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Do we really need a superconducting glass model ?

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Abstract. Muller and coworkers have introduced the concept of a superconducting glass to explain some magnetization data in high T_c superconductors. We explain this data using conventional ideas of type-II superconductivity.

Keywords. High T_c superconductors; magnetization; superconducting glass.

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Susceptibility measurements on $La_{1\cdot85}Ba_{0\cdot15}CuO_4$ have been interpreted as resulting from a "superconducting glass" state (Muller *et al* 1987). The concept of a superconducting glass has also been used as a possible explanation of the isothermal magnetization data on $La_{1\cdot8}Sr_{0\cdot2}CuO_4$ (Maletta *et al* 1987). This concept has been used to suggest the existence of Josephson junctions in the intragranular regions (Deutscher and Muller 1987; Morgenstern *et al* 1987) of high T_c superconductors. We shall show in this note that this data can be explained by conventional concepts without invoking a superconducting glass state.

It is well known (see e.g. Chandrasekhar 1969) that the state of a superconductor at any (H, T) point is independent of how this point is approached only because $B = 0$ inside the superconductor. It follows as a corollary that for a type-II superconductor in the region $H > H_{c1}$, the state of the system will depend on how the point (H, T) is approached. We will first show that the ergodic and non-ergodic behaviour of susceptibility (Muller *et al* 1987) is a manifestation of the path-dependent nature of the state above H_{c1}. They first cooled the sample to a low temperature in zero field, then applied a field H and studied the susceptibility through various stages of heating and cooling in this constant field H. They made measurements in fields varying from 0·35 T to about 0·02 T which are all larger than H_{c1} in these materials (Grover *et al* 1988).

When a zero-field cooled (ZFC) sample at T is subjected to a field $H > H_{c1}$, macroscopic shielding currents are set up and a model for the magnetization of such a ZFC sample was proposed by Bean (1962, 1964). When such a sample is heated in this field H, to a temperature T_1, we will argue that the equilibrium state will be the same as that of a ZFC sample cooled to T_1 and then subjected to H. Muller *et al* (1987) then cooled this sample, and this field cooling from (T_1, H) to (T, H) does not change the macroscopic shielding current distribution from that at (T_1, H), but the London screening increases as H_{c1} increases on cooling. A sample thus prepared at (T, H) is different from a ZFC sample at (T, H), or from an FC sample at (T, H), and its path-dependent magnetization can be obtained by following Bean's model (1962, 1964).

Ravi Kumar and Chaddah (1987, 1988) have extended Bean's model to high T_c

superconductors by assuming that J_c decays exponentially with H. It is also known from experiments that J_c decays exponentially with increasing temperature (see e.g. Senoussi *et al* 1988). With these inputs we have calculated the magnetization seen by a sample subjected to temperature and field variations as in the studies of Muller *et al* (1987). We assume that the sample is an infinite slab and the parameters and the results of our calculation are shown in figure 1. These will now be explained and compared with the results shown in figure 2b of Muller *et al* (1987).

Point A in figure 1 is the calculated magnetization of a ZFC sample in a field of

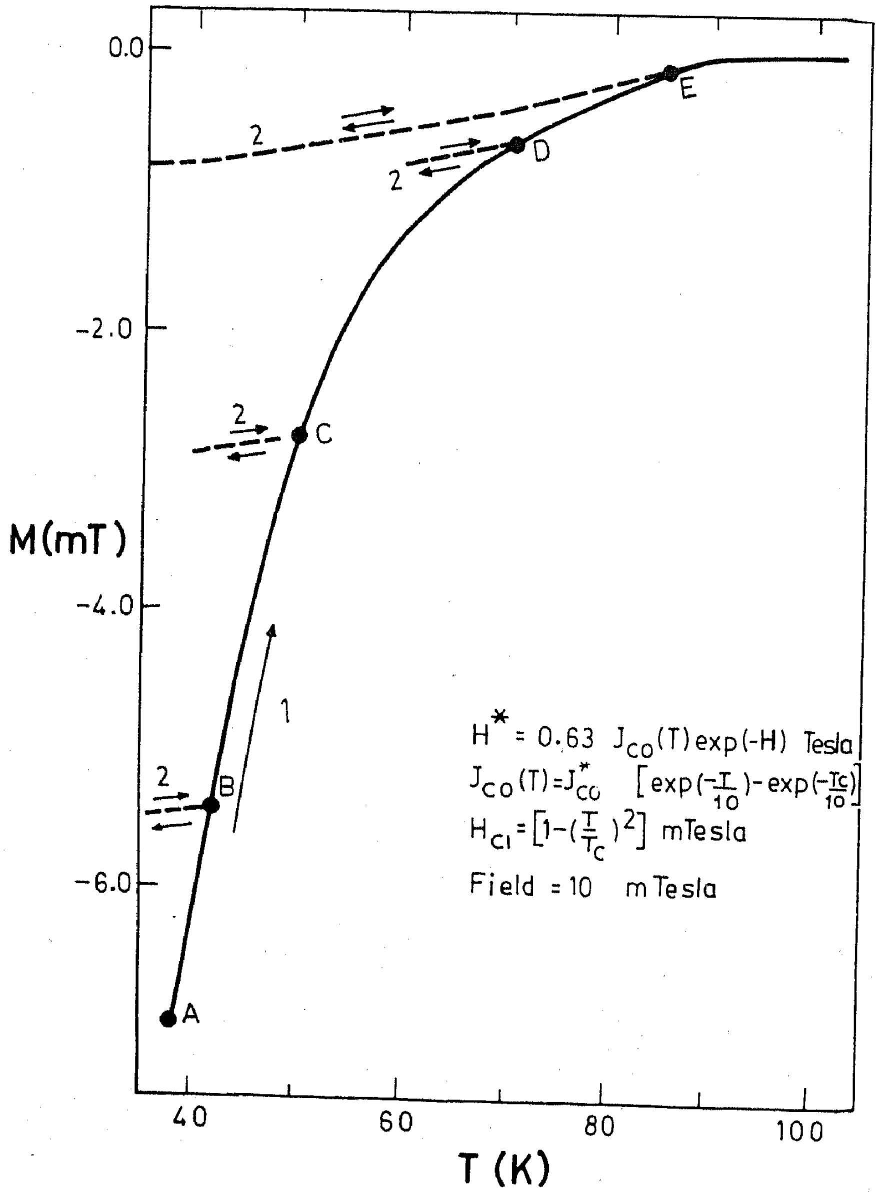

Figure 1. The calculated magnetization of a sample in an external field of 10 mT. The sample is assumed to have a $T_c = 90$ K and is prepared at point A by cooling in zero field and then applying 10 mT. It follows curve 1 on heating but is cooled and heated in between at points B, C, D and E. The curves labelled 2 are all reversible, but the magnitude of the slope increases continuously from points B to E. We have taken $J_{c0}{}^*(= 10^7\ \mathrm{Amp/cm^2}) = 1$.

10 mT, which is more than H_{c1} (0). As the temperature is raised curve 1 is followed and the magnitude of magnetization drops as $J_c(H)$ decreases with increasing temperature. When we warm the sample from (H, T) to (H, T_1), the shielding currents flowing at T start decaying because their current density is more than $J_c(T_1)$ (see e.g. section 7·2 of Wilson 1983). The decay rate is governed by the (small) flux-flow resistance. As these shielding currents decay the field profile inside the sample changes and shielding currents are set up deeper inside the sample. The final distribution of shielding currents and thus the magnetization is identical to that of a ZFC sample which was cooled only to T_1 and then subjected to a field H. If we now cool the sample from T_1 to T it does not retrace curve 1 but follows curve 2. This is because the shielding currents at (H, T_1) always remain below the critical current density during cooling, and thus will not decay and the shielding current distribution cannot change. There is a small increase in H_{c1} on cooling from T_1 to T and this results in a small increase in the magnitude of magnetization or susceptibility (magnetization and susceptibility are proportional in this constant field case). Since London screening is reversible, and since the shielding currents do not experience any flux flow resistance during the traversal of curve 2, curve 2 is reversible and this is in accordance with the results of Muller *et al* (1987).

Based on the arguments in the preceding paragraph, we can state that curve 1 is followed on heating but not on cooling. On cooling from any point on curve 1 we will get a curve similar to the set of curves 2. The magnetization along curve 2 is reversible until it merges with curve 1. The slope of curve 2 is dictated by the variation of H_{c1} with temperature, and this reversible curve will thus have a smaller slope at lower temperatures. Finally at temperatures close to T_c curves 1 and 2 will appear, within experimental error, to merge and curve 1 will appear reversible. All these features are depicted in figure 1 and explain the ergodic and non-ergodic behaviour reported by Muller *et al* (1987). We should mention that Bean's original assumption of field-independent J_c and Ravi Kumar and Chaddah's extension yield results that would appear indistinguishable on the scale of figure 1.

We now consider the field-dependent isothermal magnetization of a ZFC sample (Maletta *et al* 1987) shown in figure 2a. The magnitude of the slope decreases with increasing field and the magnetization reaches a minimum before again increasing. As shown in figure 2b, this is consistent with the model of Ravi Kumar and Chaddah (1987), but not with Bean's original model (1964) and this has been discussed in detail by Grover *et al* (1988). It should be emphasized here that irrespective of how small be the ratio of the grain size to the London penetration depth, the slope of M vs H curve must always be independent of H (see Clem and Kogan 1987) for fields below H_{c1}. A large penetration depth cannot explain the data of figure 2a. The isothermal magnetization data are also thus explained with a conventional theory of type-II superconductors.

The final feature is the decay of magnetization with time on switching off the field (Muller *et al* 1987). Within Bean's model any change in the external field requires a redistribution of the shielding currents and this is the process of flux-creep. Such a feature is well known in type-II superconductors (see e.g. figure 3.3.24 of Brechna 1973), and is explained within the Kim-Anderson model of flux creep (Anderson and Kim 1964).

We have shown in this paper that the major experimental results used to propose a superconducting glass state can be understood within existing conventional theories of type-II superconductors.

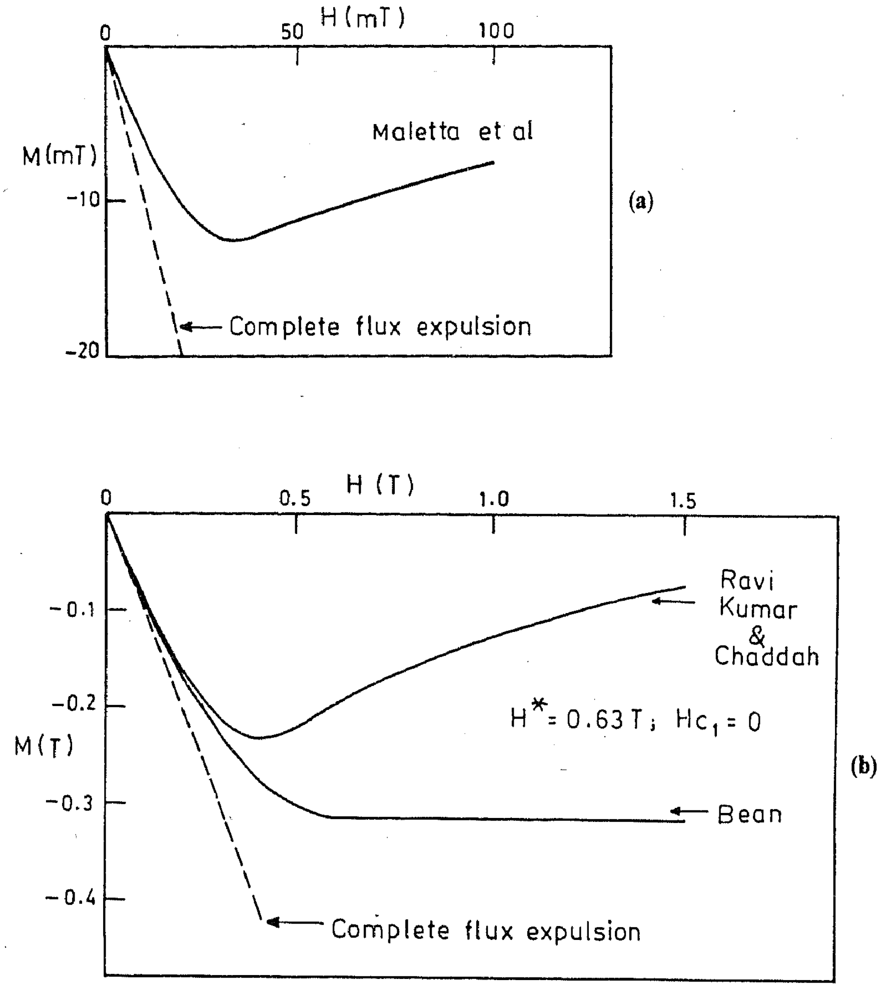

Figure 2. Measured isothermal magnetization curve of Maletta *et al* is shown in (**a**), and the calculated curves in (**b**). The agreement with the model of Ravi Kumar and Chaddah is apparent.

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