Field-Induced Superconductor-to-Insulator Transitions in Josephson-Junction Arrays

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We have studied phase transitions in fabricated 2D arrays of Josephson junctions where the charging and Josephson coupling energies are about equal. We find a crossover from superconducting behavior in low fields to insulating behavior for fields above a critical value of 0.1–0.2 flux quanta per unit cell. The quantitative aspects agree well with predictions from a recent theory for quantum vortex motion by M. P. A. Fisher and with measurements on films. Similar transitions are found around values $f=n/m$, where f is the flux per cell and $n,m=1,2,3$. The field dependence is periodic in f with period 1.

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In superconducting systems [1] such as granular films [2,3] or fabricated junction arrays [4] that consist of small grains with near-bulk properties weakly connected by Josephson junctions, a superconducting-to-insulator transition occurs at low temperatures when the Coulomb charging energy exceeds the Josephson coupling energy. This transition has been extensively discussed from a theoretical point of view [5] and has clearly been observed experimentally [4]. More recently, Fisher [6] has considered the influence of a perpendicular magnetic field on the S-I transition in disordered samples. In his description, at low magnetic fields the vortices are pinned in a vortex glass. For higher fields, the vortex density increases. At a critical density, they Bose condense. The vortex superfluid then leads to infinite resistance, i.e., insulating behavior. Fisher developed a scaling theory for the transition and predicts values for critical exponents. In the regime where the Coulomb and Josephson energies are of comparable magnitude, there exists an intriguing analogy between single charges and vortices in the system. This duality has also been discussed by others [5,7,8]. The I-S transition can in fact also be described in terms of Bose condensation of charges. Experimentally, Hebard and Paalanen [9] studied resistive transitions of disordered InO_x films in a magnetic field. The samples could be driven from superconducting to insulating behavior by the field. Quantitatively, they could fit their data well by the Fisher theory.

We have studied the same transition in fabricated regular arrays of aluminum Josephson junctions. The advantages of a fabricated system are that parameters are known, that they can to a certain extent be varied independently, and that the weakness is clearly concentrated in the junctions. Only phase fluctuations between islands are possible because the order parameter is large and homogeneous over the islands, and independent of temperature and field in the relevant range. A disadvantage is that for our array with 60×190 cells, finite-size effects are more important than in films. Different from films, in the regular fabricated arrays special ordered states exist for certain values of the magnetic flux per cell [10]. When at a certain temperature the resistance is plotted against f, the flux per cell normalized to the flux quantum ($\Phi_0=h/2e$), one finds clear sharp minima at values $f=n/m$, where n and m are integers. Also, the whole pattern is periodic with period 1.

We have observed the field-induced transition near $f=0$ and other integer values. By applying a field below 1 G, the character of the I-V curves is changed from supercurrentlike to charging-gap-like, as illustrated in Fig. 1. When f is varied from zero, the temperature dependence of the resistance changes sign at critical values $\pm f_c$. This is clearly visible in Fig. 2. In addition, similar field-induced transitions are observed around the resistance minima at $f=\pm\frac{1}{2},\pm\frac{1}{3},\pm\frac{2}{3}$. We have derived the critical exponents from the data. For the transitions close to $f=0$, the results are in good quantitative agreement with the Fisher theory.

Our all-aluminum junction arrays are made with a shadow evaporation technique. The samples are the same as the ones used in the study by Geerligs *et al.* [4]. After 3 yr the normal-state junction resistances r_n remained the

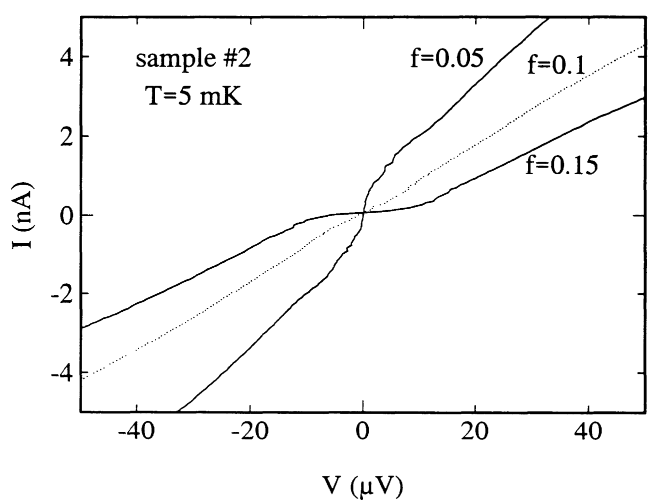

FIG. 1. Current-voltage characteristics of sample 2 measured at three different values of the frustration, showing the crossover from superconductinglike behavior at low fields to insulating behavior with a charging gap at higher magnetic fields.

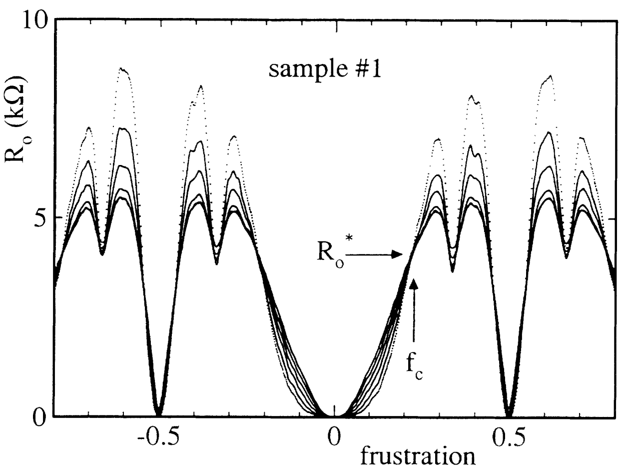

FIG. 2. The linear array resistance per square of sample 1 measured as a function of magnetic field for six different temperatures, $T=80$ (dotted line), 100, 120, 140, 160, 180 mK. Below the critical field f_c the resistance decreases when T is lowered; above f_c the resistance increases in the range $f_c < f < 0.3$. At f_c, $R_0^* \approx 4$ kΩ.

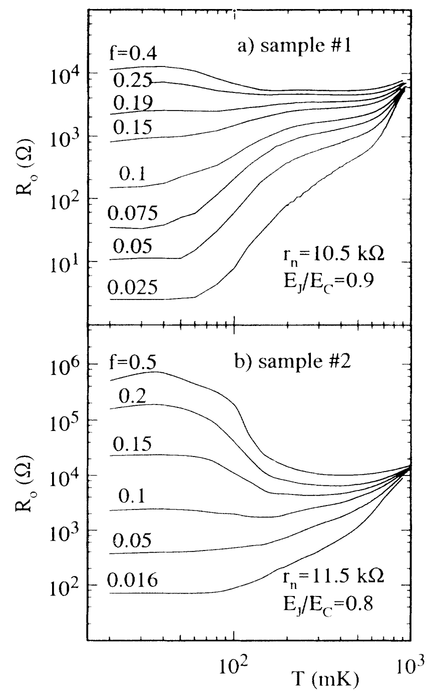

FIG. 3. The linear array resistance per square of (a) sample 1 and (b) sample 2 measured as a function of temperature for various values of the magnetic field.

same within 10%. Junctions are arranged in a square geometry and arrays are 190 cells long ($M=190$) and 60 cells wide ($N=60$). In a square geometry, the normal-state array resistance per square (the array resistance divided by M/N) is equal to r_n. Junctions have an area of 0.01 μm^2. The unit cell of the array is 4 μm^2. We assume the maximum critical current per junction i_{c0} to be given by the Ambegaokar-Baratoff value with a measured critical temperature of 1.35 K. At $T=0$, $i_{c0}r_n=322$ μV. The Josephson coupling energy E_J is proportional to i_{c0}, $E_J=\Phi_0 i_{c0}/(2\pi)$. An independent estimate of C is obtained from measuring the voltage offset (V_{offset}) across the whole array at $T=10$ mK in a magnetic field of 2 T, i.e., from the Coulomb gap for single-electron tunneling. With $V_{\text{offset}}=Me^2/(2C)$ we find a junction capacitance of 1.1 fF, corresponding to a charging energy $E_C=e^2/(2C)$ of 0.84 K.

Experiments are performed in a dilution refrigerator inside Mumetal and lead magnetic shields. Electrical leads are filtered at the entrance of the cryostat with rfi feedthrough filters and at the low temperatures with RC and microwave filters [4]. Small perpendicular fields can be applied by means of two coils in a Helmholtz configuration. The flux penetration depth is much larger than the array size, so that the magnetic field is essentially uniform over the whole array and equal to the applied field.

We discuss in this paper measurements on two different arrays with $r_n=10.5$ kΩ (sample 1) and 11.5 kΩ (sample 2). With $C=1.1$ fF the parameter $x=E_J/E_C$ is 0.9 and 0.8, respectively. In Fig. 3 measured at various values of f, we show the resistive transitions of these two arrays. Plots are on a double logarithmic scale. R_0, the array resistance per square, has been measured with a very small transport current of about 1 pA per junction or less. In zero magnetic field, the arrays undergo a vortex Kosterlitz-Thouless-Berezinskii (KTB) phase transition [11] and are superconducting at the lowest temperatures. The KTB transition temperatures [12] are about 0.55 K for sample 1 and 0.25 K for sample 2.

In Fig. 3(a) for $f<0.2$, the resistance of sample 1 first decreases with decreasing temperature. When plotted as a function of $1/T$, thermally activated behavior is found with a frustration-dependent energy barrier ($0.53E_J$ for $f=0.05$ and $0.28E_J$ for $f=0.1$). Around 50 mK the curves flatten off and the resistance remains almost constant when T is lowered further. For $f>0.2$, curves show a resistance increase with decreasing temperature and a similar flattening off at the lowest temperatures.

Figure 2 shows the resistance of sample 1 measured as a function of magnetic field at various temperatures. In the range $0<f<0.3$, the $R(f)$ curves look very similar to the ones measured in thin films [9]. Below the critical field $f_c=0.22$ the resistance becomes smaller when temperature is lowered; above f_c the resistance increases. The resistance at f_c, R_0^*, is about 4 kΩ. According to Fisher [6], the slopes of the $R(f)$ curves at f_c should follow a power-law dependence on T with power $-1/z_B\nu_B$. The exponents z_B and ν_B characterize the scaling behavior of the field-tuned S-I transition. When on a double logarithmic plot the slopes of the $R(f)$ curves at f_c are plotted versus $1/T$, we indeed find for the curves of Fig. 2 a straight line in the range $50<T<500$ mK. From the reciprocal of the slope of this straight line, we determine $z_B \nu_B = 1.5$. This value is close to the value of 1.3 found in the measurements on films [9] and consistent with theoretical expectations ($z_B = 1$ and $\nu_B \geq 1$).

Qualitatively, the data of sample 2 are very similar. As can be seen in Fig. 3(b), at high temperatures for $f < 0.1$, the sample shows a tendency to become superconducting. No clear exponential decrease is found for $T > 100$ mK when R_0 is plotted versus $1/T$. At low temperatures again metallic behavior is observed with an almost temperature-independent R_0. For $f > 0.1$, R_0 increases for $T < 300$ mK and below 150 mK a charging gap can be seen in the current-voltage characteristic. Figure 1 clearly illustrates the crossover from superconductinglike behavior at low magnetic fields to insulatinglike behavior at high magnetic fields.

From the $R(f)$ curves of sample 2 a clear critical frustration could only be defined in the temperature range $200 < T < 500$ mK. The critical frustration is close to 0.1, where $R_0^* \approx 2.5$ kΩ. We have again determined the product $z_B \nu_B$, by plotting the $R(f)$ slopes at f_c as a function of $1/T$. We find a value for the product $z_B \nu_B$ of 1.2, again consistent with the theoretical constraints.

When the f_c's of different samples are plotted as a function of the KTB transition temperatures, a straight line is expected in a double logarithmic plot [6,9]. The slope of this line determines the value of the exponent z_B. Our two data points yield an estimate for z_B of 0.7, which has to be compared with the theoretical expectation of 1.

Studying the $R(f)$ curves of Fig. 2 in more detail, we see critical behavior not only at $f = 0 \pm \delta$, but also at $f = \pm 1 \pm \delta$, at $f = \pm \frac{1}{2} \pm \varepsilon$, and at $f = \pm \frac{1}{3} \pm \gamma$, $\pm \frac{2}{3} \pm \gamma$, where $\delta = 0.22$, $\varepsilon = 0.05$, and $\gamma = 0.015$. Thus, in our sample in total eight critical points are visible when going from $f = 0$ to 1. In Fig. 4, we show the *S-I* transitions near $f = \frac{1}{2}$, $\frac{1}{3}$, and $\frac{2}{3}$ in more detail. From this figure we obtain R_0^* values of 3.4 kΩ for the transitions near $f = \frac{1}{2}$, and 4.6 kΩ for the transitions near $f = \frac{1}{3}, \frac{2}{3}$. We again determined the value of $z_B \nu_B$ from the $R(f)$ curves. We find this product to be 1.2 for the transitions near $f = \frac{1}{2}$, and 0.6 for the transitions near $f = \frac{1}{3}, \frac{2}{3}$. As yet, there are no theoretical calculations to compare these numbers with. In the inset of Fig. 4, R_0 is plotted as a function of T, for different values of f close to $\frac{1}{2}$. This plot looks very similar to the one for the transition near $f = 0$ [Fig. 3(a)] and shows the change of sign in the temperature dependence of the resistance at f_c.

Compared to the thin films, a striking result of our measurements is the metallic behavior at low temperatures observed for all $f \neq 0, \frac{1}{2}$. From other measurements we do not expect the metallic behavior to be due to an effective noise temperature of 100 mK in our heavily filtered experimental setup. For example, in Fig. 3(b) we see that for $f = 0.2$ the resistance still changes considerably for $T < 100$ mK. Self-heating can be excluded because varying the measuring current made no difference in $R_0(T)$.

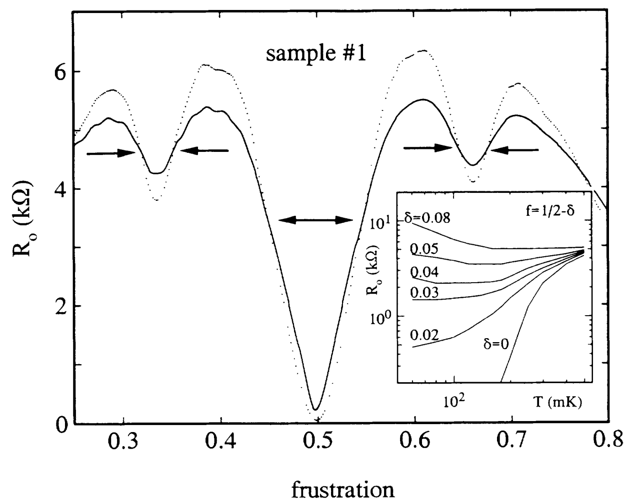

FIG. 4. The linear array resistance per square of sample 1 measured as a function of magnetic field at $T = 120$ mK (dotted line) and at $T = 180$ mK (solid line), showing the field-tuned transitions near $f = \frac{1}{2}$, $\frac{1}{3}$, and $\frac{2}{3}$. Inset: The linear array resistance per square plotted as a function of temperature for various values of the frustration near $f = \frac{1}{2}$.

In Fisher's description of the field-tuned transition, the vortices at $T = 0$ are frozen in a pinned glass. Quantum creep only occurs at nonzero temperatures, where multivortex variable-range-hopping (VRH) processes [13] are expected to be dominant. In the VRH picture, the temperature dependence of the resistance arises from the temperature dependence of the hopping length; with decreasing temperature this length increases leading to a resistivity which in the quantum regime at low T decreases with a non-Arrhenius temperature dependence. For a finite sample below some temperature, the resistance is expected to be temperature independent because the hopping length becomes larger than the width of the sample. In our samples, the VRH temperature dependence of the resistance does not continue at high temperatures; instead we observe a simple exponential decrease of the resistance [14]. This indicates that more research is needed on the quantum dynamics in Josephson-junction arrays near the *S-I* transition. Moreover, the constant conductance at low temperatures in the charging regime for higher values of the field looks like a dual of the residual resistance in the vortex regime, thereby showing that the influence of charges should be included in the theory.

Our experimental results [15] can be summarized as follows. We have observed a field-tuned superconductor-to-insulator transition in junction arrays which is qualitatively similar to the one observed in thin disordered films. In our junction arrays, however, additional field-tuned transitions can be found near fractional values of f. Our data strongly support the notion of quantum duality between vortices and single charges. Application of a field of 1 G drives the system from the vortex to the charge regime, thereby changing the resistance by orders of magnitude.

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[15] Recently, we have observed similar field-tuned transitions in a Josephson-junction array with a triangular geometry in which each island is connected to six neighboring islands. Clear transitions occur at $f=0\pm\delta$, $f=\pm 1\pm\delta$, $f=\pm\frac{1}{2}\pm\varepsilon$, $f=\pm\frac{1}{4}\pm\gamma$, and $f=\pm\frac{3}{4}\pm\gamma$ with $\delta=0.13$, $\varepsilon=0.025$, and $\gamma=0.025$. (Different from arrays with a square geometry, the resistance dips of a triangular array are more pronounced at $f=\pm\frac{1}{4},\frac{3}{4}$ than at $f=\pm\frac{1}{3},\pm\frac{2}{3}$.) The R_0^* and $z_B\nu_B$ values are, respectively, 9.6 kΩ and 2.0 for the transitions near $f=0$, ± 1, 11 kΩ and 0.7 for the transitions near $f=\pm\frac{1}{2}$, and 12 kΩ and 0.8 for the transitions near $f=\pm\frac{1}{4}$, $\pm\frac{3}{4}$.