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Dichotomic fluxoid quantization effects in a superconducting double network

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Abstract. Energy oscillations and vortex occupation as a function of the external magnetic field are calculated for the recently realized superconducting double network consisting of two interlaced sub-networks of small and large loops. The calculations, based on fluxoid quantization and energy minimization, show that at the low or high field range in each energy period only the population of the large loops increases, whereas all small loops remain equally populated with fluxoids. The small loops gain an extra fluxoid over a small field range around the center of each period, resembling the behavior of a single loop. This range increases as the ratio between the areas of the large and small loops decreases.

A variety of superconducting networks have been studied, both theoretically and experimentally, aiming at investigating collective behavior of fluxoids in such networks [1-8]. The basis of these studies is the fluxoid quantization condition [9] which must be satisfied for each and every loop in the network. In addition, the arrangements of fluxoids on the underlying network must fulfill the requirement of minimum energy. Calculations of the energy *vs.* magnetic field in such networks can be done in the framework of the 'J^2-model' [3-5] that accounts for contribution from the field-dependent kinetic energy of the Cooper pairs as being proportional to the square of the average current, J, flowing in the material, assuming that all the other contributions to the energy remain the same. This model is a good approximation at temperatures where thermal fluctuations may be neglected.

Based on the J^2 model we recently simulated the behavior of a novel type of superconducting network [10, 11] consisting of two interlaced sub-networks of small and large loops as illustrated in figure 1. This 'double' network is made up of a square lattice of side L and square loops of side $\ell < L$ oriented at 45° with respect to this lattice and placed at every vertex of the large lattice. Each large loop has four short edges of length ℓ and four long edges of length $x = L - \sqrt{2}\ell$. The areas of the

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small and large loops are $a = \ell^2$ and $A = L^2 - \ell^2$, respectively. Our numerical simulations [12] showed that in double networks with large ratio of A/a, the sub-networks of the large and small loops exhibit completely different behavior: The population of fluxoids in the sub-network of the large loops increases linearly with the field, while in the sub-network of the small loops it grows in steps, resembling the behavior in a single loop. The energy oscillations in the sub-network of the large loops are of low amplitude and short period and resemble that of a regular square network, exhibiting cusps at the beginning and at the end of each period. In contrast, the sub-network of the small loops exhibits high amplitude and long period energy oscillations with upward cusps at the middle of each period, resembling the energy oscillations in a single loop. In this paper we apply the same numerical simulations to investigate how the behavior of the double network is changed as the ratio A/a decreases.

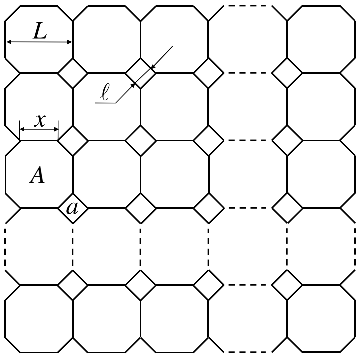

Figure 1. Schematic diagram of the double network.

To demonstrate the results of the simulations for small values of A/a, we present in figure 2 results obtained for $A/a = 4$. The solid (red) lines in figures 2a and 2b show the field dependence of the average populations of fluxoids, n_v and N_v, in the small and large loops, respectively. The dotted (blue) lines in these figures describe the energy E of the double network and the energy E_x of the interconnecting wires (of length x in figure 1), respectively. The energy E exhibits a periodic dependence on the ratio ϕ/ϕ_0 between the external flux through a *small* loop and the flux quantum. Short period oscillations corresponding to the large loops are superimposed on the long period oscillations. The occupation of both sub-networks is monotonic with field: at the low or high field range in each energy period, the population of the large loops increases linearly with field, whereas all small loops remain equally populated with fluxoids. The small loops gain an extra fluxoid over a small range in magnetic field, ΔH, in the middle of each period, around half integer values of the ratio ϕ/ϕ_0. Note that in this field range the energy E_x is zero, reflecting average zero current in each of the long wires.

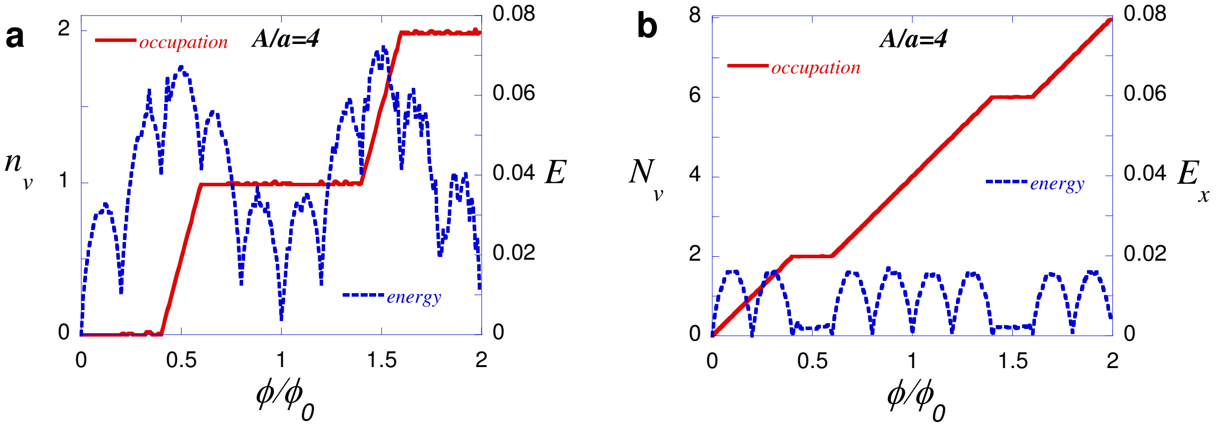

Figure 2. (Color on line) The solid (red) lines in (a) and (b) show the field dependence of the average populations, n_v and N_v, of the small and large loops, respectively, for $A/a=4$. The dotted (blue) lines in these figures describe the energy E of the double network and the energy E_x of the interconnecting wires (of length x in figure 1), respectively.

The simulations show that the field range ΔH decreases as the ratio A/a increases. Interestingly, as shown in figure 3, ΔH decreases linearly as ℓ^2/L^2 decreases.

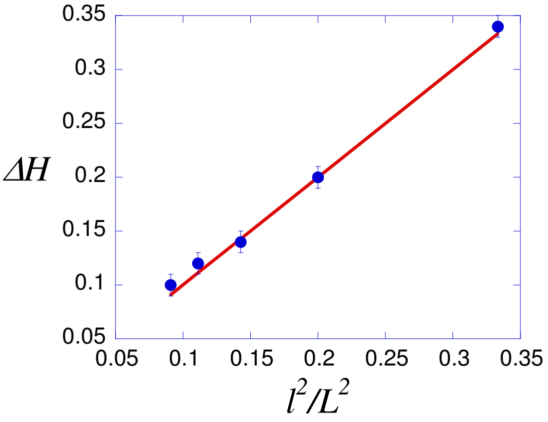

Figure 3. The field range ΔH over which the population of the small loops changes, as a function of the ratio ℓ^2/L^2. The solid line is a linear fit.

The behavior of the two sub-networks comprising the double network depend not only on the value of the ratio A/a but also on the parity of this ratio. When A/a is an even integer, the occupation of both sub-networks is monotonic with field as described above. Our simulations show that when A/a is an odd integer, the small and large loops exchange fluxoids in the field range around half integer values of ϕ/ϕ_0, giving rise to a non-monotonic occupation of both sub-networks with increasing field. The more complicated results obtained for odd values of A/a will be described and discussed elsewhere.

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