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# Complex mixed state of Pauli limited superconductor CeCoIn<sub>5</sub>

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Magnetization measurements were performed on CeCoIn<sub>5</sub> at temperature down to 20 mK and magnetic field up to 17 T applied along different crystallographic orientations. For the near parallel to *ab*-plane field configurations ( $\theta \lesssim 40^\circ$  and  $T \leq 50$  mK), we have found an intriguing vortex dynamics regime evidenced by an hysteretic and metastable anomalous peak effect (APE) which gives evidence for surface barrier effects enhanced by antiferromagnetic fluctuations in the mixed state of CeCoIn<sub>5</sub>. Furthermore, we have observed crossover features in the torque/magnetization traces at fields below  $H_{c2}$ , which are consistent with vortices lattice phase transitions and with the anomalies speculated as the Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) superconducting state in CeCoIn<sub>5</sub>. All of the above features were found to be dramatically perturbed in Ce<sub>0.98</sub>Gd<sub>0.02</sub>CoIn<sub>5</sub>.

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## INTRODUCTION

The heavy-fermion (HF) CeCoIn<sub>5</sub> is a clean unconventional superconductor ( $T_c = 2.3$  K) which has been intensively investigated in last decade owing to several unusual properties of its superconducting (SC) state[1, 2]. For instance, it was established that the transition at the upper critical field  $H_{c2}$  changes from second to first-order below a temperature  $T_0$ [3–5], which is considered strong evidence that CeCoIn<sub>5</sub> is a Pauli limited superconductor[3–5]. In addition, a number of studies controversially claimed that CeCoIn<sub>5</sub> exhibits the inhomogeneous Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) SC state near  $H_{c2}$  [4–10], which has been theoretically predicted[11, 12], but never unambiguously observed.

More recently, small-angle neutron scattering (SANS) experiments on CeCoIn<sub>5</sub> have revealed a complex phase diagram and an anomalous field dependence of the form factor, which is not consistent with the Abrikosov-Ginzburg-Landau scenario [13].

All the above motivates many theoretical models in attempt to describe the complex low- $T$ /high- $H$  mixed state of CeCoIn<sub>5</sub> [14–17]. Some of them take into consideration the presence of antiferromagnetic (AFM) fluctuations [17]. In fact, high-field neutron diffraction and nuclear magnetic resonance results provided evidence of a magnetically ordered phase within the mixed state when the field is along the tetragonal basal plane. [18, 19].

The complexity of the mixed state of the HFS CeCoIn<sub>5</sub> is unprecedented for any type-II SC material and its vortex dynamics have not been explored in detail by magnetization measurements. In fact, even concerning the occurrence of the FFLO state, results from magnetization studies are contradictory [3, 4, 21]. Here we report

magnetization studies on single crystals of CeCoIn<sub>5</sub> and Ce<sub>0.98</sub>Gd<sub>0.02</sub>CoIn<sub>5</sub> at temperatures down to 20 mK and fields up to 17 T applied along different crystallographic orientations.

## EXPERIMENT

The single crystals used in this work were grown by In self-flux and their phase purity and SC transition were checked, respectively, by x-rays diffraction and zero-field heat capacity experiments. The zero field superconducting temperature  $T_c = 2.3$  K and the heat capacity jump at  $T_c$   $\Delta C/\gamma T_c \approx 5$  for pure CeCoIn<sub>5</sub> and  $T_c = 2.1$  K and the heat capacity jump at  $T_c$   $\Delta C/\gamma T_c \approx 4$  for pure CeCoIn<sub>5</sub> were in perfect agreement with the literature.[1, 5, 20]

Our magnetization experiments were carried out in a diaphragm force magnetometer and the sample magnetic response was detected by a capacitance technique. The measurement technique used in this work is different from refs [3, 21] revealing new features of the magnetization of CeCoIn<sub>5</sub>. Our experiments were carried out using a diaphragm force magnetometer[22, 23] inside a plastic diluted refrigerator operating in a 20 T SC magnet (see details in ref.[22, 23]). The magnetic force on the sample was produced by a field gradient ( $630 \text{ Oe/cm} \leq dH_z/dz \leq 1.8 \text{ kOe/cm}$ ) superimposed on the main magnetic field and the sample magnetic response was detected by a capacitance technique. The contribution of the magnetic response caused by the torque was determined by repeating the measurement with no current in the gradient coil. From one set of runs (with and without field gradient), we were able to extract the component of the magnetization parallel to the mag-

netic field ( $M_z$ ) by a simple subtraction of the contribution of the torque from the total response for  $dH_z/dz \neq 0$ . This is not clearly the case by cantilever measurements [21]. Our experimental method is similar to ref [3] but the force magnetometers are different. In the present work, the movable capacitor plate of the magnetometer is a diaphragm which gives a stronger response to the torque than the apparatus used by Tayama *et al.*[24]. The data were taken for increasing and decreasing magnetic field ( $|dH/dt| \approx 35$  Oe/s) after zero-field cooling the sample from well above  $T_c$ .

## RESULTS AND DISCUSSION

Figure 1 shows the capacitance response of CeCoIn<sub>5</sub> for increasing and decreasing magnetic field at  $T = 30$  mK and three orientations, measured with and without field gradient ( $dH_z/dz$ ). For  $\mathbf{H} \perp \mathbf{c}$  (Fig.1(a)),  $\mathbf{M}$  is clearly not aligned to the field direction. The response with  $dH_z/dz \neq 0$  shows two contributions: one caused by the torque (measured for  $dH_z/dz = 0$ ) and the other due to  $M_z$  (displayed in Fig.2(b)). For both up-sweep traces (with and without field gradient), the traces show a sharp jump at  $H_{c2}^\perp$  due to the first-order superconducting-normal state transition (FOSNT). The data also show the existence of a broad peak (that we called anomalous peak effect (APE))[25] at  $H_{APE}$  which shows a very intriguing behavior: it is observed *only* on decreasing field. The inset presents data for the Ce<sub>0.98</sub>Gd<sub>0.02</sub>CoIn<sub>5</sub> crystal that we will discuss later.

Figure 1(b) shows data for  $H$  rotated 40° from the  $ab$ -plane. The magnetic behavior is qualitatively the same as for  $\mathbf{H} \perp \mathbf{c}$ , but the APE becomes asymmetric and it is shifted to a lower field, while a small bump start to develop on sweeping up. When  $\mathbf{H} \parallel \mathbf{c}$  (Fig.1(c)), the response for  $dH_z/dz \neq 0$  is due only to the magnetization ( $\mathbf{M}$ ) parallel to the field direction ( $\mathbf{M} = M_z$ ). (The capacitance response is constant as a function of the field for  $dH_z/dz = 0$ .) The FOSNT manifests itself by a sharp jump at  $H_{c2}^\parallel$ . At lower fields we observed an hysteretic peak effect (PE) near 25 kOe which follows the same trend reported in Ref.[3].

The angular dependence of the magnetic behavior of CeCoIn<sub>5</sub> at  $T = 30$  mK in the vicinity of  $H_{c2}$  can be seen in Fig.2. The magnetization traces for  $\mathbf{H} \parallel \mathbf{c}$  and  $\mathbf{H} \perp \mathbf{c}$  are shown in panels (a) and (b), respectively. The sharp jump due to the FOSNT is clearly observed for both traces. From our data, we obtained  $H_{c2}^\parallel = 49.2$  kOe and  $H_{c2}^\perp = 117.7$  kOe with the hysteresis width of  $\Delta H_{c2} \approx 0.4$  kOe, in very good agreement with the literature. In addition, for both directions, we have newly observed a change in the monotonic variation of the magnetization near  $H_{c2}$ . This crossover to a high field phase (HFP) manifests itself in the derivative ( $dM_z/dH$ ) trace by a step. The observed singularity takes place at a

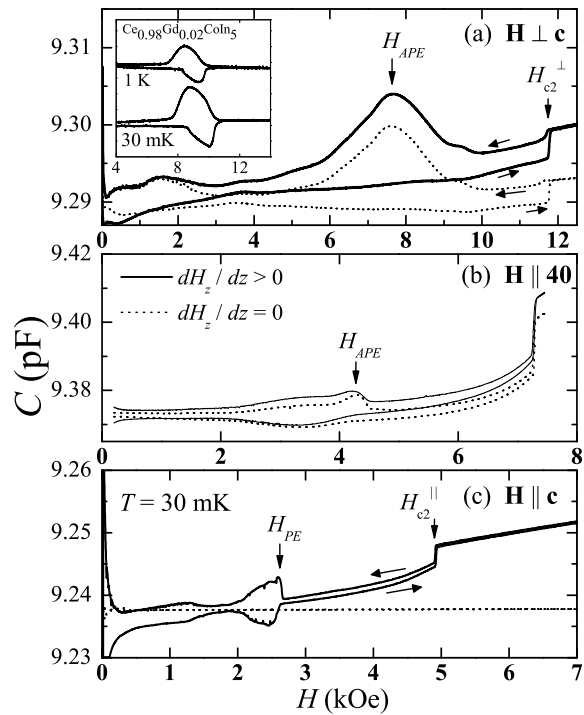


FIG. 1: Capacitance  $C(H)$  loops for CeCoIn<sub>5</sub> at 30 mK taken with and without field gradient for (a)  $\mathbf{H} \perp \mathbf{c}$ , (b)  $\mathbf{H} \parallel 40^\circ$  and (c)  $\mathbf{H} \parallel \mathbf{c}$ . The inset shows similar set of data obtained at 30 mK and 1 K for Ce<sub>0.98</sub>Gd<sub>0.02</sub>CoIn<sub>5</sub> with  $\mathbf{H} \perp \mathbf{c}$ .

field  $H_{\text{HFP}}$  indicated by the vertical arrows in panels (c) and (d) for data obtained at different temperatures. For  $\mathbf{H} \parallel \mathbf{c}$ ,  $H_{\text{HFP}}$  is found to be nearly independent on  $T$ . On the other hand, for  $\mathbf{H} \perp \mathbf{c}$  the  $H_{\text{HFP}}$  is clearly shifted to higher fields for increasing temperature. The angular evolution of the characteristic high- $H$  anomalies as seen in the derivative traces are shown in panels (e) and (f).

To further explore the nature of the APE we have performed additional experiments. Firstly, we repeated the measurements shown in Fig.1 for the  $H$  rotated 20° from the basal plane. Figure 3(a) shows the results for  $dH_z/dz = 0$  up/down sweep traces at  $T = 20$  mK and  $T = 50$  mK. According to our data, the APE is rapidly suppressed by thermal effects and it is absent for  $T > 50$  mK. Secondly, as the anomalous peak apparently starts to develop in the vicinity of the HFP crossover feature, we repeated the measurement at 20 mK by sweeping the field up to the value where the anomalous peak is centered, and than sweeping it down, that is, without passing through the HFP anomaly (dashed curve in panel (a)). As can be seen, the up-sweep trace follows exactly the same behavior previously obtained and, on reversing the sweeping direction, the anomalous peak is still observed but its size is smaller. This is a strong evidence

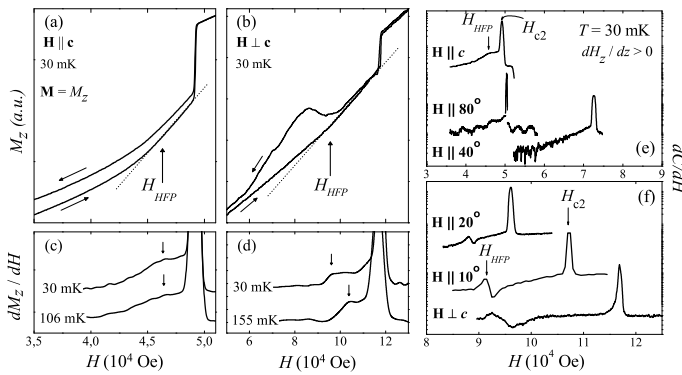


FIG. 2: Magnetic behavior of  $\text{CeCoIn}_5$  near  $H_{c2}$ .  $M_z(H)$  at  $T = 30$  mK for (a)  $\mathbf{H} \parallel \mathbf{c}$  and (b)  $\mathbf{H} \perp \mathbf{c}$ . The dotted lines emphasize the change in the monotonic variation of  $M_z(H)$  near  $H_{c2}$ . For  $\mathbf{H} \perp \mathbf{c}$ , the APE is seen in the down-sweep trace. The respective  $dM_z/dH$  traces are shown in panels (c) and (d) for two temperatures.  $dC/dH$  versus  $H$  curves near  $H_{c2}$  showing the angular evolution of the HFP anomaly for orientations (f) out and (e) near parallel to the  $ab$ -planes. The vertical arrows indicate  $H_{\text{HFP}}$  while the other arrows indicate the direction of field sweep.

that the APE is not related to the high field phase.

We also performed time relaxation measurements for selected  $H$ -values in the region where the APE is observed ( $0^\circ \leq \theta \leq 40^\circ$ ) and at the hysteretic peak found for  $\mathbf{H} \parallel \mathbf{c}$ . Before each measurement, the field was swept up to 140 kOe, subsequently swept down to the target value and then the signal was measured as a function of time. The sweep rate was identical in all these measurements.

The time dependent  $C(t) \propto \tau(t) \propto M(t)$  is depicted in Fig.3(b) for distinct field orientations.

The results in Fig.3 indicate that the APE in down-sweep traces for  $0^\circ \leq \theta \leq 40^\circ$  is related to relaxation effects, however the APE relaxation time shows a non-monotonic angle dependence. This result evidenced another unusual aspect of the APE which indicates a very peculiar vortex dynamics regime in  $\text{CeCoIn}_5$  in this  $T$ - $H$  range. For  $\mathbf{H} \parallel \mathbf{c}$ , no relaxation effects for PE is observed in the same time window.

By mapping the temperature and angular dependencies of the distinct features identified in our  $M(T, H)$  data, we constructed the phase diagrams depicted in Fig.4. Panel (a) presents the high- $H$  low- $T$  phase diagram of  $\text{CeCoIn}_5$  for  $\mathbf{H} \perp \mathbf{c}$  and  $\mathbf{H} \parallel \mathbf{c}$ . Results from heat capacity[5] and NMR[8, 26] experiments are also shown for completeness. The evolution of the  $H_{\text{HFP}}$  line determined from our data for both orientations is in good agreement with the line identified by distinct techniques and claimed by some authors to be the inhomogeneous FFLO SC state. However, from our data we can not reach any conclusion about the microscopic nature of the HFP.

Concerning the low- $H$  region of the diagram, when  $\mathbf{H} \parallel \mathbf{c}$ , the  $T$ -dependence of the hysteretic peaks obtained

from our measurements is consistent with the behavior reported on Ref.[3]. As revealed by SANS experiments [13], this PE is related to transitions in the vortex lattice.

The  $\theta$ -dependence of the characteristic fields is displayed in panel (b). According to our data, the HFP anomaly persists only for fields slightly disorientated from the  $ab$ -plane or from the  $c$ -axis. In addition, the  $H - T$ -area of the phase diagram corresponding to the HFP diminishes as the field is rotated away from the  $ab$ -plane. On the other hand, the APE persists up to higher angles ( $\sim 40^\circ$ ) and it is linearly shifted to lower fields as the angle is increased, while the hysteretic PE takes place for field orientations almost parallel to the  $c$ -axis.

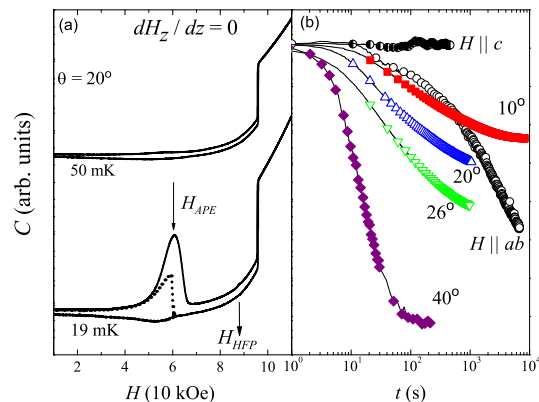


FIG. 3: (a)  $C(H)$  at two temperatures for  $\mathbf{H} \parallel 20^\circ$ . The dashed line denotes the trace obtained when reversing the sweeping direction at  $H_{\text{APE}}$ . (b) Results of  $C(t)$  measured at  $H_{\text{APE}}$  for different orientations of the applied field.

Now we discuss the origin of the APE found below the HFP for  $H$ -(near)parallel to the  $ab$ -plane. In general, magnetic relaxation in type-II superconductors originates from the vortex motion driven by the gradient in the vortex density  $\nabla n_v$ , in presence of the vortex pinning (vortex creep regime). For our studies in the (nearly) parallel to the  $ab$ -plane field configuration the torque is proportional to the  $c$ -axis component of the magnetization  $M_c(t)$ . Then, in the vortex creep regime, the time dependent signal  $C(t) \propto \tau(t) \propto M_c(t)$ . Because  $\text{CeCoIn}_5$  is an anisotropic (layered) superconductor, the appearance of vortex kinks along the  $c$ -axis and their interaction with vortex systems parallel to  $ab$ -planes should also be taken into account; this would provide the information on pinning of both in- and out-of-plane vortex systems[32]. In principle, our observation of the time relaxation of the measured signal  $C(t) \sim M(t)$  in the peak region for  $\theta \leq 40^\circ$  (Fig.3) suggests that the vortex pinning efficiency is enhanced in this field interval. However, in contrast to the more conventional PE behavior observed for  $\mathbf{H} \parallel \mathbf{c}$ , for which we have peak manifestation in

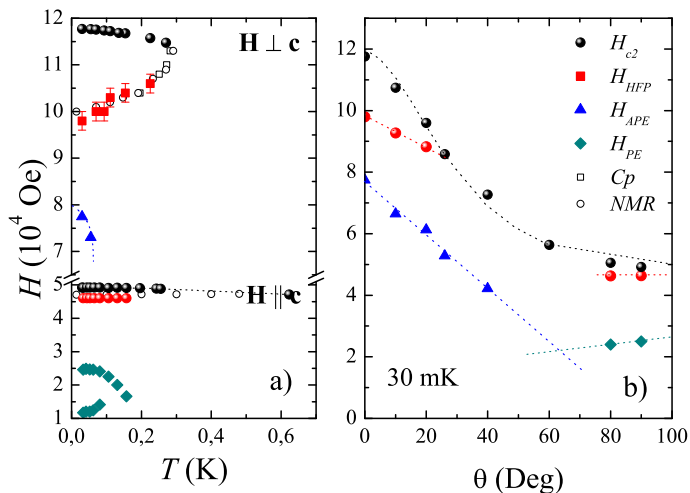


FIG. 4: (a)  $H - T$  phase diagram of  $\text{CeCoIn}_5$  for  $\mathbf{H} \perp \mathbf{c}$  and  $\mathbf{H} \parallel \mathbf{c}$ . It includes previous  $c_p(T)$ [5] and NMR[8, 26] data. (b) Angular dependence of the characteristic fields at  $T = 30$  mK for  $\text{CeCoIn}_5$ . Dotted lines are guides to the eyes.

both up and down-sweep traces (see Fig.1(a) and Ref.[3]), the APE measured for  $\mathbf{H} \perp \mathbf{c}$  and  $\mathbf{H}$  near parallel (see Fig.1(a) and Fig.3), takes place only under field decreasing at very low- $T$  ( $T \leq 50$  mK).

In attempts to shed light on the origin of the APE, we note that irreversible under increasing/decreasing field state, characterized by a glassy-like time relaxation, has been also reported for others spin-paramagnetically limited superconductors such as Al [29, 30] and Be [31] films. Interestingly, the low- $T$ /high- $H$  portion of the  $H - T$  plane (see Fig.4), resembles very much the metastable  $H - T$  phases identified in Al and Be films, where SC and normal (N) states coexist [29–31].

Although the pinning mechanisms in Al or Be films certainly differs from that operating in highly pure  $\text{CeCoIn}_5$ , it is not impossible that the magnetization time relaxation occurring in  $\text{CeCoIn}_5$  for  $\mathbf{H}$  nearly parallel to the  $ab$ -planes may be governed by dynamics of coexisting SC and N domains, or possibly BCS-like superconducting (vortex state (VS) in our case) and the high-field phase identified as the FFLO phase by some authors. However, such interpretation can be ruled out since the results presented in Fig.3 for  $\theta \leq 40^\circ$  indicate that the APE takes place well outside of the field hysteresis region associated with the FOSNT.

Irreversibility on the vortex dynamics has also been proposed in the context of surface barrier [36]. In the model by Bean and Livingston [35], two magnetic forces are considered to act on a vortex located near and parallel to the surface of a superconductor. The first one arises from the repulsion by the external magnetic field and tends to push the vortices into the interior of the sample. The second one tends to dominate very close to the surface. It is originated from the image vortex on

the outside of the surface and is directed in the opposite sense. Therefore, there is a distance from the surface at which the vortex energy is maximum, thus providing a barrier to vortex penetration. In the work by Walton et al. [36], the authors discuss how vortex entry (or exit) is modified when the order parameter at the surface is strongly modulated, introducing the idea of *nascent vortices*. They assume that in thermal equilibrium in the mixed state, both the order parameter and the magnetic field at the surface are periodically modulated in the direction perpendicular to the magnetic field. The order parameter at the modulation minima is not necessarily equal to zero. Hence, the *nascent vortices* are lines of reduced surface order parameter and increased magnetic field penetration. The minima of this modulation act as nucleation and denucleation sites for vortices. Within this picture, irreversibility arises due to the fact that it is easier to get a vortices into the sample than to get it out when decreasing the magnetic field. It is also important to mention that the above scenario can be experimentally realized only in a very clean superconductor, since this effect cannot be detected if the mixed state dynamics is dominated by bulk pinning sites. Therefore highly clean  $\text{CeCoIn}_5$  would be a perfect candidate to allow the formation of *nascent vortices* and reveal the irreversibility on the vortex dynamics dominated by surface barriers as long as there is a modulated SC order parameter at the surface. Based on experimental evidences for a high field induced magnetic phase in  $\text{CeCoIn}_5$  given by NMR [19] and neutron diffraction experiments [18], a modulation of the order parameter at the surface may arise from a surface nucleation of a field induced magnetic phase at fields well below the HFP. Indeed, x-ray magnetic diffraction studied on the antiferromagnetic  $\text{GdIn}_3$  [37], demonstrates that a magnetic phase can emerge in a sub-micrometric near-surface region with a Néel temperature higher than the bulk transition temperature. Therefore, our results allow us to claim that the APE found in this work provides an experimental realization of the *nascent vortices* and their related vortex dynamics regime. Furthermore, the SC order parameter modulation that keeps vortices parallel to the surface, enhanced by the field induced AFM ordering nucleated at the surface allow the observation of the *nascent vortices* at much higher angles than theoretically predicted[36].

Finally, if our interpretation is correct, the features observed in the magnetization curves in  $\text{CeCoIn}_5$  should disappear as sample is driven away from the clean limit. To verify this idea we have performed similar experiments for  $\text{Ce}_{0.98}\text{Gd}_{0.02}\text{CoIn}_5$  single crystal (inset of Fig. 1). According to our data, Gd-doping suppresses the FOSNT at  $H_{c2}^\perp$  and the HFP anomalies. The PE becomes conventional due to the stronger pinning and remains to higher- $T$ , and magnetic relaxation does not take place for the same temperature and time window (not shown) as measured for pure  $\text{CeCoIn}_5$ .

## CONCLUSION

In conclusion, by torque/magnetization measurements in the mixed state of  $\text{CeCoIn}_5$ , we have found a peculiar vortex dynamics regime marked by an APE, possibly related to an enhancement of the surface pinning potential induced by AFM fluctuations initially nucleated at the surface. Besides, our data reveals crossing over anomalies at the vicinity of  $H_{c2}$  that coincide with the  $H_{FFLO}(T)$  line determined by others [4–7] for  $\mathbf{H} \perp \mathbf{c}$  and indicates that the this HFP persists for out-of-plane field orientations.

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