Un-quantized Vortices Observed

Observation of superconducting vortices carrying a temperature-dependent fraction of the flux quantum
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Recommended with a Commentary by Jung Hoon Han, Sungkyunkwan University and Patrick A. Lee, MIT

Quantized vortices in superfluids and superconductors are among the most fascinating demonstrations of macroscopic quantum phenomena and the topological characterization of matter. Confirmation of quantized circulations in liquid ^{4}He and of the quantized flux in the superconductor are hailed as vindications of the condensate wave function description of these quantum fluids. Indeed, the quantized vortices are a direct consequence of the fact that the entire system is described effectively by a macroscopic wave function ψ.

In the recommended paper, this time-honored notion is challenged through SQUID measurement of trapped magnetic flux in a single crystal of pnictide superconductor $Ba_{1-x}K_xFe_2As_2$. When the sample was cooled in the presence of a few mG magnetic field, a number of vortices nucleated whose flux measured by SQUID came close to the expected value of $\Phi_0 = h/2e$. However, as summarized in Fig. 1, a small number of other nucleated vortices were found to have the flux $\Phi(T)$ substantially smaller than Φ_0, and furthermore seen to depend drastically on the temperature T, with the maximum value reached at slightly below T_c. The existence of these fractional vortices (FVs) alongside the conventional vortices (CV) in the pnictide superconductor was carefully checked by the continued presence of FVs through several cooling cycles and by an independent means of applying external magnetic field through the SQUID coil itself, which also led to the formation of FVs. Moreover, the FVs were seen to hop from one nucleation site to a nearby one under the externally prepared magnetic pulse, giving a sense of robustness to this newly found object. To make matters more interesting, the sample studied has the doping $x = 0.77$, squarely in the regime of the phase diagram (Fig. 2) that previous μSR investigation has associated with the BTRS (broken time-reversal symmetry) phase [1]. It is thus tempting to speculate that the BTRS as well as the multi-component nature of the Fermi surface and the gap functions in the pnictide superconductor all come into play in the possible formation of FVs.

Already in 2002, Babaev pointed out [2] that in a two-component superconductor whose order parameter symmetry is $U(1)\times U(1)$, the Ginzburg-Landau theory for the two-component condensate fields $\Psi = (\psi_1, \psi_2)$ predicts the un-quantized flux

$$\Phi/\Phi_0 = r_1 n_1 + r_2 n_2, \tag{1}$$

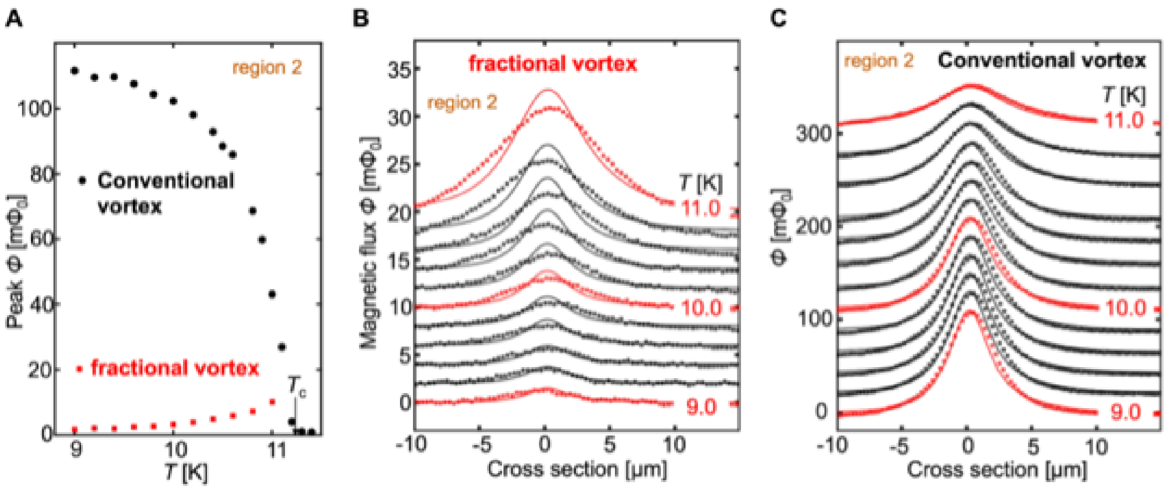

Figure 1: Reproduced from Fig. 2 of the recommended paper. **A** shows the maximal magnetic flux through the SQUID's pick-up coil for conventional (integer) and fractional vortices. The temperature dependence in the conventional vortex case reflects that of the penetration depth λ. For smaller λ the flux gets more tightly squeezed and mostly pass through the coil. **B** shows the position dependence of the flux through the coil as the coil location is varied over the vortex. The lack of fit to the theoretical curve (solid lines) compared to the integer vortex case shown in **C** indicates that the magnetic field profile of the fractional vortex may be unconventional.

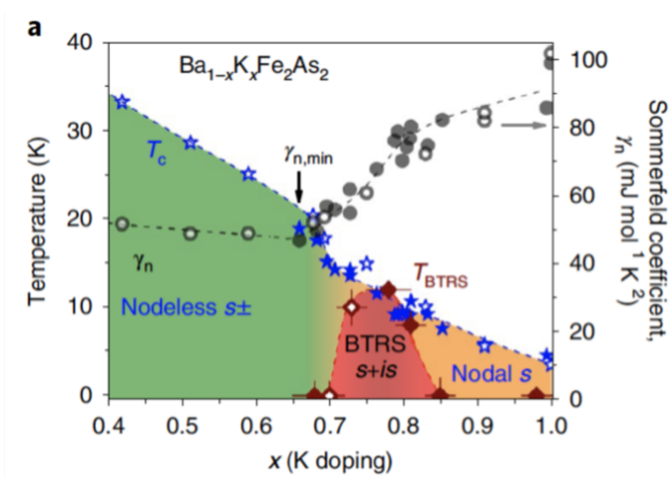

Figure 2: Phase diagram of $Ba_{1-x}K_xFe_2As_2$ reproduced from [1]. The report of fractional and temperature-dependent vortices is being made in the $x = 0.77$ sample which falls into the broken time-reversal symmetry (BTRS) state in this phase diagram.

where n_1, n_2 are the integer winding numbers of each wave function ψ_1, ψ_2, and r_1, r_2 are the (temperature-dependent) relative condensate fractions $r_i = |\psi_i|^2/(|\psi_1|^2 + |\psi_2|^2)$. In general, phase coherence among the condensates is likely to enforce $n_1 = n_2 = n$ and restore the quantization, $\Phi/\Phi_0 = n$ even for a multi-gap superconductor, but still condensing FV remains a possibility. For example, we can imagine a vortex where one order parameter winds by 2π but the orther does not. The relative phase costs energy but may be allowed under appropriate conditions of frustration and metastability.

A number of open questions remain. Firstly, the measured value of the fractional flux $\Phi(T)$ is very small at low temperature and increases upon heating the sample, as shown in Fig. 1A. Such temperature dependence may be hard to reconcile with any simple theoretical scenario. Secondly, only a small portion of the nucleated vortices are FVs while the rest of the vortices are conventional. Presumably some special local environment plays a role in nucleating FV over CV. Understanding this at the level of local, impurity physics seems a necessary step in fully grasping the nucleation process of FV.

In fact, the story of the nucleation of vortices in a BTRS superconductor around non-magnetic impurities in the form of spontaneously generated current has a long history. For the Sr_2RuO_4 whose gap symmetry has long been suspected to be p_x+ip_y, calculation showed that a circular current pattern is generated around a non-magnetic impurity [3]. A similar circular pattern of current was predicted for a magnetic impurity in a d-wave superconductor [4]. For the multi-gap BTRS superconductivity in the pnictides, the scenario gets necessarily more complex as can be found in a number of papers [5, 6, 7, 8]. Both $s + id$ and $s + is$ pairing states have been considered. In all cases, the induced current patterns around an isotropic impurity were of higher multipole structures such as vortex dipole and quadrupoles, with zero net vorticity. Such current (vortex) patterns may be difficult to reconcile with the SQUID data showing a more or less circular flux density profile with nonzero net vorticity.

Despite the several challenges mentioned, the seemingly robust observation of fractional flux in the (potentially) BTRS superconductor $Ba_{1-x}K_xFe_2As_2$ will surely spur further work on the true nature of the superconducting ground state in this compound at large, and the effect of impurity in the BTRS superconductor and its role in generating fractional vortices in particular.

References

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