heterogeneous or homogeneous intermediate state. The $J(E)$ shape found gives an explanation to the voltage instabilities and hysteresis effects detected in transport measurements.

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