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Simulations of transitions in superheated superconducting granules

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Abstract

We perform simulations of both colloidal suspensions and planar arrays systems of superheated superconducting granules. Transitions induced by an increasing external field appear in both situations as an ordering mechanism. Concentrated planar arrays present an interval of external field for which no transitions are produced. These effects can be interesting in applications for superheated superconducting granule detectors.

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1. Introduction

Systems of superheated superconducting granules have been proposed as detectors for low-energy neutrinos and dark matter [1]. In these devices, a great number of microgranules of type I superconductor are maintained in metastable states by an external field. Energy deposition in a granule can result in its transition to the normal state which can be detected by the loss of Meissner effect. In disordered suspensions of microgranules, different size of granules, surface defects and mainly diamagnetic interactions produce a spreading of 20% in the transition fields, affecting the resolution of the detector. When the microspheres are located in planar arrays (Planar Arrays of Superconducting Spheres, PASS) as was proposed by Turrell et al. [2], the spreading is reduced by an order of magnitude.

We have simulated both kind of systems, solving the Laplace equation for the magnetic potential, with adequate boundary conditions, by an iterative method [3]. Comparison of surface magnetic fields with superheated field values permit us to know which spheres are able to transit to the normal state. Defects on spheres are introduced by a threshold distribution B_{th} fitted to experimental results. The spheres cannot move, but transit to the normal state once their maximum surface fields reach their threshold values. Calculation is repeated after each transition until all the spheres have transited.

2. Results and discussion

Simulations on colloidal systems are performed by placing N spheres of radius a at random in the

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desired geometry. We present the results for filling factor values $\rho = 0.001$, 0.002, 0.01, 0.05, 0.10, 0.15 and 0.20. The number of spheres selected are $N = 250$ for dilute configurations (up to 0.05) and $N = 150$ in the other cases.

The fraction f of remaining superconducting spheres as a function of the external field B_{ext} (normalized with the superheating field B_{sh}) for systems with different concentration is shown in Fig. 1. The most dilute case closely follows the threshold limit distribution. However, transitions occur for increasingly lower external fields as the concentration of the sample is increased. This effect is produced by diamagnetic interactions, stronger in concentrated systems, but still important for filling factors of a few per cent [4]. These results are similar to those of experiments of Dubos and Larrea [5].

In our present simulations we observe that after successive transitions, the remaining superconducting spheres present a certain spatial order. Maximum surface field distribution tends to be more uniform as the number of transitions increases. This is more evident for initially concentrated systems. In Fig. 2 the surface field distributions are presented for systems that reach the same final $\rho = 0.02$ value. They are compared with the distribution of a random configuration

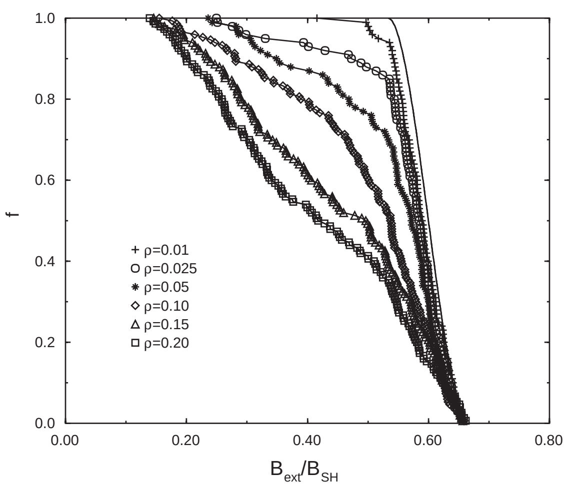

Fig. 1. Fraction f of still superconducting spheres versus B_{ext}/B_{sh} corresponding to different initial concentrations ρ. Single line corresponds to the threshold distribution.

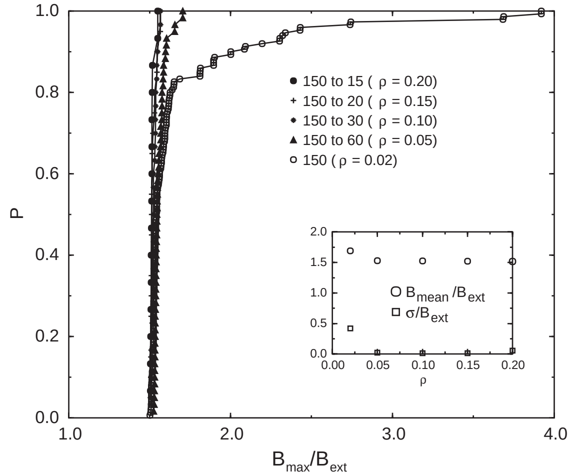

Fig. 2. Fraction P of spheres with maximum surface field value lower than the x-axis value (in units of B_{ext}) for configurations with different initial ρ and the same final value $\rho_{ef} = 0.02$. In the inset, the corresponding mean value (circles) and standard deviation (squares) as a function of ρ are shown.

with $\rho = 0.02$. The observed spread in the random configuration, despite its small concentration, shows clearly the effect of disorder [4], whereas equivalent concentration after transitions appears as more homogeneous. The ordering mechanism shown by transitions can be then used to reduce the uncertainty in the minimum energy experimentally detected.

Simulations of PASS systems are performed on square arrays with lattice spacing (in units of radius a) $d/a = 7.482$, 4.376, 3.473, 3.034, 2.757 and 2.5 (equivalent to $\rho = 0.01$, 0.05, 0.10, 0.15, 0.20 and 0.268 in 3D arrays). The number of spheres considered were $N = 169$ for diluted systems and $N = 400$ for concentrated configurations, (for which finite size effects on diamagnetic interactions are more important). The magnetic field is applied perpendicular to the system.

The response of the system to increasing field is represented in Fig. 3. The fraction of remaining superconducting spheres is displayed for several lattice distances. The spreading of transition curves still increases as the lattice distances are reduced, but the spread is lower than in disordered systems. More relevant is the breakdown of the continuous response and the appearance of a gap or plateau zone clearly different for shorter lattice

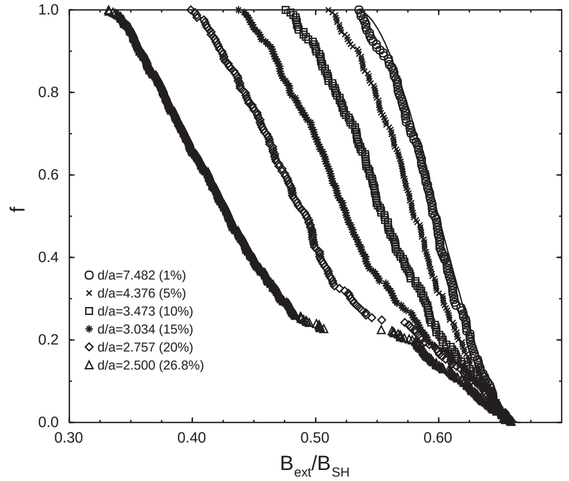

Fig. 3. Fraction f of still superconducting spheres versus $B_{\mathrm{ext}}/B_{\mathrm{sh}}$, after an increase of the perpendicular external magnetic field from zero, for systems with different initial lattice spacings. The continuous line corresponds to the threshold distribution.

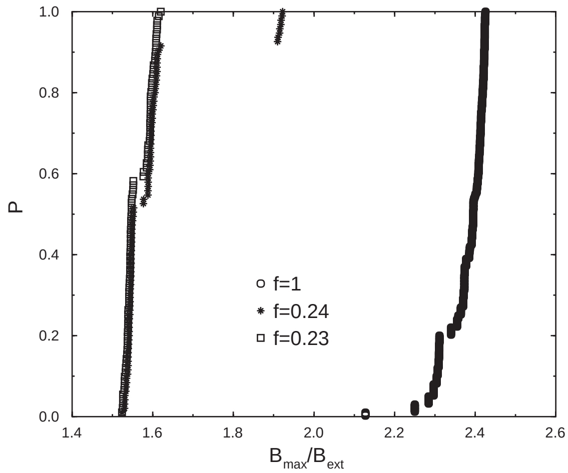

Fig. 4. Fraction P of spheres with maximum surface field lower than the x-axis value (in units of B_{ext}), in the evolution of a system with initial $d/a = 2.5$ and $N = 400$ near the plateau zone.

distances. This plateau appears when the fraction of remaining superconducting spheres becomes slightly lower than $f = 0.25$ and its width increases as the lattice spacing is reduced. In this zone no transitions are produced by small changes of external field. This corresponds to an effective hot border in the sense that only increase in temperature can induce transitions to normal phase [6]. These results qualitatively agree with those obtained by Esteve et al. [7], although they found the plateau zone always around $f = 0.3$.

The appearance of the plateau is related to the evolution of maximum surface field distributions. In Fig. 4 surface field distribution values are represented for a system with $d/a = 2.5$ at several external field values. The initial distribution ($f = 1$) splits after successive transitions ($f = 0.24$) into two distinct branches. Just at the plateau ($f = 0.23$), the distribution features a single branch. Remaining superconducting spheres need higher external field to transit. This explains the appearance of the plateau [8].

Our simulations show that the concentrated systems present at $f = 0.5$ forms an ordered configuration separated in striped domains which would produce the appearance of plateau at $f = 0.25$. This order does not appear in systems without the plateau. Following transitions these domains are produced in such a way that, when the plateau appears, only spheres with third next-neighbours remain superconductor. We have found this to correspond to the $f = 0.25$ value.

Simulations of a single domain allows us to test if the ordered configuration is achieved at $f = 0.5$. Results from simulations for different values of lattice distances have allowed us to obtain the limit for the appearance of the ordered configuration, and consequently, the existence of the plateau to $d/a = 2.871$ ($\rho = 17.7\%$) value [8].

We have shown in the results presented here that transitions induced by increasings of the external field constitute a geometrical ordering mechanism, both in disordered and ordered configurations. In the last case, and for concentrated systems, this effect is associated with transitions in preferential positions, giving rise to a 'hot border' effect. This could have interesting consequences on experimental detectors.

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