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# Hot-border effects, ordering, and avalanches in planar arrays of superheated superconducting granules

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## Abstract

We present results of simulations of transitions in planar arrays of superheated superconducting granules (PASS) immersed in an external magnetic field parallel to the system. Analysis of the behaviour of the system when the external field is slowly increased from zero shows the existence of an interval of external fields for which no transitions are produced. This gap is found to be a consequence of ordering induced by transitions. However, this ordering is different for diluted and for concentrated systems. Avalanches of different sizes with distributions depending on concentration are observed.

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## 1. Introduction

Experiments on dispersions of superheated superconducting granules (SSG) have investigated the feasibility of these systems as detectors of neutrinos, dark matter and other particles [1]. In these devices an ensemble of superconducting type I microgranules are maintained in a metastable superheated state by adequate conditions of

temperature and external field. If a particle or radiation with enough energy collides with a microgranule it can produce a transition to the normal conducting state. The disappearance of the Meissner effect, inherent to the transition, produces a change in the magnetic flux that can be detected by a magnetometer.

Despite their promising applications, some intrinsic features of SSG limit the efficiency of these detectors. The metastability of each grain of the suspension depends on its shape and surface quality and on the diamagnetic interactions with the other microgranules. Dispersion in size

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combined with these effects produces a spread of transition fields of about 20%, which affects the accuracy of these devices.

Planar systems of microgranules arrayed in a regular configuration (PASS) have been presented as an alternative to SSG to reduce this spread [2]. The present manufacturing techniques of PASS devices can only produce arrays of a relatively small size, but with good sensitivity in both energy and position. The regular arrangement allows the control of magnetic interactions. Furthermore, the photolithographic procedure employed in their manufacture enables microgranules with excellent uniformity in shape and size to be obtained. Although these characteristics do not completely eliminate the dispersion of superheated transition field values, reductions of an order of magnitude have been observed [2].

On the other hand, the regular spatial configuration and the greater uniformity in shape and size of these systems suggest the possibility of the presence of avalanches that could amplify the magnetic signal. Avalanches are a consequence of diamagnetic interactions between grains, which screen the magnetic field of neighbouring granules. The transition of a simple grain can reduce or eliminate this screening in such a way that the maximum surface field of the nearest granules can increase. Consequently, transitions in several neighbours can occur almost simultaneously. Diffusion of released heat, inherent to any first-order transition could also produce transitions in neighbouring grains. This avalanche effect could be useful for devices with very small granules to provide high-energy sensitivity or a triggering mechanism in high-energy particle experiments.

Avalanche experiments have been carried out on PASS devices with different geometries, such as regular square configurations immersed in a magnetic field perpendicular to the plane, or systems of a few lines of microgranules with the magnetic field applied along the lines. Results of these experiments show that the simultaneous flip of several granules are produced in these latter systems with a higher incidence than in the square configuration [3]. The existence of partial avalanches and a lack of transitions of complete lines

were explained as a consequence of imperfections in the manufacturing process [3].

We have performed extensive simulations of transitions in PASS systems immersed in an increasing external field in both perpendicular and parallel magnetic field set-ups. Results from the perpendicular case were presented in Ref. [4], showing a reduction of the spread in transition fields, analogous to that experimentally observed. In the same work, and in agreement with other authors [5], the existence of a gap or interval of external field values for which no transitions occur was shown for concentrated systems. This corresponds to a hot border, in which only transitions by increasing temperature can be produced [6]. This gap, which appears in concentrated configurations, but not in dilute systems, was related to transitions occurring in preferential positions, which induced spatial ordering. The presence of this ordering was found to be consistent with the value of the fraction  $f$  of remaining superconducting microgranules for which the gap appears. This effect could have relevant consequences on the minimum energy detected by experimental detectors.

In this work, we present the results corresponding to the other case: transitions in planar arrays with the magnetic field applied parallel to the system. A gap or plateau zone in the transition field values will be shown to exist for concentrated configurations, but not for dilute ones, for microgranules assumed to be microspheres with defects on their surface. This effect is similar to that produced in the perpendicular external field case, but appears for a higher fraction  $f$  of remaining superconducting microgranules. The avalanche effect is hardly observed in these concentrated systems. An additional analysis is performed on PASS with more perfect grains in order to reduce the influence of the defects on the response of the system. In this case all configurations, both concentrated and dilute, present plateau zones, but are shown to correspond to two types of different behaviour depending on lattice distance. For separated spheres, transitions are produced in such a way that remaining superconducting spheres are ordered on complete lines when the plateau appears. After this zone, avalanches

corresponding to transitions of these complete lines are observed. On the contrary, transitions in configurations with smaller lattice distances produce a quasi-homogeneous spatial distribution of remaining superconducting spheres in the plateau zone. Furthermore, there are a smaller number of avalanches in the evolution of these concentrated systems, but which involve a larger number of spheres. We will explain the appearance of the plateau zone and develop a criterion to determine the lattice distance value that separates the two types of behaviour.

These results are presented in this paper as follows: in the next section transitions undergone by systems corresponding to different lattice distances are analysed. Section 3 is devoted to studying the behaviour of more perfect granules. Spatial order produced by transitions, the existence of a plateau and the value of the fraction  $f$  of spheres that remain superconducting for which it appears are explained in this section. The avalanche effect is described in Section 4. Section 5 provides our conclusions.

## 2. Transitions

We perform simulations of transitions on systems of superheated superconducting microgranules in an increasing external magnetic field  $B_{\text{ext}}$ . Microgranules are considered as spheres of equal radius  $a$ , much larger than the London penetration length. Results presented in this paper correspond to planar configurations of spheres ordered on square lattices immersed in an external field applied parallel to the lines of spheres. To take into account the existence of possible defects on spheres we assign a random threshold magnetic field value  $B_{\text{th}}$  to each sphere following a distribution related to the superheated value  $B_{\text{SH}}$ . This distribution takes the form of a parabolic distribution in an interval of values between  $B_{\text{SH}}(1 - \Delta)$  and  $B_{\text{SH}}$ . A larger value of  $\Delta$  is related to a larger range of defects. Results presented in this section correspond to a  $\Delta = 0.2$  value in agreement with experimental estimations for tin spheres [7]. We then consider that the transition of a sphere occurs when the maximum surface field at any

point on its surface reaches its threshold value, and that the transition is complete. We further assume that the latent heat corresponding to transitions is small enough so as not to affect bath temperature and not to originate transitions in neighbouring spheres.

The method of calculus in our simulations is as follows:  $N$  spheres are placed at the vertices of a planar square lattice with the lattice parameter  $d$  giving the distance between neighbours. Without loss of generality, we place the system in the plane  $XZ$  and  $(l_x, l_z)$  are the coordinates of the spheres. After assigning a random threshold field value to each sphere, the system is immersed in an external magnetic field  $B_{\text{ext}}$ , applied in the  $Z$  direction, which is slowly increased from zero. Resolution of the Laplace equation for the magnetic scalar potential with the appropriate boundary conditions enables the surface magnetic field to be known on each microsphere. We have used a numerical procedure that allows us both to consider the complete multi-body problem and to reach multipolar contributions of an arbitrary order [8]. When the maximum local magnetic field on the surface of any sphere reaches its threshold value  $B_{\text{th}}$ , the sphere transits and the configuration becomes one of  $N - 1$  superconducting spheres. Interactions between remaining superconducting microgranules change after each transition, due to the long range of diamagnetic interactions. This leads us to repeat the process until all spheres have transited. The applied field for which each sphere transits, and the maximum surface magnetic field value of each sphere are monitored after each transition, allowing us to study the evolution of the system in the successive transitions.

Numerical simulations have been performed on several configurations with distances between sphere centres, in units of radius  $a$ , of  $d/a = 4.376, 3.473, 3.034, 2.757$  and  $2.5$ . In a 3-D array these distances correspond to values of filling factors (fraction of volume occupied by the spheres), of  $\rho = 0.05, 0.10, 0.15, 0.20$  and  $0.268$ . The number of spheres was  $N = 169$ , that is a  $13 \times 13$  square lattice.

Results of transition simulations are shown in Fig. 1. In this figure the fraction of remaining superconducting spheres versus the increasing

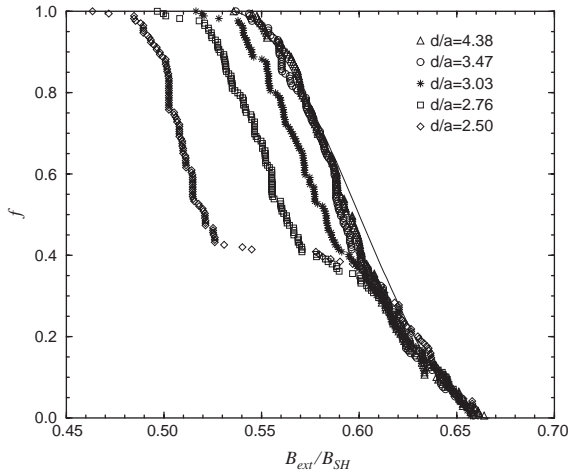


Fig. 1. Fraction  $f$  of spheres that remain superconducting versus  $B_{\text{ext}}/B_{\text{SH}}$  after an increase of the external field from zero for several samples of  $N = 169$  initially superconducting spheres corresponding to different lattice spacings. The continuous line corresponds to the dilute limit.

external field (in units of  $B_{\text{SH}}$ ) is represented for several lattice distances. We can observe an increase in the spread of transition fields as lattice distance decreases, as a consequence of the stronger diamagnetic interactions. The first transitions, produced at the smallest external field values, correspond in all cases to spheres placed at the centre of both the top and bottom borders of the system, which have the maximum surface magnetic field. This is because diamagnetic interactions between microgranules produce a screening effect, especially in the direction of the applied field. This can be seen in Fig. 2, where maximum surface fields for spheres on a central line of granules, parallel to the external magnetic field, and on a line at the lateral border are represented for two different lattice distances. However, the most relevant feature of Fig. 1 is the appearance, in concentrated configurations, of a gap or plateau zone corresponding to an interval of external field values for which no transition occurs. This plateau appears at a fraction of spheres that remain superconducting at approximately  $f = 0.41$ . In this zone, flips to the normal state can only be induced by thermal nucleation. In this sense, this effect corresponds to a hot border [6]. This

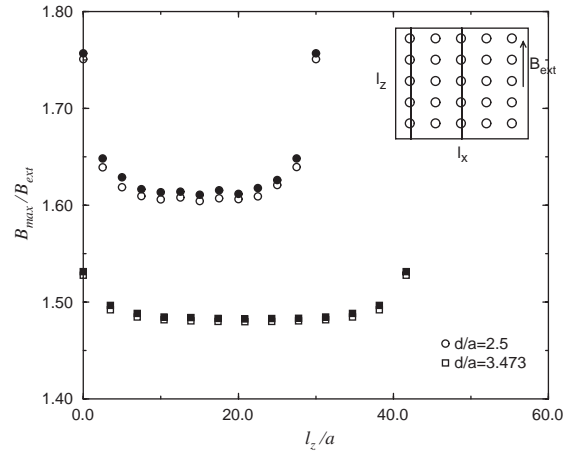


Fig. 2. Maximum surface field values for spheres on lines parallel to the external field, as shown in the inset, as a function of the  $l_z$  coordinate. Results correspond to a central line (full symbols) and a lateral border (hollow symbols).

behaviour is apparently similar to that observed in systems immersed in a perpendicular applied magnetic field [4], but here the plateau appears for a higher  $f$  value.

The reason why the plateau appears in concentrated systems, but not in dilute ones, can be related to the different dynamics in the evolution of the system during the transitions. We have analysed the dynamics by studying the evolution of both maximum surface magnetic fields and spatial distributions. Fig. 3 shows such an evolution for two representative cases. The first, Fig. 3a, is a concentrated configuration with lattice distance  $d/a = 2.5$  (that would correspond to a filling factor of  $\rho = 26.8\%$  in 3-D systems) and whose evolution presents the plateau zone. The second, in Fig. 3b, is a dilute system ( $d/a = 4.38$ ,  $\rho = 5\%$ ). Distributions of maximum surface magnetic field are represented for both configurations and correspond to values of fraction of spheres that remain superconducting  $f = 1$  (initial state, all spheres superconducting),  $f = 0.71$  (120 superconducting spheres),  $f = 0.45$  (74 superconducting spheres, which corresponds to some transitions before the plateau) and  $f = 0.41$  (69 superconducting spheres, when the plateau appears in the concentrated case). It can be seen that initial distributions present different intervals of

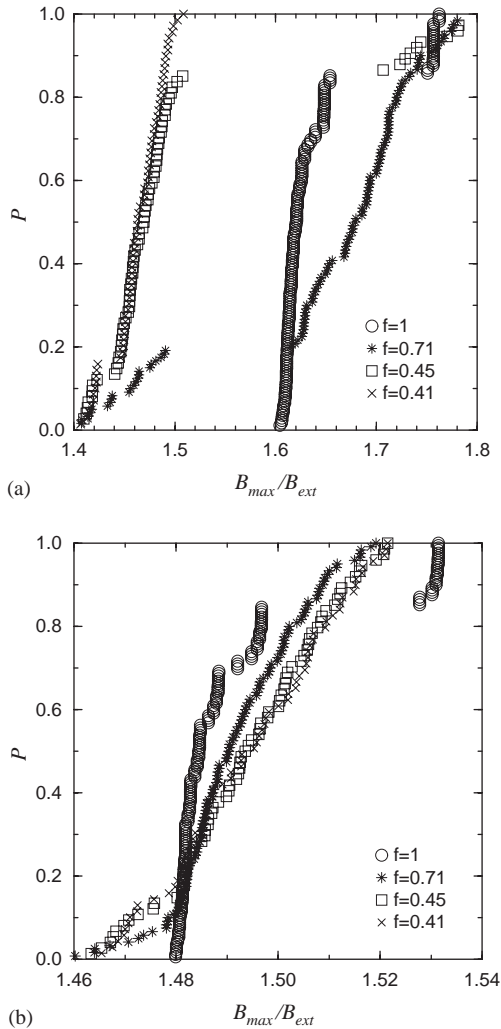


Fig. 3. Fraction  $P$  of spheres with maximum surface field value lower than the  $x$ -value (in units of  $B_{ext}$ ) in the evolution of configurations with initial lattice spacings (a)  $d/a = 2.5$  and (b)  $d/a = 4.376$ . Results for  $f = 1$  (all spheres superconducting),  $f = 0.71$ , 0.45 and 0.41 (120, 74 and 69 spheres that remain superconducting, respectively) are shown.

maximum surface magnetic field values that are larger for concentrated systems and which are a sign of the relevance of diamagnetic interactions. However, a similar distribution in two separated branches is shown for both concentrations. The smaller branch, with higher surface magnetic values, corresponds to spheres placed at both the top and bottom borders of the system. Some of

these will be the next spheres to transit. Transitions change the maximum surface magnetic field values in a large number of spheres. There is competition between the increment of surface magnetic field, due to the reduction of the screening effect, and the decreasing number of interacting microgranules. For concentrated systems a change in the population of the two branches is produced, with an increment in the distance between both branches. The complete disappearance of the upper branch causes the system to enter the plateau zone and only granules with low surface magnetic field values remain superconducting, and are thus far from their threshold values. They need much larger external fields to flip to normal state. This explains the appearance of the plateau. On the contrary, the two initial branches merge and change to a more continuous distribution after some transitions in dilute systems. Slight increments of the applied field are able to produce subsequent transitions and therefore no gap interval is observed.

Relating these types of behaviour with the position of the ensemble of spheres in a phase diagram, this evolution could be described in the following way: the initial state could be represented by a set of points along a vertical line at the bath temperature, distributed into two separated segments, one of which is near the superheated line (Fig. 4a). Each point represents the state  $(T, H)$  of a sphere and, consequently, the upper segment shows the population corresponding to the upper field branch. The separation between the segments coincides with the separation between both branches. Changes in diamagnetic interactions by transitions produce a change in the population of each segment. In dilute configurations a connection of both segments is produced and the phase diagram presents a population with an approximately continuous distribution below the superheated line. On the other hand, transitions in concentrated systems are produced in such a way that the two segments remain separated until the upper segment disappears (Fig. 4b). It is at this stage that the plateau zone appears. Remaining superconducting spheres correspond to the population of the remaining segment, separated from the superheated line. This effect, for each

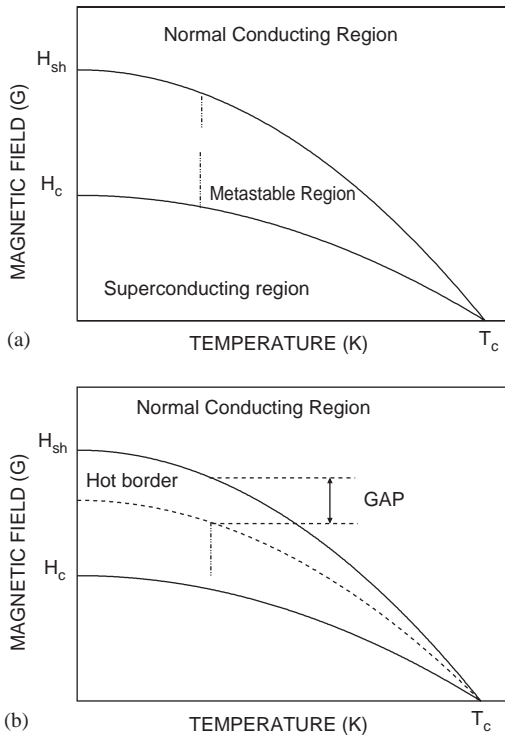


Fig. 4. (a) Phase diagram corresponding to initial PASS configurations. (b) Phase diagram of remaining superconducting spheres, in concentrated systems, when the plateau appears.

temperature, describes a hot border line in the phase diagram separated from the superheated line by an interval of magnetic fields corresponding to the plateau zone gap.

We have studied the relation between surface magnetic distributions and spatial distributions of the remaining superconducting spheres. The evolution of these spatial distributions present distinct features depending on the concentration of the system, as is shown in Fig. 5 for two representative cases ( $d/a = 2.5$  and  $4.376$ , respectively). It can be observed that transitions in concentrated systems produce, when the plateau appears, two separated domains with different kinds of spatial order. For both domains the tendency is not to have any superconducting next neighbour in the direction perpendicular to the external field. While spheres of the first domain are mainly placed along vertical lines, a tendency to align along the diagonal direction is observed for the other domain. Dilute

systems only show partial lines of superconducting spheres.

### 3. Defect-free granules

Results presented above correspond to spheres with a relatively large range of defects. It is well known that defects can act as nucleation centres and therefore transitions are produced at smaller external fields than in more perfect spheres. This fact could have an influence on the dynamics of the system, because it can alter spatial distributions and thus diamagnetic interactions between spheres after transitions.

In order to gain insight into the intrinsic dynamics of the evolution of these systems, we have reduced the influence of defects and analysed the response of systems formed by nearly perfect spheres. Results are obtained following the same calculus protocol, but the threshold magnetic field distribution is changed in a smaller interval, that is using a smaller  $\Delta$  value. In this section, the value selected is  $\Delta = 10^{-6}$ .

Fig. 6 displays the fraction  $f$  of remaining superconducting spheres as a function of the external field for two lattice distances,  $d/a = 2.5$  and  $3.473$  (26.8% and 10%, respectively), comparing the results obtained for  $\Delta = 0.2$  and  $10^{-6}$ . The reduction of the spread in transition fields for the lower delta value is observed in this figure, although the influence of diamagnetic interactions is clearly seen in the wider interval of transition fields shown by the more concentrated systems. On the other hand, the more discontinuous aspect of these transition lines for  $\Delta = 10^{-6}$  suggests the possibility of a more important avalanche effect. A further significant feature in the figure is the appearance of a plateau zone for dilute configurations. Calculations on different lattice distance values show the existence of such plateau zones in all configurations. This zone is larger for small lattice distances. In addition, the plateau is produced near the  $f = 0.45$  value, i.e. slightly higher than in spheres with defects. This plateau appears in dilute systems for a fraction of remaining superconducting spheres of about  $f = 0.47$ .

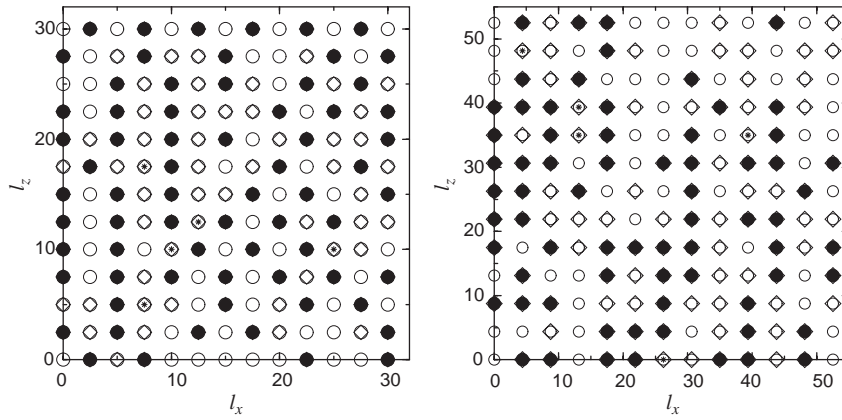


Fig. 5. Spatial distributions of superconducting spheres in  $13 \times 13$  systems with lattice distances  $d/a = 2.5$  (left) and  $d/a = 4.376$  (right), for  $f = 0.71$  (diamonds),  $f = 0.45$  (diamonds with dots) and  $f = 0.41$  (full symbols) (120, 74 and 69 remaining superconducting spheres, respectively).

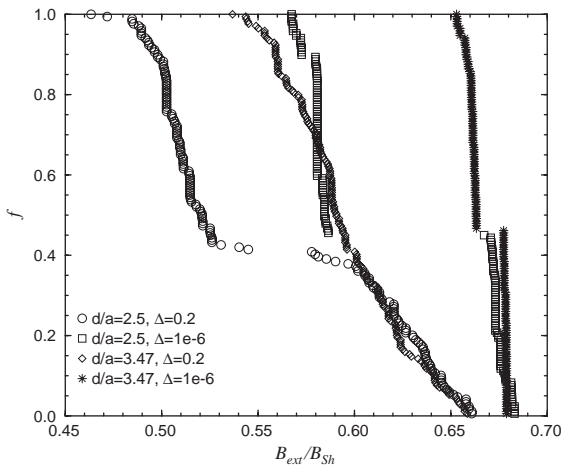


Fig. 6. Fraction  $f$  of remaining superconducting spheres versus  $B_{\text{ext}}/B_{\text{SH}}$  after an increase of the external field from zero, for several samples of  $N = 169$  initially superconducting spheres corresponding to different lattice spacings and defect distributions. Results obtained for  $\Delta = 0.2$  and  $10^{-6}$  are represented for lattice spacings  $d/a = 2.5$  and  $3.473$ .

This change in the behaviour of the system due to the influence of defects, especially in larger lattice distances, and the value of  $f$  for the appearance of the plateau, can be related to the different dynamics shown in their evolution, reflected in both spatial and surface magnetic field distributions. Maximum surface field distributions corresponding to systems with lattice distances

$d/a = 2.5$  and  $3.473$  are displayed in Fig. 7. The concentrated case (Fig. 7a) presents an evolution similar to those of spheres with defects, showing the two branches until the disappearance of that corresponding to higher surface field values when the plateau appears. The only differences are the slightly smaller interval of values of the surface magnetic field and the fact that the upper branch disappears at a larger value of  $f$ . The dilute configuration (Fig. 7b) presents, on the other hand, a qualitative change in its evolution. The two branches of the initial distribution split into several close branches after successive transitions. In the plateau zone ( $f = 0.46$ ) the surface magnetic fields of the remaining superconducting spheres are in a smaller interval, quite far from their threshold values. A larger increment of the applied field is therefore necessary to produce the next transition. This is the reason for the appearance of the plateau in this case. This gap in external field values originates a hot border zone analogous to the concentrated case. Only a temperature increase in this zone can originate a flip to the normal state.

The changes in magnetic surface field distributions, especially for dilute systems, suggest a change in the evolution of spatial distributions with respect to less perfect spheres. The study of spatial distributions during transitions reveals interesting behaviour. The more perfect spheres present ordered configurations at the plateau, both

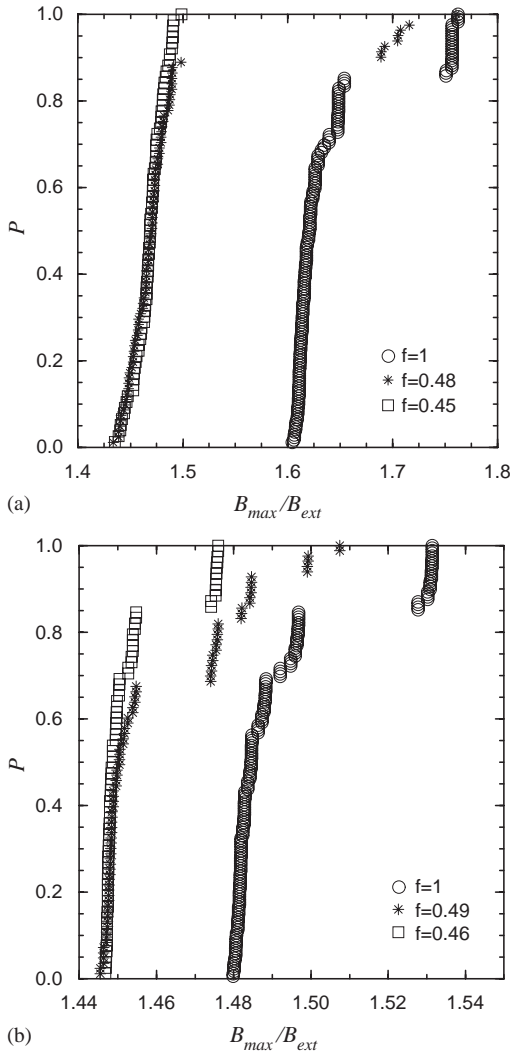


Fig. 7. Fraction  $P$  of spheres with maximum surface field value lower than the  $x$ -value (in units of  $B_{ext}$ ) in the evolution of configurations with initial lattice spacings (a)  $d/a = 2.5$  and (b)  $d/a = 3.473$ . Results correspond to the initial distribution ( $f = 1$ ) and those corresponding to several transitions before the plateau ( $f = 0.48$ ) and at the plateau zone ( $f = 0.45$ ).

for concentrated and dilute systems, but the order is clearly different, as is shown in Fig. 8. Evolution in dilute systems is produced in such a way that, when the plateau appears, remaining superconducting spheres display a spatial disposition in complete lines parallel to the external field alternating with complete lines of spheres in the normal

conducting state. This spatial distribution explains the  $f$  value for which the plateau appears. Perfect alternation of superconducting and normal lines would correspond to a  $f = 0.5$  value. A small deviation of perfect alternation is coherent with the  $f = 0.47$  value obtained for these dilute systems. Repeating simulations for different lattice distance values, we observe that this kind of order is achieved for configurations with lattice distance values  $d/a = 3.034$  and larger, but not for  $d/a = 2.757$  or  $2.5$ .

For more concentrated systems the remaining superconducting spheres appear on the plateau aligned in the diagonal direction, i.e. with next neighbours in the normal state, but with superconducting second neighbours. Hence, microgranules present a square lattice configuration with a parameter of  $\sqrt{2}d$  value. This fact corresponds to a  $f = 0.5$  value for the plateau zone. Defects in this ordering can be seen as boundaries between perfectly ordered domains and their effect is to slightly reduce this value to the obtained  $f = 0.46$ .

The existence of one or another kind of order depends on the concentration of the systems. We have developed a criterion to determine the limit of lattice distances that separates the two different dynamics. For this criterion we consider a configuration similar to that of the domains present in concentrated systems. We have simulated systems of 81 superconducting spheres placed on a  $9 \times 18$  array in the diagonal configuration. An additional superconducting sphere is placed in the middle of the 9th row, i.e. nearly in the centre of the system and with 4 nearest neighbours. A scheme of this configuration is presented in the inset of Fig. 9. The extra grain should be the first to transit to achieve the order present in concentrated systems. In another case this order is not possible. We have calculated the maximum surface magnetic field values on all spheres of this configuration for several values of lattice distances. Results of these simulations are shown in Fig. 9 for domains corresponding to  $d/a = 3.473$  and  $2.756$ , respectively. In this figure, maximum surface field values on the extra sphere (full symbols) and the values corresponding to spheres with the same  $l_z$  coordinate, shown by the dashed line in the inset of the figure, are represented. It can be observed that,



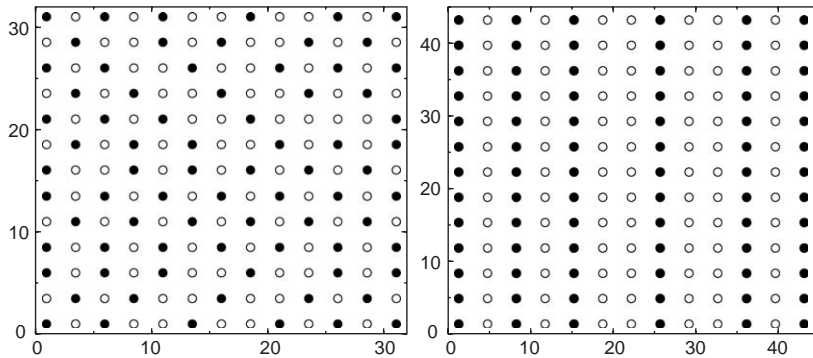


Fig. 8. Spatial distributions of initial  $N = 169$  spheres with lattice distances  $d/a = 2.5$  (on the left) and  $d/a = 3.473$  (on the right), and those corresponding to the plateau zone.

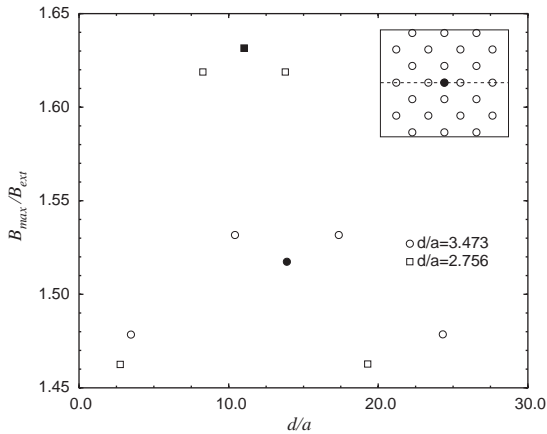


Fig. 9. Maximum surface magnetic field values (in units of  $B_{\text{ext}}$ ) for configurations prepared as shown in the inset. Field values on spheres lying on a line containing the central sphere are represented for  $d/a = 2.5$  and  $d/a = 3.473$ .

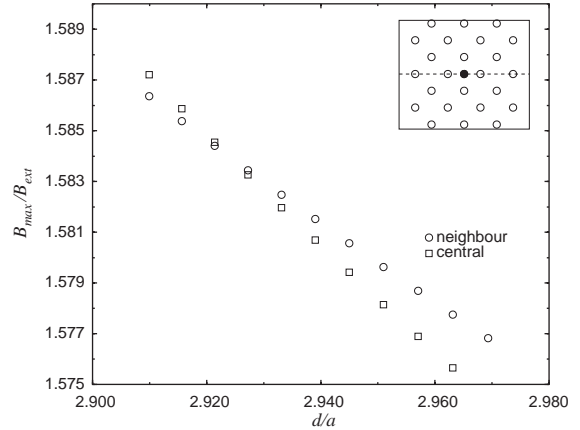


Fig. 10. Maximum surface magnetic field values (in units of  $B_{\text{ext}}$ ) versus lattice distances, corresponding to the central sphere and its nearest horizontal neighbour in the prepared configuration.

for the lower lattice distance value, the extra sphere has a higher surface magnetic field than its neighbours so it will be the next one to transit. Consequently, the configuration can present the order observed in concentrated systems. On the other hand, for  $d/a = 3.437$  the maximum surface magnetic field on the central sphere is smaller than on its neighbours, one of which will be the next to transit, so it is thus impossible to achieve such an ordering of the domain. By repeating simulations for additional intermediate lattice distances we can find the limiting value for which the change of behaviour is produced. We

obtain this limit for a distance between sphere centres of  $d/a = 2.921$  ( $\rho = 16.8\%$ ). Results displayed in Fig. 10 near this limit clearly show this change.

#### 4. Avalanche effect

Avalanches can occur in SSG systems. The transition of any microgranule changes diamagnetic interactions in the system, especially between its neighbouring granules. Depending on the relative position of the microgranules and on the

direction of the applied field, a transition of a single grain can then produce the flip of other microspheres to the normal state.

This effect can be useful in detecting low-energy radiation. To produce the transition of a microgranule to the normal state a quantity of energy proportional to the volume of the grain is necessary in the global heating model [9]. In this sense, a device composed of small microspheres could act as an ultrasensitive low-energy detector. The change of magnetic flux induced by the loss of the Meissner effect could be amplified if an avalanche of transitions is produced. The enhancement of the signal would permit the detection of the incident particle or radiation. In addition, the amplified signal could be used as a trigger in high-energy experiments.

PASS systems with the external field parallel to the plane seem suitable systems to show avalanches. Diamagnetic interactions can favour the screening effect of a granule on neighbours, mainly on those placed on lines parallel to the external field. The maximum surface magnetic field is, in consequence, lower on internal spheres than on the spheres at the top and bottom borders. Transition of a sphere to the normal state allows the introduction of magnetic field lines around their neighbours due to the reduction of screening, and increases their surface magnetic field. Some of the spheres can achieve their threshold magnetic field values and transit simultaneously producing an avalanche.

Results from simulations on systems with defect-free spheres are coherent with the existence of avalanches. Fig. 11 shows the fraction of remaining superconducting spheres in an increasing external field for several lattice distance values. The shape of transition lines indicates that a great number of transitions are produced at very close values of the applied field indicating an avalanche effect.

A deeper study shows that first avalanches correspond, in all configurations, to simultaneous transitions of two or four spheres placed at the borders, reflecting the top–bottom and left–right symmetry. After this initial transition, systems present clearly differentiated behaviour depending on the lattice distances.

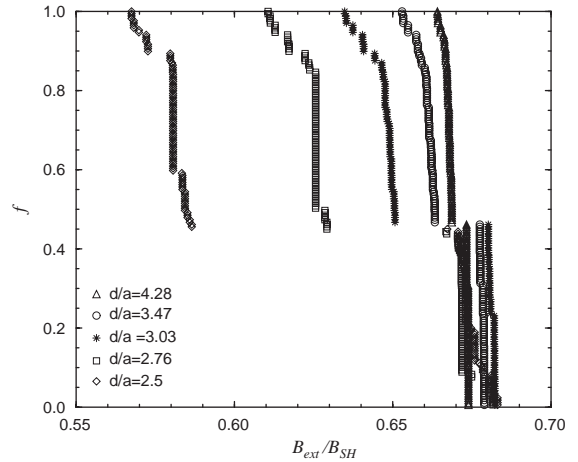


Fig. 11. Fraction  $f$  of spheres that remain superconducting versus  $B_{\text{ext}}/B_{\text{SH}}$  after an increase of the external field from zero for several samples of  $N = 169$  initially superconducting spheres corresponding to different lattice spacing. Results correspond to defect-free spheres.

In dilute systems the next avalanches, of 2 or 4 spheres, are only produced in lines that have undergone previous transitions. They include transitions of both top- and bottom-ending superconducting spheres. When 3–4 spheres at both ends have transitioned on each of these lines, an avalanche of the remaining superconducting spheres of the line takes place. This situation corresponds to the appearance of the plateau zone, with a spatial distribution of only complete lines of spheres that remain superconducting. An increment of the external field larger than the gap value generates successive avalanches of complete lines.

In concentrated systems, on the other hand, initial avalanches of spheres at the borders are followed by a small number of simultaneous transitions of 2 or 4 spheres in alternate sites near the top and bottom borders. A further small increment of the applied field produces a large avalanche. This avalanche includes a large number of spheres following the same alternate pattern. After this avalanche the plateau zone appears. Remaining superconducting spheres are located in several domains with regular square distributions. The next avalanches correspond to simultaneous transitions of spheres from each domain.

In Fig. 12 the number of observed avalanches versus their size (the number of spheres that are involved) are represented for several lattice distances. Results show that large avalanches only appear for concentrated systems. On the contrary, dilute configurations show a higher number of small-size avalanches.

Experimental devices can make use of this effect by placing the detector in the desired zone of transition lines. Knowledge of the different types of behaviour of the system enables selection of the type of configuration according to the required size of avalanche. It should be pointed out that the experimental precision could not be sufficient to resolve very close avalanches, which in consequence would be detected as a single flip.

Experimental results presented by Meagher et al. [3] correspond to a system of separated lines ( $l/a = 16.66$ ) of closed spheres ( $d/a = 2.22$ ). It is thus a type of configuration different from that studied here and could be considered to be a hybrid of both the concentrated and diluted configurations. It could therefore show intermediate behaviour. This could explain the absence of avalanches of complete lines observed in these experiments.

This study can be extended to other geometrical configurations of superheated superconducting granules than can favour some types of multiple flip. Simulations of experimental systems and different superpositions of planar structures are presently in progress.

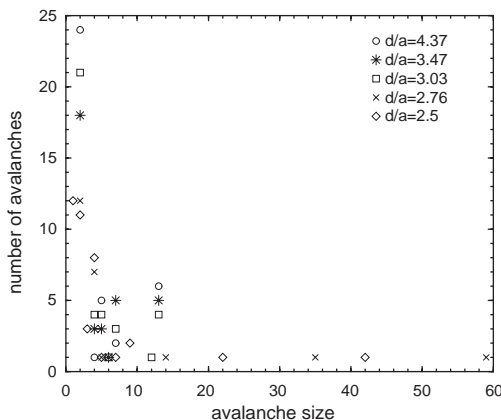


Fig. 12. Number of avalanches of defect-free spheres versus avalanche size for several lattice distances.

## 5. Conclusions

Simulations of transitions in PASS systems immersed in a parallel external field have been performed for several lattice distance values. Spheres with defects on their surface, which can act as nucleation centres, and quasi-defect-free spheres are considered. A plateau zone is observed in concentrated systems for both kinds of spheres. This zone corresponds to a gap in the external field values that are able to produce transitions. On the other hand, for large lattice distances the plateau only appears for more perfect spheres. This plateau corresponds to a hot border, in which only transitions by a finite temperature increment can be produced. This effect can have relevant consequences in experimental detectors due to the fact that the uncertainty in the energy threshold for transitions can be reduced. On the other hand, transitions in this zone could characterize the emission spectrum of a source of radiation.

The existence of the plateau and the fraction of remaining superconducting spheres for which it appears are explained as a consequence of two different dynamics during transitions, for dilute and concentrated configurations, respectively, which lead to two different spatial orders. Systems with small lattice distances present, at the plateau zone, a distribution on domains where the superconducting spheres are homogeneously located. Dynamics for larger lattice distances generates, at the plateau zone, an ordering of spheres that remain superconducting on complete lines parallel to the external field at the plateau zone. This ordering is consistent with the fraction value of remaining superconducting spheres for which the plateau appears. A criterion has been developed in order to find the limit between the two distinguishable dynamics. This limit is obtained for a distance between spheres of  $d/a = 2.921$  ( $\rho = 16.8\%$  in 3-D systems).

A study of the avalanches produced in these systems show distinct types of behaviour depending on the lattice distance values. Concentrated systems present, after small initial avalanches corresponding to the first transitions, a large avalanche before the gap is reached. After this zone, successive avalanches corresponding to transitions of spheres from each domain are

observed. Dilute configurations show relatively small avalanches before the plateau appears. After this zone, successive avalanches of complete lines are produced. These effects could be used in experimental devices to detect low-energy radiation that can be amplified by multiple transitions.

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