Multiple magnetization peaks in weakly pinned \( \text{Ca}_3\text{Rh}_4\text{Sn}_{13} \) and \( \text{YBa}_2\text{Cu}_3\text{O}_7-\delta \)


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The second magnetization peak and the peak effect anomaly coexisting in a given isothermal magnetization hysteresis loop show striking similarities in \( \text{Ca}_3\text{Rh}_4\text{Sn}_{13} \), a low-\( T_c \) superconductor and \( \text{YBa}_2\text{Cu}_3\text{O}_7-\delta \), a high-\( T_c \) superconductor. The observed variation of the hysteresis width with field could imply a modulation in the degree of the plastic deformation of the elastic vortex solid. The characteristics of the high-\( T_c \) cuprates, such as large Ginzburg number, short coherence length, decoupling of the Josephson coupled pancake vortices, etc., are unlikely to be the cause of the observed behavior.

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The inhomogeneities in the atomic lattice are convenient pinning sites for the normal cores of the vortex lines and this localization leads to a threshold critical current density \( J_c \) for the superconductor. Hence, \( J_c \) is a material attribute and it could provide information on the state of the spatial and temporal correlations in the vortex matter. The collective pinning description of the vortex medium due to Larkin-Ovchinnikov 1 relates \( J_c \) inversely to the correlation volume \( V_c \), i.e., \( J_c \propto V_c^{-1/2} \), within which the vortex array responds elastically, while nominally retaining the translation symmetry of the flux line lattice (FLL). The deviations from the usual monotonic decay in \( J_c(H,T) \) with increase in the field \( (H) \) or the temperature \( (T) \) have been reported to span different regions of the thermomagnetic \( (H,T) \) phase space in a variety of superconductors since the early 1960's. 2–11

Isothermal \( M-H \) loops conveniently provide the information on \( J_c(H) \) through the width of the hysteresis loop, \( \Delta M(H) \), where \( M(H) \) represents the magnetization in the increasing and decreasing directions of the magnetic field, respectively. The well documented anomalous behavior in \( \Delta M(H) \) or \( J_c \) are the fish-tail effect (FE) (also often referred to as the second magnetization peak) and the peak effect (PE). The FE derives its name from the characteristic shape of the \( M-H \) loop and also corresponds to a hump feature in \( J_c(H) \) far below the upper critical field \( H_{c2} \). The PE, as the name may suggest, is usually identified with a well-defined peak in \( J_c(H,T) \) on approaching the \( H_{c2} \) boundary. The PE phenomenon, ever since the initial proposal by Pippard, 12 is widely believed to be signaling a rapid collapse of the elastic moduli of the vortex solid vis a vis that of the elementary pinning force at the incipient FLL melting transition. On the other hand, for the so-called second magnetization peak (SMP) which is ubiquitous in high-\( T_c \) cuprates, a variety of explanations have appeared in the recent literature. These range from (i) the enhancement in pinning due to matching effects in oxygen deficient structures, 13 (ii) the collective creep phenomenon, 14 (iii) the surface barrier effect, 15 (iv) the thermomagnetic instability, 16 (v) the nonuniform current flow, 17 (vi) the interplay between disordered and ordered regions, 18 (vii) the Bragg glass (BG) (dislocation free vortex solid) to a vortex glass (VG) transition due to proliferation of dislocations, 19 etc. Thus, the SMP and the PE are being discussed in apparently different terms. Recent simulation studies 20 of the driven vortex matter also anticipate two anomalous maxima in \( J_c(H) \) at the interfaces of the Bragg glass to the vortex glass and the vortex glass to vortex liquid transitions. The issue of possible connection and distinction between the SMP and the PE remains open experimentally 4–7 and a comprehensive theoretical account for both the effects is still lacking. Some of us 10,21 have recently reported the observation of the splitting of the composite fishtail-effect-like behavior in the \( M-H \) loop of \( 2H-\text{NbSe}_2 \) \( (T_c \approx 7.2 \text{ K}) \) into two well separated anomalies in \( J_c(H) \), one of which could be termed as the plateau effect and the other as the usual PE. The plateau effect relates to a crossover [or transition 10,21,22] in a characteristic manner from an interaction-dominated collectively pinned state to a small bundle (or individual) pinning regime at low fields where the inter vortex spacing \( a_0 \approx 1/\sqrt{B} \) exceeds the range of the interaction \( \lambda \) (i.e., the penetration depth) between the vortices. In this paper, we report the occurrence of the SMP and the PE and their striking resemblances in single crystals of two entirely different types of superconductors \( \text{Ca}_3\text{Rh}_4\text{Sn}_{13} \) (CaRhSn), an isotropic low-\( T_c \) superconductor \( (T_c \approx 8.2 \text{ K}) \) and \( \text{YBa}_2\text{Cu}_3\text{O}_7-\delta \) (YBCO), an anisotropic high-\( T_c \) cuprate superconductor \( (T_c \approx 93.2 \text{ K}, \Delta T_c = 0.8 \text{ K}) \). The YBCO crystal is the same piece, with a very low density of twin boundaries, 24 in which the locus of the PE temperatures \( T_p(H) \) displays a reentrant characteristic at low \( H \), analogous to the behavior first reported in \( 2H-\text{NbSe}_2 \) (Ref. 25) and identified with the reentrant nature of the ideal (pinning free) FLL melting curve. 26

The present results in CaRhSn and YBCO, in conjunction with the earlier data from \( 2H-\text{NbSe}_2 \) (Ref. 21) and YBCO, 4–6 not only establish the distinct character of the SMP and the PE, but, also, inter alia illustrate the different
classes of superconductors and behavior for the vortex matter, notwithstanding an individual vortex line in the high-

arising out of the Josephson coupling! Note that in CaRhSn, \( H_c \) immediately follows \( H_{irr} \) (see Fig. 1), whereas in YBCO, \( H_{irr} \) lies far below \( H_c \) (the latter is not marked at 72 K in Fig. 2, as it is expected to be \( > 20 \) T). The much wider reversible region in YBCO reflects the role of larger thermal fluctuations in high-\( T_c \) cuprates.

The relative heights of maxima II and III in Figs. 1 and 2 appear different, however, this does not hide the similarity in the possible transformations of the vortex matter in these two systems in the limited temperature windows. The interaction between vortices, the elastic moduli of vortex solid, the pinning effects, etc., all vary with the field and the interplay between elastic, pinning, and thermal energies could favor the stabilization of the vortex phases having different characteristics. The log-log plot of \( J_c \) vs \( H \) offers a possibility to distinguish and classify these phases. In Fig. 3, we focus on the plot of \( J_c(H)/J_c(5 \text{ mT}) \) vs \( H \) in CaRhSn and YBCO at 1.7 and 72 K, respectively. The two curves are vertically separated for clarity, \( H_{sm} \) and \( H_p \) mark the maxima of the SMP and the PE (see Figs. 1 and 2). The graphical similarity in the two curves is striking. We first draw attention to the conspicuous power law regime (PL I), which precedes the onset of the SMP in CaRhSn. A crossover from field independent (or weakly field dependent) to field dependent (notional) power law behavior in \( J_c(H) \) is often invoked in weakly pinned samples of low-\( T_c \) superconductors to proclaim the arrival of collectively pinned elastic vortex solid phase. If we identify PL I in Fig. 3 with a collectively-pinned ordered solid, then at its lower field end, the crossover to the nearly field independent behavior at \( H < 20 \) mT could be termed as the approach to the small bundle or individual pinning regime for the dilute vortex array (for \( H < 10 \) mT, the \( a_v \) of FLL \( > 0.5 \) \( \mu \)m). Near the upper field end of PL I, the slow decay in \( J_c(H) \) could be viewed as a precursor to the effective enhancement in the role of quenched random pins via a vis interaction between vortices. Following Kokkaliaris et al., we have searched for the memory effects in \( J_c(H) \) across the SMP and the PE via a comparison of the tracings of the neighboring minor hysteresis curves and found that the fingerprint of the CaRhSn and YBCO at 1.7 and 72 K, respectively. Three peaks (I, II, and III) can be distinctly observed in each sample. In these data, the second (II) and the third (III) peaks could be ascribed to the anomalous variations in \( J_c \). The approach to the first peak (I) just reflects the setting up of the shielding currents \( J_c(B) \) within the body of the superconductor as the applied field penetrates deeper into the zero field cooled (ZFC) state. The sharpness of the first peak indicates the rapid decline in \( J_c(H) \), once the shielding currents flow in the entire sample. The field at which the forward envelope loop (i.e., the \( M-H \) curve from \( -H_{max} \) to \( +H_{max} \)) meets the virgin ZFC curve (dotted curve) provides a measure of the threshold field \( H \) at which the vortices first permeate the entire sample. For instance, in CaRhSn, this value is 17 mT at 1.7 K.

The peaks II and III in CaRhSn and in YBCO point towards the generality of the underlying process. It is natural to identify the latter maximum (III), located at the edge of the irreversibility line, with the notion of the usual PE. The modulation II, therefore, becomes the choice for the SMP. Note that in CaRhSn, \( H_{irr} \) immediately follows \( H_{irr} \) (see Fig. 1), whereas in YBCO, \( H_{irr} \) lies far below \( H_c \) (the latter is not marked at 72 K in Fig. 2, as it is expected to be \( > 20 \) T). The much wider reversible region in YBCO reflects the role of larger thermal fluctuations in high-\( T_c \) cuprates.

The forward leg (-\( H_{max} \) to +\( H_{max} \)) of the envelope loop meets the virgin M-H curve just above the peak I at \( H \approx 17 \) mT. \( H_{irr} \) and \( H_p \) mark the maxima of the SMP and the PE, respectively. \( H_{irr} \) and \( H_{irr} \) have also been identified at 1.7 K. The insets (a) and (b) show portions of the M-H loops at 3.5 and 5 K, respectively.

The three peaks in the magnetization are marked as I, II, and III. The relative heights of maxima II and III in Figs. 1 and 2 can be distinctly observed in each sample. In these data, the second (II) and the third (III) peaks could be ascribed to the anomalous variations in \( J_c \). The approach to the first peak (I) just reflects the setting up of the shielding currents \( J_c(B) \) within the body of the superconductor as the applied field penetrates deeper into the zero field cooled (ZFC) state. The sharpness of the first peak indicates the rapid decline in \( J_c(H) \), once the shielding currents flow in the entire sample. The field at which the forward envelope loop (i.e., the \( M-H \) curve from \( -H_{max} \) to \( +H_{max} \)) meets the virgin ZFC curve (dotted curve) provides a measure of the threshold field \( H \) at which the vortices first permeate the entire sample. For instance, in CaRhSn, this value is 17 mT at 1.7 K.

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plastic deformation in FLL in CaRhSn and YBCO surfaces near the onset of the SMP ($H_{sm}$) and it eventually ceases at $H_p$, the peak position of the PE. This motivates us to ascribe the SMP as a transformation from an elastic to a plastic regime due to the possible permeation of topological defects, such as the dislocations in an ordered FLL. In the Larkin-Ovchinnikov\textsuperscript{1} collective-pinning description, the enhancement in $J_c(H)$ would amount to a progressive shrinkage of the volume of the Larkin domain within which the vortex medium remains elastically pinned. Above $H_{sm}$, $J_c(H)$ once again decays with $H$ and another power law regime could ensue (see PL I and PL II in the curve for YBCO in Fig. 3). It is therefore reasonable to assert that between $H_{sm}$ and the onset of the PE ($H_{env}^\alpha$), the balance between interactions and pinning shifts towards the interactions as the vortex density increases further. At the onset of the PE, a marked increase in the memory effects in $J_c(H)$ is witnessed via a characteristic anomaly in the minor hysteresis curves\textsuperscript{35} and this could be due to the ease with which additional plastic deformations can be caused at the incipient FLL softening stage (i.e., the PE).

To substantiate the above stated assertion further, we show in Fig. 4(a) the field cooled (FC) minor hysteresis curves along with the envelope hysteresis loop in CaRhSn sample at 1.7 K. Note first that the FC minor curves initiated from the FC magnetization values [$M_{FC}(H_{FC})$] overshoot across the envelope loop as the external field is either increased or decreased. The overshooting feature\textsuperscript{37,38} elucidates the inequality, $J_{c FC}^H(H) > J_{c ZFC}^H(H)$ for $H_{sm} < H < H_p$, where $J_{c ZFC}^H(H)$ corresponds to the current density values along the envelope loop. This inequality implies that a FC vortex state having higher $J_c(H)$ is relatively less ordered\textsuperscript{37} and has smaller Larkin volume $V_c$ than the corresponding ZFC state. The difference between the saturated (i.e., the peak value) of a FC minor curve ($M_{FC}^\alpha$) and the correspond-
the analogue of the pinned liquid state, and the amorphous
precise location of the underlying phase transformation
transition!

state loses its pinning ability in a rapid fashion while ap-
power law regions I and II in the two materials. In low
T_c
5
H
vary as
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CaRhSn, n has values of about 1.1 and 1.3 in the regions I
and II, respectively. These values compare favorably with
those reported in widely studied weakly pinned crystals of
2H-NbSe_2, where they range between 1 and 1.5. In
2H-NbSe_2, the pinning is considered to be largely governed
by point defects. In YBCO, the SMP and the PE are ob-
served in the temperature range of 70 K. In this region, giant
flux creep is operative. In such a region, J_c is expected to
vary as H^{-3} in the large bundle pinning regime (see Fig. 17
of Ref. 28). In our crystal of YBCO, n \sim -3 in the region
preceding the arrival of the PE.

The magnetization M(H) represents the composite re-
response of the entire sample at a given H (and at a given
instance), while the local macroscopic field B exhibits the
spatial variation within the sample.41 Thus, the locus of
(H,T) values pertaining to a given characteristic feature in a
M-H loop may have only a limited meaning regarding the
precise location of the underlying phase transformation (or transition) in the sample.41,42 In spite of this caveat, it is
instructive to gain information on the T dependence of the
two anomalies described above. The insets in Figs. 1 and 2
show how the two anomalies coalesce with the change in T
in CaRhSn/YBCO. Figures 5(a) and 5(b) show the plots of
H_{sm}, H_p, and H_{irr} as a function of reduced temperature [t
\equiv T/T_c(0)] over limited spans in the two systems. In
CaRhSn, H_{sm}(t) appears to be independent of T (H_{sm}
\approx 1.6 T), while H_p(t) follows the H_{irr}/H_{c2} curves. At about
4.5 K (t \approx 0.55), H_p approaches H_{sm} and above 5 K, only
the PE survives at H<1.6 T. On the other hand in YBCO,
the PE and the SMP broaden and their centers of gravity shift
towards each other as T is decreased below 72 K (t \approx 0.77).
At T=62 K (t \approx 0.67), the two anomalies merge and only a
composite SMP-like feature remains visible (see the inset in
Fig. 2). Further reduction in T (<60 K) flattens out the
hump of the SMP, with little movement in its center of grav-
y. On the other hand, above 72 K (t \approx 0.77), the PE peak
diminishes rapidly such that only the SMP remains visible
above 75 K (t \approx 0.8). Also, note that H_{sm}(t) continues to
decrease as t increases from 0.65 to 0.93 (i.e., T from 60 to
86 K). This in turn could imply that the regions PL I and PL
II (in Fig. 3) could shrink/expand and may even eventually
merge as t increases further (i.e., when the SMP becomes
dormant). Finally, it may be pertinent to state that in the
theoretical framework of Giamarchi and Le Doussal,19 the
phase boundary separating the ordered Bragg glass phase
from the dislocation mediated vortex glass phase is field/
disorder driven and is insensitive to the temperature variation
as is the case for the H_{sm}(t) line [or even H_{irr}^m(T)] in
CaRhSn. In YBCO, the higher temperature region
(>60 K) in which the thermal fluctuations can renormalize
the disordering effects of pins.29,30 H_{sm}(t) decreases as t
increases, whereas H_p(t) increases. Giller et al.5 and Nishizaki
et al.6 have surmised that the H_{irr}(t) variation with the posi-
tive temperature gradient could be ascribed to the disordering
line given by Ertas and Nelson29 and Kierfield et al.30
thereby reflecting the smoothening of the quenched disorder
by thermal fluctuations. A theoretical description of the two
disordering lines with opposite slopes in the temperature re-
gion 60–70 K is awaited.

To conclude, the results in weakly pinned crystals of
CaRhSn and YBa_2Cu_3O_7-\delta show that if we identify the
regimes of anomalous modulations in J_c(H) with the degree
of disorder in the vortex matter and the regime of usual de-
cay in J_c(H) having a notional power law dependence with
the collective pinned ordered state, then the features of the
coeexistence of the SMP and the PE in isothermal scans ex-
emplify a modulation in the degree of plastic deformation in
the elastic vortex solid as field increases. A plausible sce-
nario to account it in terms of the competition between the
elastic, pinning and thermal energies has been sketched. This
scenario finds an echo in the recent observations of Avraham
et al.,43 who have projected the occurrence of two first order
transitions and the presence of an ordered vortex lattice
phase sandwiched between disordered phases in an isofield
scan in a crystal of Bi_2Sr_2CaCu_2O_x for H||c via local mag-
etization measurements.

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D. Pal, D. Dasgupta, B.K. Sarma, S. Bhattacharya, S. Ramakrishnan, and A.K. Grover, Phys. Rev. B 62, 6699 (2000); Most of the YBCO crystal (0.5×0.5×0.4 mm3) is twin-free with few widely spaced (∼ 50 µm) twins running across the crystal.


We may state here that the split (two peak) structure in YBCO has already been observed by a number of investigators (see, for instance, Refs. 4–6 and Ref. 34).


We have assumed that $\Delta M(H)$ provides a measure of $J_c(H)$. The existence of a giant creep in YBCO could imply that the functional form of the macroscopic currents $[J(H)]$ vs $H$ in the sample could be different at different instants. However, we have confirmed that the overall shape of the $\Delta M(H)$ vs $H$ curve at a given temperature remains the same even though the position of $H_p$ somewhat varies with the time window of the magnetization measurement.