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Quantum phase transitions in Josephson junction arrays

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Abstract

Experiments on arrays of Josephson junctions show a transition from superconducting to insulating behaviour induced by a small magnetic field, and evidence for quantum tunneling of vortices.

Phase transitions in two dimensional superconductors have been studied experimentally in granular and amorphous thin films as well as in artificially fabricated arrays of Josephson tunnel junctions. One of the advantages of using arrays is that sample parameters are well known and can be varied over a wide range. Their behaviour is determined by two energy scales: the charging energy $E_C = e^2/2C$, where C is the capacitance of the junction, and the Josephson coupling energy E_J, which is inversely proportional to the normal state resistance R_n. Arrays with $E_J \ll E_C$ become insulating at low temperatures. Arrays with $E_J \gg E_C$ are more easily described in terms of vortices and the lack of single vortices at low temperatures leads to a superconducting phase [1]. Experimentally, the transition from the superconducting to the insulating phase is found to occur for $E_J/E_C = 0.6$ [2], in close agreement with the predictions of ref.1.

In experiments on thin films a superconducting to insulating phase transition has been found which is induced by a magnetic field. This field-tuned transition was described by M.P.A. Fisher in terms of scaling theory[3]. He argued that the temperature dependence of dR/dB at the transition should be independent of sample parameters and predicted values for critical exponents. We have experimentally studied several Josephson junction arrays with E_J/E_C values close to the zero-field transition. The samples used were the same as those of ref. 2 and consisted of square networks of all-aluminum junctions that were fabricated with a shadow evaporation technique. The capacitance of the junctions was 1 fF and the normal state resistance ranged from 1 to 50 kOhm. In samples with $E_J/E_C = 0.8$ and 0.9 we have found that a small applied magnetic field can drive the array from superconducting to almost insulating behaviour. Measurements were performed in a dilution refrigerator inside μ-metal and lead magnetic shields. Electrical leads are filtered at the entrance of the cryostat with rfi feedthrough filters and at low temperatures with RC and microwave filters. For measuring the linear resistance we used a bias current of less than 1 pA. A typical set of resistance versus temperature curves in different magnetic fields is shown in fig. 1. The magnetic field is given in units of frustration, f, defined as the number of fluxquanta per unit cell.

When the applied magnetic field exceeds the critical value f=0.1 the resistance increases strongly as the temperature is lowered from 500 to 100 mK. At 100 mK the resistance of the array for different frustrations differs by five orders of magnitude. For a sample with $E_J/E_C = 0.9$ similar behaviour was found above a critical field f=0.2. The resistance at this critical field was in both cases observed to be about 5 kOhm and almost temperature independent.

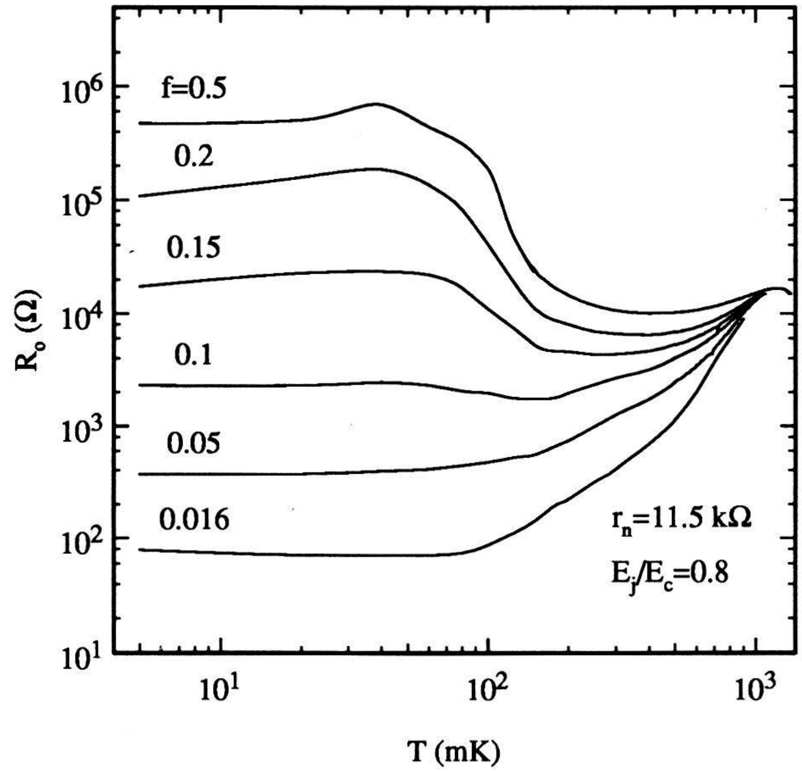

Figure 1: *Resistance versus temperature for various values of magnetic field measured in units of frustration, f, defined as the number of fluxquanta per unit cell.*

For temperatures higher than 100 mK our results both qualitatively and quantitatively resemble the field-induced transition that was observed in thin films. We found values for the critical exponents consistent with theoretical constraints and close to the reported values in thin films. Details of these experiments will be published elsewhere[4].

For low frustrations we have observed a finite and almost temperature independent resistance below about 100 mK in samples with E_J/E_C of order 1. This can not be due to an effective noise temperature because the resistance of the array for higher frustration is still seen to change below this temperature. We therefore attribute this residual resistance to quantum tunneling of vortices in analogy with quantum tunneling of the phase in single junctions. Because of the predicted duality between vortices and charges, the flattening off of the resistance in a magnetic field above the field-induced transition might be explained by quantum tunneling of charges.

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