Friedel Oscillations of Vortex Bound States under Extreme Quantum Limit in $KCa_2Fe_4As_4F_2$

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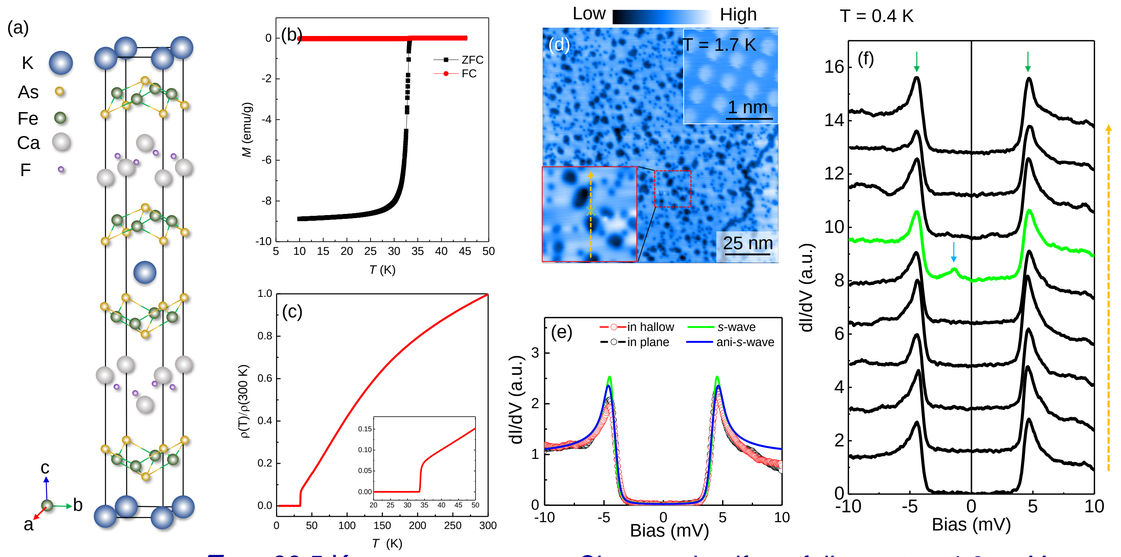
Abstract: We perform scanning tunneling microscopy/spectroscopy (STM/STS) studies on the layered iron-based superconductor $KCa_2Fe_4As_4F_2$ with $T_c \approx 33.5$ K. A clean and uniform full gap with $\Delta \approx 4.6$ meV is observed. Quasiparticle interference (QPI) patterns show an intra-pocket scattering pattern possibly from the hole like α pocket. The Fermi energy of this band is only about 24 ± 6 meV. Then we measured the vortex bound states and found that the bound state energy levels are clearly deviating from the widely believed ratio 1/3/5. We also observed Friedel oscillations arising from these bound states. By doing self-consistent calculations of the BdG equations, we found that the superconducting order parameter exhibits a Friedel-like oscillation, and all the observations are quite natural in the extreme quantum limit (EQL) $T/T_c \ll \Delta/E_F \sim k_F\xi_0$. The results indicate that the vortex bound state energy is not necessary to follow the widely believed ratio 1/3/5, and Friedel oscillations of the vortex bound states are expected in the extreme quantum limit. Our work shed new light on the generalized understanding of the vortex core states in superconductors.

Motivation

1. $KCa_2Fe_4As_4F_2$ is a newly found iron-based superconductor with layered structure, which exhibits similar structure to the cuprates. The STM/STS studies are really important to uncovering the pairing mechanism in this compound.
2. The $KCa_2Fe_4As_4F_2$ single crystal has high critical temperature ($T_c \approx 33.5$ K), large superconducting gap ($\Delta \approx 4.6$ meV), and small Fermi energy ($E_F \approx 24$ meV). Thus it satisfies the extreme quantum limit (EQL) condition ($T/T_c \ll \Delta/E_F \sim k_F\xi_0$), making it an ideal platform to study the vortex bound states in type-II superconductors.

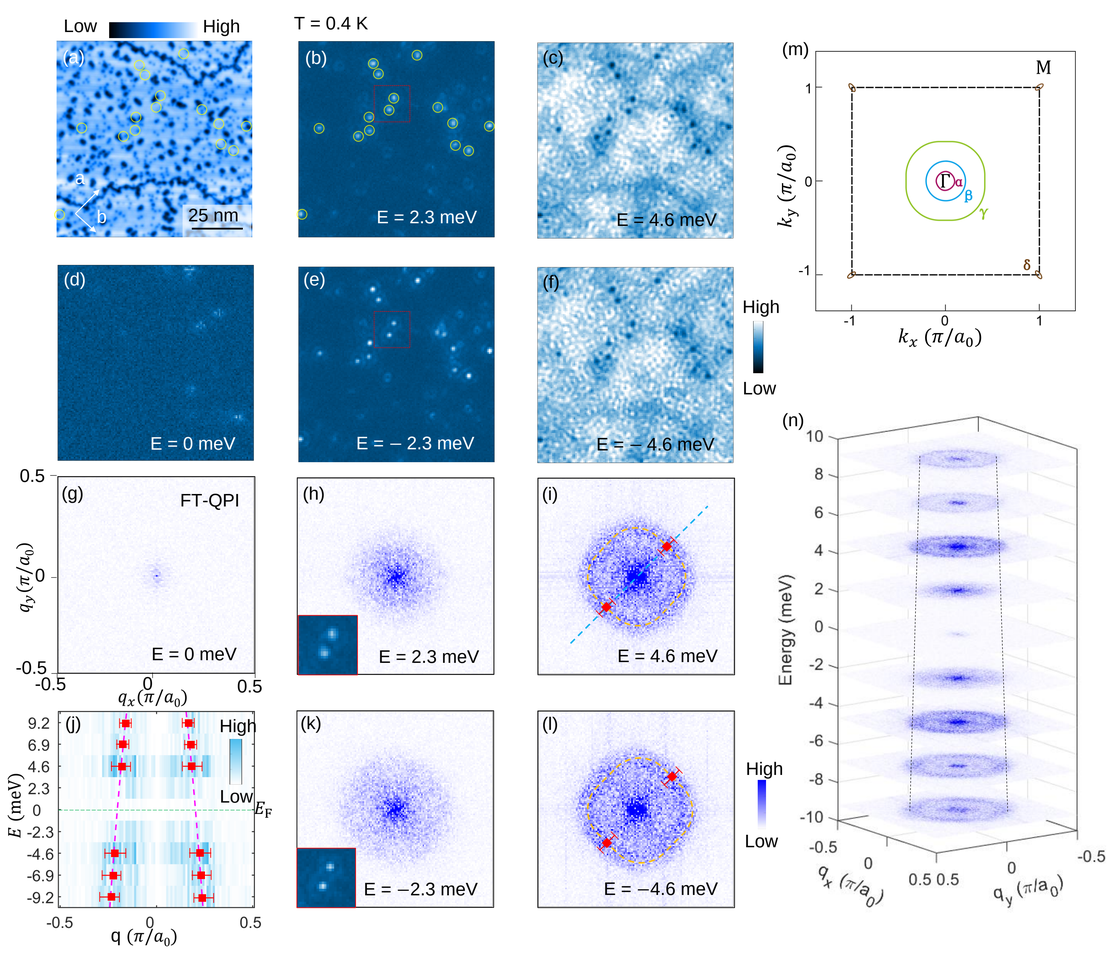
physical characterization and STM/STS measurements



$T_c \approx 33.5$ K

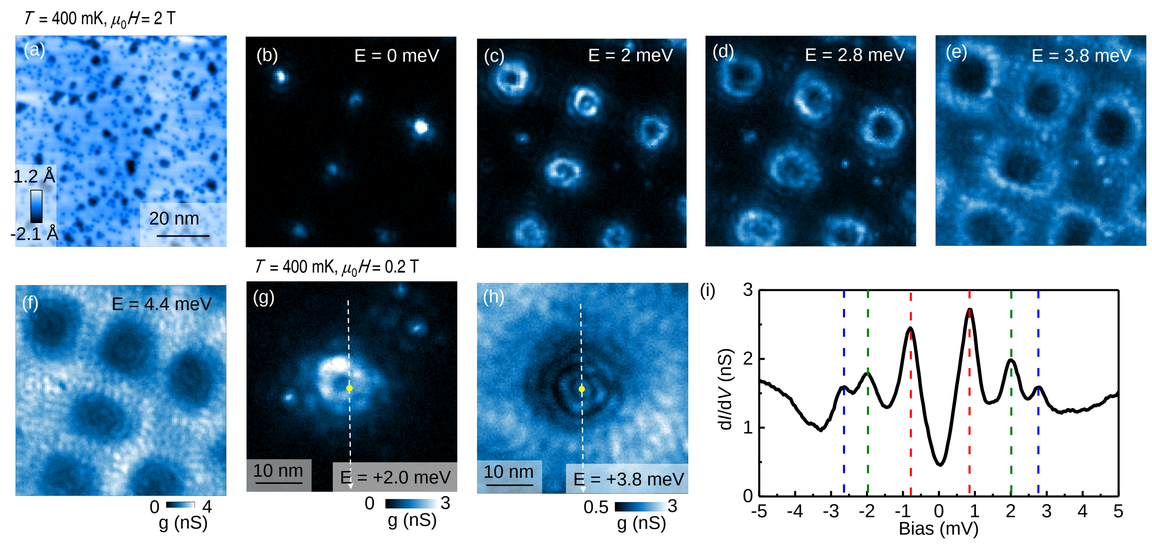
Clean and uniform full gap $\Delta \approx 4.6$ meV

Quasiparticle interference (QPI) pattern

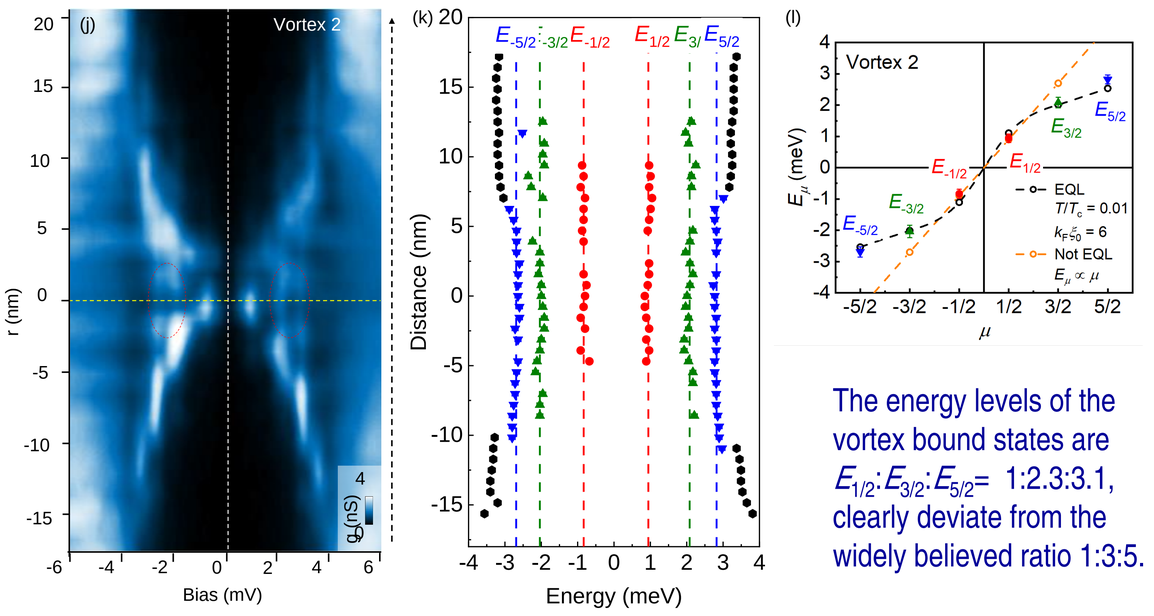


The scattering wave vector $q \approx 0.18\pi/a_0$, possibly from the intra-pocket scattering in the α pocket with hole like dispersion. The Fermi energy is estimated to be 24 ± 6 meV.

Vortex bound states in EQL



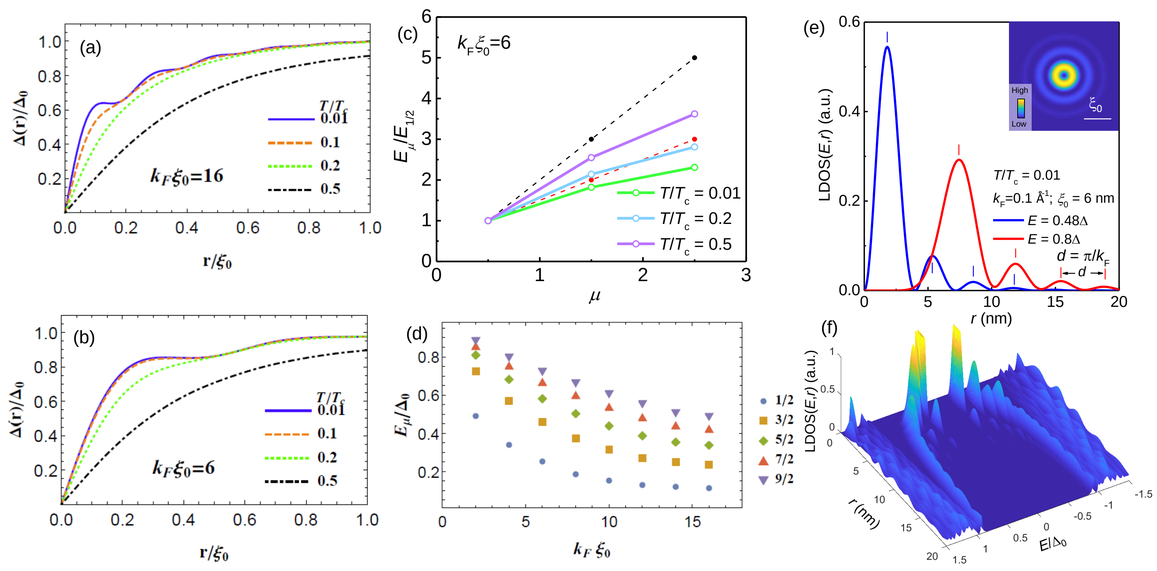
Vortex images measured at different energies. A single vortex is measured at $\mu_0 H = 0.2$ T to minimize vortex-vortex interaction in (g)(h). Friedel oscillations can be observed in (h).



The energy levels of the vortex bound states are $E_{1/2}:E_{3/2}:E_{5/2} = 1:2.3:3.1$, clearly deviate from the widely believed ratio 1:3:5.

Self-consistent calculations of the BdG equations

Extreme quantum limit condition: $T/T_c \ll \Delta/E_F$



The order parameter function Δ(r) exhibits a Friedel like oscillation on top of the smooth relation $\Delta(r) \approx \Delta_0 \tanh(r/\xi_0)$ in EQL. Thus the ratio of the bound states energies deviate from 1:3:5. Also, the LDOS of vortex bound states exhibit Friedel oscillations from the theoretical calculations.

Conclusions

1. Extreme quantum limit condition: $T/T_c \ll \Delta/E_F$ ($T_c \approx 33.5\ K$, $\Delta \approx 4.6\ meV$, $E_F \approx 24\ meV$)
2. Discrete energy levels of Caroli-de Gennes-Martricon states have been observed in some vortex cores of $KCa_2Fe_4As_4F_2$, and the energy levels deviate from the widely believed ratio of 1 : 3 : 5.
3. The order parameter function $\Delta(r)$ exhibits a Friedel like oscillation on top of the smooth relation $\Delta(r) \approx \Delta_0 \tanh(r/\xi_0)$ in the extreme quantum limit.
4. Clear Friedel oscillations are also observed.

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