# Vortex state of a 2D Josephson junction array at irrational frustration

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**Abstract**

$IV$ characteristics of a 2D Josephson junction array are studied experimentally at frustrations $f = 0.382$, as an approximation of the irrational filling $f = (3 - \sqrt{5})/2$, and its nearby rationals 3/8, 8/21, and 2/5, with a focus on the irrational frustration. For all four frustrations, the $IV$ characteristics exhibit a scaling behavior, indicating a finite-temperature continuous superconducting transition. Scaling analyses show that the critical behaviors for $f = 0.382$ are similar to those of $f = 3/8$, 8/21, and 2/5. The finite transition temperature and the similarity in critical behaviors suggest that the vortex state at the irrational frustration is not a vortex glass but possibly an ordered phase with a configuration which can be viewed as an interpolation between the states for $f = 3/8$ and $f = 2/5$.

*Key words:* Vortex state; Irrational frustration; Josephson junction array; Frustrated $XY$ model

For two-dimensional (2D) Josephson junction arrays (JJAs), frustration without disorder can be introduced by applying an external magnetic field. In the presence of frustration, a finite density of vortices are induced in the array as a function of the frustration parameter $f$, the fraction of a flux quantum per plaquette. Possible glassy natures of the vortices at irrational frustration have drawn particular interest for many years since they are exotic glasses without any intrinsic randomness [1–5]. Halsey [1] claimed that vortices form a metastable glass for $f = (3 - \sqrt{5})/2$ below some finite temperature. Other arguments, however, suggest a zero-temperature glass transition in 2D [2,6]. Recent numerical studies [3] show that vortices at the irrational frustration undergo two separate transitions: a sharp first-order phase transition to an ordered state with incoherent phase and a vortex pinning transition at a lower temperature. A single finite-temperature transition to an ordered phase with periodically-distributed parallel domain walls has also been suggested by a different numerical work [4]. Details of the vortex states obtained by numerical efforts have been found to strongly depend upon the imposed boundary condition. There have been very few experimental works on the issue [5]; they agree on a finite-temperature superconducting transition. The experiments were performed on superconducting wire networks where fluctuations are much weaker than in JJAs; therefore, the behavior is suspected to be dominated by a mean field transition [2]. In this paper, we present an experimental investigation of the vortex state of a proximity-coupled JJA at $f = 0.382$, as an approximation of the irrational frustration $f = (3-\sqrt{5})/2$, and its nearby rationals $f = 3/8$, 8/21, and 2/5 by examining scaling behaviors of the $IV$ characteristics.

The experiments were performed on a square array of 200×1000 Nb/Cu/Nb Josephson junctions described in Ref. [7]. The zero-field superconducting transition was completed at $T_{KT} = 6.24$ K with a transition width $\sim 0.4$ K. The frustration was adjusted from the resistance minima at simple fractional $f$s of the magnetoresistance curve of the sample. The standard four-probe technique utilizing a transformer-coupled lock-in volt-

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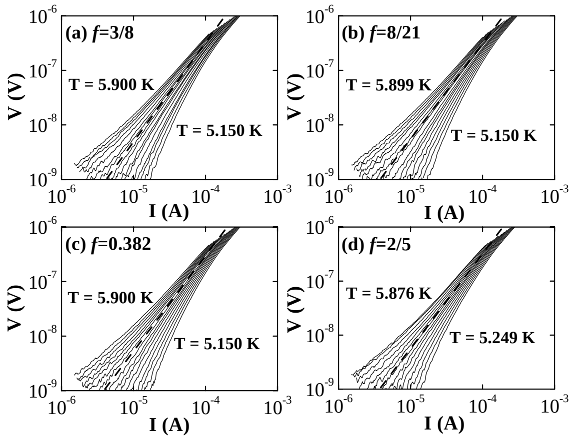


Fig. 1. $IV$ characteristics for four different frustrations: (a) $f = 3/8$, (b) $f = 8/21$, (c) $f = 0.382$, and (d) $f = 2/5$. The dashed lines are drawn to show the power law ($V \sim I^{z+1}$) behavior at the critical temperatures.

meter with a square-wave current at 23 Hz was adopted for the $IV$ characteristics measurements.

Fig. 1 shows the $IV$ curves for four different frustrations $f = 3/8$, $8/21$, $0.382$, and $2/5$. The $IV$ curves at high temperatures are concave upward. At low temperatures, the curves become progressively more concave downward. The temperature dependence of the $IV$ curves meets the criterion proposed by Strachan *et al.* [8] for $IV$ data supporting a superconducting transition. The $IV$ data indicate that for all these $f$s the sample experiences a superconducting transition at temperatures where straight $IV$ curves appear. If the transition is continuous, the $IV$ data are expected to satisfy the scaling relation in 2D, $V/I|T - T_c|^{z\nu} = \mathcal{E}_{\pm}(I/T|T - T_c|^{\nu})$ [9]. The scaled $IV$ data are shown in Fig. 2. We find the four sets of data exhibit good scaling behaviors, which confirms a finite-temperature superconducting transition for $f = 0.382$, as well as for $f = 3/8$, $8/21$, and $2/5$. The critical exponents $\nu$ and $z$ for $f = 0.382$ are identical, within experimental errors which are 0.1 for $\nu$ and 0.05 for $z$, with those for $f = 3/8$, $8/21$, and $2/5$, but not with those for $f = 1/3$ [7], $5/12$ [10], and $1/2$ [7]. We also found from the scaling analyses that not only are the critical exponents similar for $f = 3/8$, $8/21$, $0.382$, and $2/5$ but the scaling functions are also.

The finite-temperature superconducting transition at $f = 0.382$ and the similarity in scaling behaviors at $f = 3/8$, $8/21$, $0.382$, and $2/5$ indicate that the vortex state at the irrational frustration is not a vortex glass but possibly an ordered phase of pinned vortices with a configuration which can be viewed as an interpolation between the states for simple rational frustrations $f = 3/8$ and $2/5$. This finding seems to be compatible with the numerical results of Denniston and Tang [4], which indicate a single finite-temperature phase transition for the irrational frustration to a striped phase consisting of domains of $f = 8/21$ phase separated by parallel walls. The $f = 8/21$ phase has a vortex configuration which can be viewed as a combination of the configurations for $f = 3/8$ and $f = 2/5$. Our observations are, however, inconsistent with other numerical works predicting two separate finite-temperature phase transitions [3] or a zero-temperature glass transition [2]. The discrepancies are possibly, as suggested by Denniston and Tang [4], from the imposition of a periodic boundary condition that is incompatible with incommensurate or long-period commensurate phases.

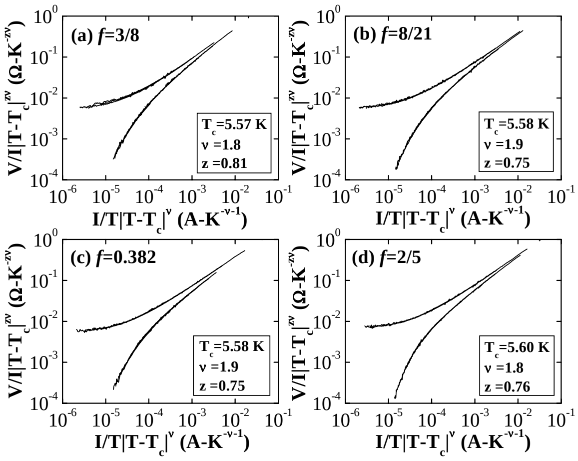


Fig. 2. Scaling plots of the $IV$ curves. The values of $T_c$, $\nu$, and $z$ used to scale the data are shown in the insets.

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## References

[1] T. C. Halsey, Phys. Rev. Lett. **55** (1985) 1018.

[2] E. Granato, Phys. Rev. B **54** (1996) R9655.

[3] P. Gupta, S. Teitel, M. J. P. Gingras, Phys. Rev. Lett. **80** (1998) 105; M. R. Kolahchi, H. Fazli, Phys. Rev. B **62** (2000) 9089.

[4] C. Denniston, C. Tang, Phys. Rev. B **60** (1999) 3163.

[5] F. Yu, et al., Phys. Rev. Lett. **68** (1992) 2535; X. S. Ling, et al., Phys. Rev. Lett. **76** (1996) 2989.

[6] C. Dekker, P. J. M. Wöltgens, Phys. Rev. Lett. **69** (1992) 2717.

[7] Young-Je Yun, In-Cheol Baek, Mu-Yong Choi, Phys. Rev. Lett. (to be published).

[8] D. R. Strachan, et al., Phys. Rev. Lett. **87** (2001) 067007.

[9] D. S. Fisher, M. P. A. Fisher, D. A. Huse, Phys. Rev. B **43** (1991) 130.

[10] We found that for $f = 5/12$, $T_c = 5.52$ K, $\nu = 1.9$, and $z = 0.89$.