Frustrated magnetic response of a superconducting Nb film with a square lattice of columnar defects

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Abstract. The magnetic response of a superconducting system presenting a frustrated state is investigated. The system is a superconducting film with mechanically pierced columns, cooled in a field which is then removed. Frustration originates from the competition between return flux of a dipole – created by flux trapped in the empty columns – and flux exclusion by the surrounding superconductor in the Meissner state. The system resolves the incompatibility among conflicting constraints, leading to frustration, by eliminating return flux, which is possibly assimilated by nearby columns, as manifested by a sudden reduction of the magnetic moment on the decreasing field branch of the hysteresis loop.

1. Introduction
It is well-known that, as a consequence of a negative energy of the normal-superconducting interface, quantized vortices nucleate in type II superconductors (SC) submitted to applied magnetic fields of sufficient magnitude. These vortices aggregated to form a Vortex Matter (VM), i.e., a structure exhibiting properties equivalent to those encountered in condensed matter. However, as they move into and through the SC, a normal region is dragged together with its core, dissipating energy. To avoid catastrophic transitions to the normal state, pinning centers can be created, to attract and trap vortices, what might also enhance the critical current of the material [1-6]. Exotic behaviors arise when pinning centers are columnar defects (CDs), in which case flux penetrates abruptly, in packages containing one flux quantum per CD. This sudden entrance of vortices takes place at multiples of the so-called matching field [7-9], i.e., the value of the applied magnetic field that provides one vortex per CD. Vortex dynamics under the influence of arrays of CDs is a complex problem involving a number of relevant parameters, whose study might reveal important characteristics of the sample.

In this contribution we discuss an experiment designed to disclose some aspects of the correlations between a CD perforated in a superconductor and the nearby VM which resides in adjacent superconducting regions. To describe the problem, we first consider a field-cooled superconducting cylinder with a through hole (columnar defect). Magnetic flux is trapped within its clear bore and, upon removal of the magnetic field, a remanent moment is left, so that the sample might be envisaged...
as an extended magnetic dipole. However, if the empty column were in the middle of a superconducting sea, e.g., a hole pierced in a film, and if the local field at the neighbourhood were below the critical field ($H_{c1}$), the returning lines of flux would have to trespass the strongly repelling media represented by the superconducting film in the Meissner state. The system would then be posed to a couple of conflicting constraints, namely, the unavoidable requirement of displaying closed flux lines (no magnetic monopoles) and the local conditions leading to flux exclusion (Meissner). As in the classical definition by G. Toulouse [10,11], the system would then exhibit frustration, as a consequence of competing constraints that cannot be simultaneously satisfied. Conflicting interactions between antiferromagnetically coupled spins in a triangular lattice (geometrical frustration, as in a spin-glass) [11, 12], and continuous variation of the applied magnetic field on a superconducting network [13] are examples of systems that present frustration. The magnetic response of such a frustrated system should then exhibit some kind of anomaly, related to the above discussed situation.

2. Materials and Method

The physical system used to create and study the frustrated state discussed above, consists of a good-quality 200 nm thick film of Nb, deposited on a Si (100) substrate, using a UHV DC-magnetron sputtering system in a chamber below 100 °C cooled with liquid nitrogen. The base pressure was better than 3 x 10⁻⁹ mbar, with a partial oxygen base pressure below 10⁻¹¹ mbar. A square array of 900 indentations was pierced in the film, using an MTS Systems Nanoindenter XP. The arrangement covers an area of 300 µm x 300 µm, with a lattice parameter $d = 10$ µm. As shown in Fig. 1, each indentation has an effective diameter of the order of 1 µm, and the distance between them is much larger than the typical scales of the superconducting phase, i.e., the coherence length and the London penetration depth ($d \gg \xi, \lambda$), so that no interaction is expected between neighbors. The simultaneous occurrence of 900 similar events facilitates the experimental detection of the magnetic response of the system, carried out in a Quantum Design SQUID Magnetometer MPMS-5S.

![Fig. 1. An image of a fraction of the array of CDs, whose lattice parameter is 10 µm. As we can see in the amplified view of one CD, each column has a damaged region around, whose effective diameter is of the order of 1 µm.](image)

To prepare the frustrated state, we zero-field-cool the sample down to the measuring temperature and then ramp the magnetic field up and down. As the field is decreased, screening currents develop on the borders between each hole and the superconducting sea. The intended frustrated state will be generated by the returning flux associated with the dipole-like supercurrents if the local field experienced by the surrounding material is below $H_{c1}$. Low-temperature isothermal measurements of the magnetic moment of such a system, as a function of the applied magnetic field, $M_xH$, show an anomaly in the form of a jump on the decreasing field branch, indicating that retained flux is suddenly released.
3. Results and Discussion

An important condition to be fulfilled is that the whole sample has achieved the mixed state, so that vortices have entered the film and arrived to the columns, otherwise flux could not be trapped. It is well-known [14] that the average field in the interior of a superconducting sample achieves $H_{c1}$ when the applied field is typically twice as large. One would then conclude, from this simple argument, that the behavior discussed here would be enhanced when the field were ramped up to a value equivalent to $\sim 2H_{c1}$.

Fig. 2 shows some selected curves of $M_xH$, carried out at $T = 2$ K, for different values of the maximum applied field, $H_{\text{max}}$. These experiments, conducted for $H_{\text{max}} = 50, 60, \ldots, 190, 200$ Oe, confirm that the frustrated state is created only if a threshold field is reached. At 2 K, this limiting field corresponds to $(110 \pm 5)$ Oe. In practice, the field above which the entire sample is in the mixed state is taken as $H_p$, i.e., the field on a virgin curve at which the magnetic response has a local minimum. The upper right panel of Fig. 2 shows that, at 2 K, $H_p \sim 60$ Oe, in excellent agreement with the independent determination of the threshold value of $110$ Oe $\sim 2H_p$.

Hysteresis loops were measured for different values of $H_{\text{max}}$, some of which are shown in Fig. 3. For $H_{\text{max}} = 100$ Oe, $M(H)$ is smooth along the entire excursion, whereas jumps appear on the decreasing field branch for $H_{\text{max}} = 200$ Oe ($> 2H_p$). A further evidence in support of the above discussed scenario is the fact that the jumps occur for fields around 60 Oe, which is not a mere coincidence, but a confirmation that the abrupt variation on the magnetic response removes the conflicting conditions that otherwise would occur for $H < H_p$, at the imminence of a frustrated state.
Fig. 3. Magnetization isotherms for the pierced Nb film at 2 K. For $H_{\text{max}} = 100$ Oe (squares), no jumps are seen. When $H_{\text{max}}$ exceeds $2H_p$ (circles and triangles), jumps appear.

Also shown in Fig. 3 is an asymmetrical loop, which combines the already discussed features present in symmetrical loops, and further emphasizes that, along with a magnetization jump the system is actually cleaning its previous history. In fact, the subsequent application of a reverse field, smaller in magnitude than the threshold limit of $H_{\text{max}}$, leads the system to respond smoothly, since jumps become unnecessary when the film is not fed with sufficient flux to provoke frustration.

4. Final Remarks
We have investigated the behavior of a superconducting system presenting a frustrated state, which is originated by the competition between return flux of a dipole, created by flux trapped in empty columns, and flux exclusion by a superconductor in the Meissner state. To avoid this incompatibility leading to system frustration, antivortices (return flux) are most probably eliminated, being possibly assimilated by nearby columns, so that trapped flux and antiflux mutually annihilate, giving rise to a sudden reduction of the magnetic moment.

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