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To cite this version:
Liwen Liu, J. Kouvel, T. Brun. ROTATIONAL MAGNETIC PROCESSES IN A TYPE-II SUPERCONDUCTOR. Journal de Physique Colloques, 1988, 49 (C8), pp.C8-2189-C8-2190. ⟨10.1051/jphyscol:19888982⟩. ⟨jpa-00229272⟩

HAL Id: jpa-00229272
https://hal.archives-ouvertes.fr/jpa-00229272
Submitted on 1 Jan 1988

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ROTATIONAL MAGNETIC PROCESSES IN A TYPE-II SUPERCONDUCTOR

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Abstract. - Magnetisation-vector (M) measurements were made on a disk of compacted Nb powder in a fixed field H at 4.2 K. M is separable into a non-rotating diamagnetic component (≈ -H/4π) plus a penetrating-flux component which (for H > H_{c1}) rotates with the sample but only up to some critical angle, indicating a frictional torque due to flux pinning.

Our vibrating-sample magnetometer has recently been modified to allow simultaneous measurements of the magnetization components parallel and perpendicular to a fixed magnetic field H in the plane of a rotating sample disk. Initially, we have used such magnetization-vector (M) measurements to study rotational magnetic processes in various spin glasses [1, 2]. In the case of Au-Fe, it was found that the anisotropy field H_K produced by field-cooling turns rigidly with the sample but only up to some critical angle relative to H, thus exhibiting a constant frictional torque between H_K and the sample [2]. These results alerted us to the possibility of applying this technique to study analogous rotational processes in superconductors, especially since any observed frictional torque would relate to the magnetic flux pinning that ultimately determines the critical current [3]. Although this is an urgent consideration today with regard to the various high-T_c superconducting oxides, our initial M measurements on a superconductor were performed on a more familiar material, namely elemental (but impure) niobium. Our results are reported herewith and reveal new basic information about the magnetic states of a type-II superconductor. Our Nb sample was a 60-mesh powder of 99.8 % nominal purity, which had been mixed with an adhesive and compacted into a thin disk, 5 mm diam., 0.5 mm thick. (This configuration simulated the powder samples of the high-T_c superconductors that we are currently investigating.) The sample magnetization measured after zero-field cooling to 4.2 K is shown in figure 1 for increasing and then decreasing field. The two M-vs.-H curves, representing the initial magnetization curve (MC) and the upper branch of a hysteresis loop (HL), coincide in the normal state above H_{c2} ≈ 5.2 kOe. The initial part of MC is linear up to H_{c1} ≈ 0.7 kOe, but its slope is about 1.5 times -1/4π, the plotted M referring to the volume of the metal powder. Since the packing fraction of the powder is about 0.7, the anomalously large initial slope of MC is consistent with a complete magnetic shielding of the powder grains and the voids between them. The critical temperature of our sample measured magnetically at low H is only 7.5 K, which together with the large H_{c2}/H_{c1} ratio indicates that the impurity level is fairly high [4]. The starting conditions of our rotational experiments are indicated by the circled points in figure 1; the closed circles are the subset discussed below in detail. In each experiment, the sample was rotated quasi-statically about its disk axis from θ = 0° to 360° and back to 0° relative to the fixed H, and the components of M parallel and perpendicular to H in the disk plane were measured at each rotational step. For small θ (typically < 10°), the measured M at angle φ relative to H was assumed to consist of a non-rotating diamagnetic component M_d and a penetrating-flux component M_p that turns rigidly with the sample. Thus, with reference to figure 1 (inset), the angle θ_p between M_p and H was taken to equal initially the sample rotation angle θ. It was further assumed that the M_d determined at small θ stays the same during all subsequent changes of θ, thus allowing us to determine the evolution in the magnitude and direction of M_p. For M_p and θ_p, at H = 0.6 kOe (on HL), our results deduced under the above assumptions (with M_d = -65.5 emu/cm^3) are plotted versus θ in figure 2. We see that M_p decreases steadily as θ is raised to about 180° and then remains small for the rest of the rotational cycle, and that θ_p follows θ fairly closely over the entire cycle. Thus, despite its reduced size, M_p continues to rotate rigidly with the sample. This behavior is typical for H < H_{c1} on HL. For H < H_{c1} on MC, M_p is found to be zero, as expected, with M_d having the same value.) When H exceeds H_{c1}, M_p rotates with the sample but only up to a lower θ_p (which decreases from 360° with increasing H), at which point θ_p drops rapidly to a small

Fig. 1. - Magnetization of Nb powder sample zero-field cooled to 4.2 K versus increasing field (along magnetization curve MC) and then decreasing field (along hysteresis loop HL). Circles on HL and MC represent starting conditions for rotational experiments. Diamonds show deduced values of M_d compared to dashed line of slope -1/4π. Squares show values of frictional torque τ_f. (Inset: vector diagram indicating separation of measured M into M_d and M_p for sample-rotation angle θ, as described in text.)
value as $\theta$ is raised to $360^\circ$ and then becomes negative as $\theta$ is reduced to $0^\circ$. This peculiar behavior is transitional in that at higher $H$ (but still well below $H_{c2}$) the variations of $M_p$ and $\theta_p$ with $\theta$ settle into a simple hysteretic pattern. As exemplified by our results for $H = 1.3$ kOe (on HL) shown in figure 3 (closed symbols), $M_p$ descends with increasing $\theta$ until it reaches and then stays at a fairly constant value for the rest of the cycle. Meanwhile, $\theta_p$ rises to a plateau value where it remains up to $\theta = 360^\circ$ and then decreases to a negative plateau value of the same magnitude as $\theta$ is lowered to $0^\circ$. Thus, for both directions of rotation, $M_p$ turns with the sample but only up to some critical angle ($\theta_{pc}$) relative to $H$, showing that the torque exerted on $M_p$ by $H$ is balanced macroscopically by a constant frictional torque between $M_p$ and the sample. Since $\theta_{pc} \approx 20.5^\circ$, $H = 1.3$ kOe, and the plateau value of $M_p$ is $\sim 62$ emu/cm$^3$, the size of this frictional torque, $\tau_f = H M_p \sin \theta_{pc} \approx 2.8 \times 10^4$ erg/cm$^2$ per radian of rotation. Microscopically, this quantity may be regarded as the average energy loss arising from the unpinning and repinning of the penetrating (vortex) flux as it progresses past the imperfections in the rotating sample while maintaining a constant mean orientation relative to $H$.

Fig. 3. $- M_p$ and $\theta_p$ versus increasing and then decreasing $\theta$ for Nb powder at 4.2 K and $H = 1.3$ kOe starting on HL and on MC. Dashed line for $\theta_p = \theta$ represents rigid initial rotation of $M_p$.

The rotational experiment at $H = 1.3$ kOe was also performed with the starting point on the magnetization curve (MC). In both the MC and HL cases, $M_d$ was deduced to be $-112.2$ emu/cm$^3$. For comparison, our results for $M_p$ and $\theta_p$ versus $\theta$ in the MC case are also displayed in figure 3 (open symbols) and, aside from $M_p$ starting from below rather than above the same plateau value, the variations of $M_p$ and $\theta_p$ are essentially identical to those in the HL case. The similarity of the two cases is found to continue at higher $H$, but with a rising plateau value of $M_p$ and a decreasing $\theta_{pc}$, such that the frictional torque $\tau_f$ grows rather slowly. In fact, as shown in figure 1, $\tau_f$ appears to be leveling out at $H$ just above 2 kOe, after having grown rapidly when $H$ exceeded $H_{c1}$ ($\sim 0.7$ kOe).

Another striking feature of our results concerns $M_d$, the diamagnetic component of the magnetization, whose deduced values for the cases investigated are plotted versus $H$ in figure 1. It is clear that $M_d$ follows the initial negative slope of MC up to $H$ just above $H_{c1}$, where it starts to change more slowly. But even at $H = 2$ kOe (i.e., well above $H_{c1}$) $M_d$ is still fairly close to the dashed line of slope $-1/4 \pi$. To our knowledge, this remarkable persistence of an almost perfect Meissner-effect shielding has not been anticipated theoretically. This property, of course, has not been accessible by conventional (non-rotational) magnetic measurements. Indeed, except for the frictional torque, which can be determined directly by magnetic-torque measurements [5], all our findings reported here derive uniquely from the capability of rotational magnetization-vector measurements.

We thank Dr. N. Rivier for stimulating discussions of type-II superconductors and H. P. Goeckner for his experimental help. This work was supported at the University of Illinois at Chicago by the National Science Foundation (Grant No. DMR84-06898) and at the Argonne National Laboratory by the U.S. Department of Energy (BES-Materials Sciences, Contract No. W-31-109-Eng-38).

Addendum

We have recently become aware of an earlier rotational magnetic study of type-II superconductors (V and V-Ti) by R. Boyer, G. Fillion, and M. A. R. Le Blanc (J. Appl. Phys. 51 (1980) 1692), where a sample disk was rotated inside two coils mounted orthogonally and the changes of magnetic flux parallel and perpendicular to a fixed field were integrated with respect to some reference state. Though operationally less direct, these experiments are quite analogous to our M measurements performed with a vibrating-sample magnetometer, and the results appears to be basically consistent. However, the earlier work did not include a decomposition of the measured magnetic moments into diamagnetic and penetrating-flux components, which is the central revealing feature of our data analysis.

[5] Magnetic torque measurements on a high-$T_c$ superconductor (La, Sr)$_2$CuO$_4$ have been performed by Giovannella, C., Collin, G. and Campbell, I. A., J. Phys. France 48 (1987) 1835, who report "viscous" rotations of the penetrating flux, consisting of nearly instantaneous changes (which we call "frictional") followed by slower relaxation effects (which are negligibly small in our Nb study).