Chirality sensitive effect on surface state in chiral p-wave superconductors

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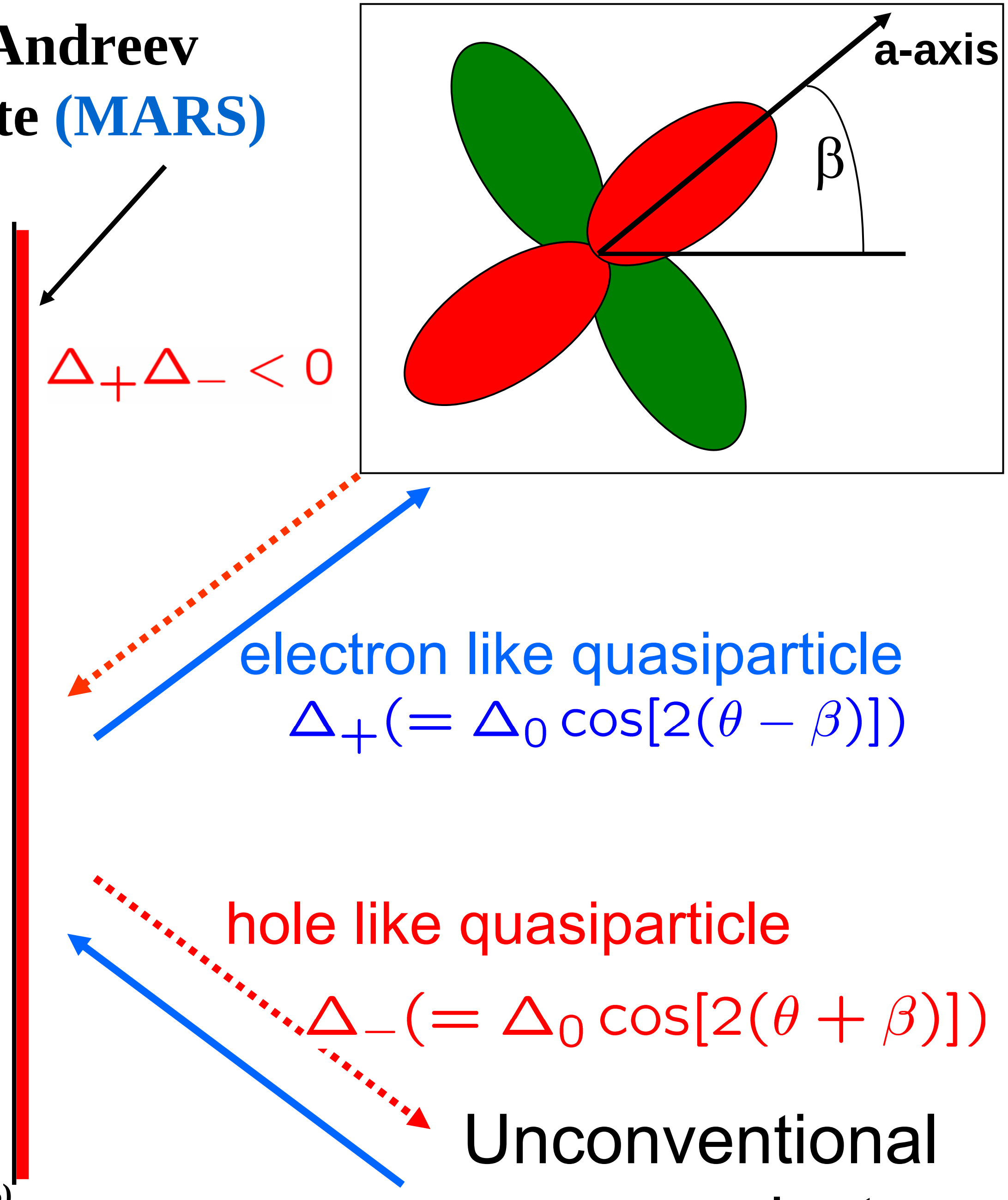
Mid gap Andreev resonant state (MARS)



Hu(1994)
Tanaka Kashiwaya PRL 74 3451 (1995)
Rep. Prog. Phys. 63 1641 (2000)
Matsumoto Shiba(1995)

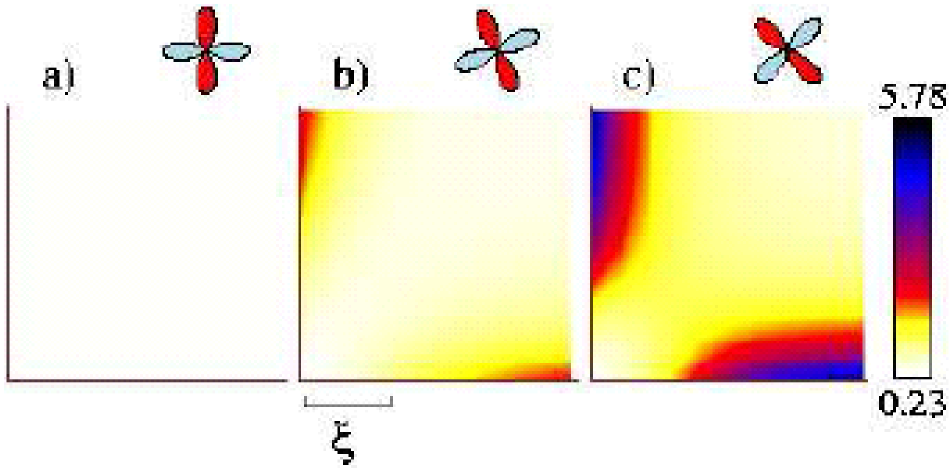


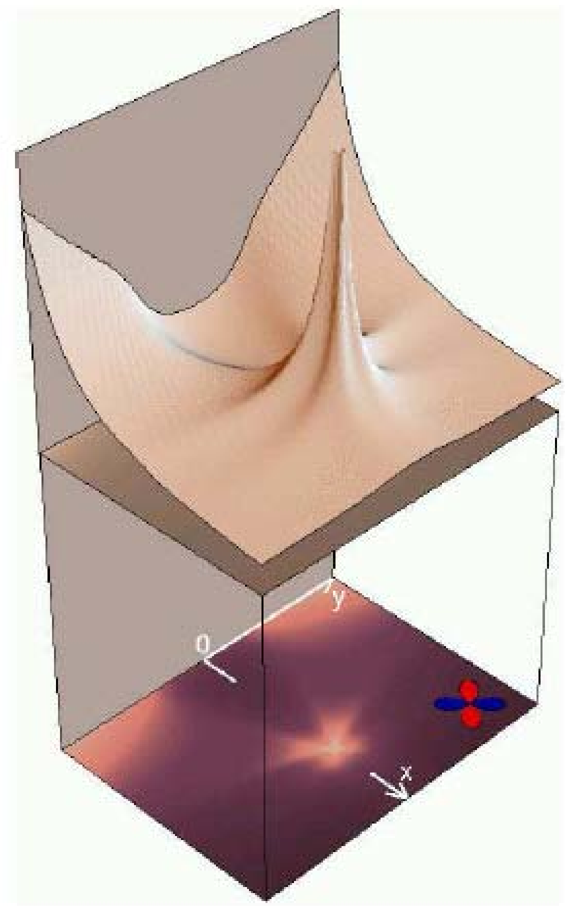
FIG. 2: Zero-energy density of states of a $d_{x^2-y^2}$-wave superconductor for a wedge-shaped boundary with opening angle $\alpha = \pi/2$. The density of states is normalized to the density N_0 of the normal state. The effective scattering parameter is chosen to be $\delta = 0.1\Delta_0$. The rotation of the d-wave with respect to the bisecting line is a) $\gamma = -\pi/4$, b) $\gamma = -\pi/8$, c) $\gamma = 0$.

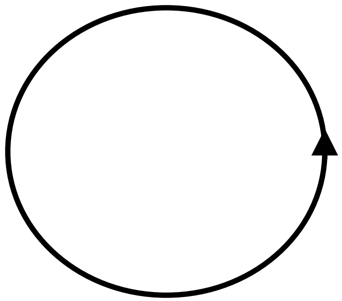
Zero energy states at the surface

Iniotakis et al. PRB 2005

Shadow on the wall cast by an Abrikosov vortex

Graser et al. PRL 2004





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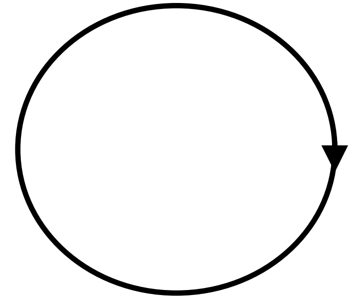

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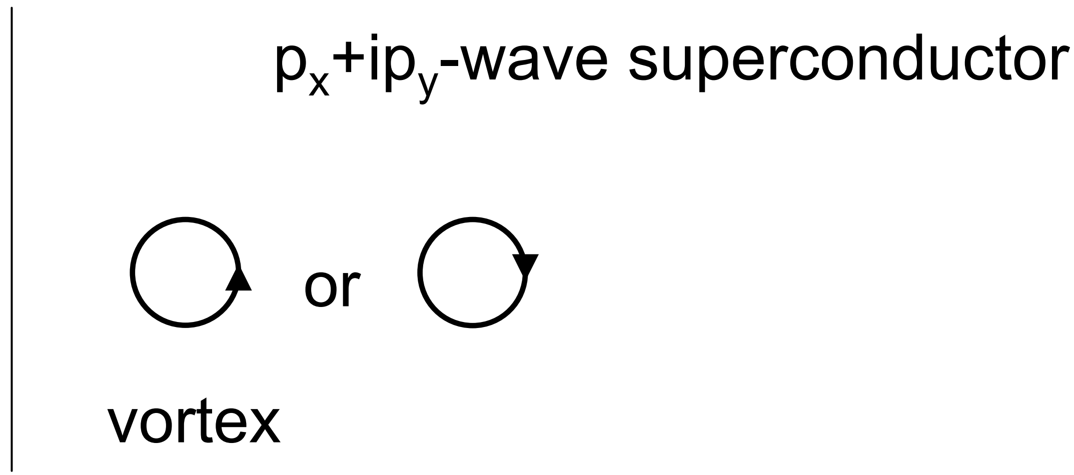
p_x+ip_y-wave superconductor and vortex have chirality (vorticity)

How do these chiralities (chirality and vorticity) interplay in p_x+ip_y-wave superconductor?

The answer is:

The relation between these chiralities crucially influences the density of states at the shadow region of the vortex



We solve Eilenbreger equations with specular surface

$$v\nabla\hat{a} + 2\omega\hat{a} + \hat{a}\Delta^{\dagger}\hat{a} - \Delta = 0$$

Graser et al. PRL 2004

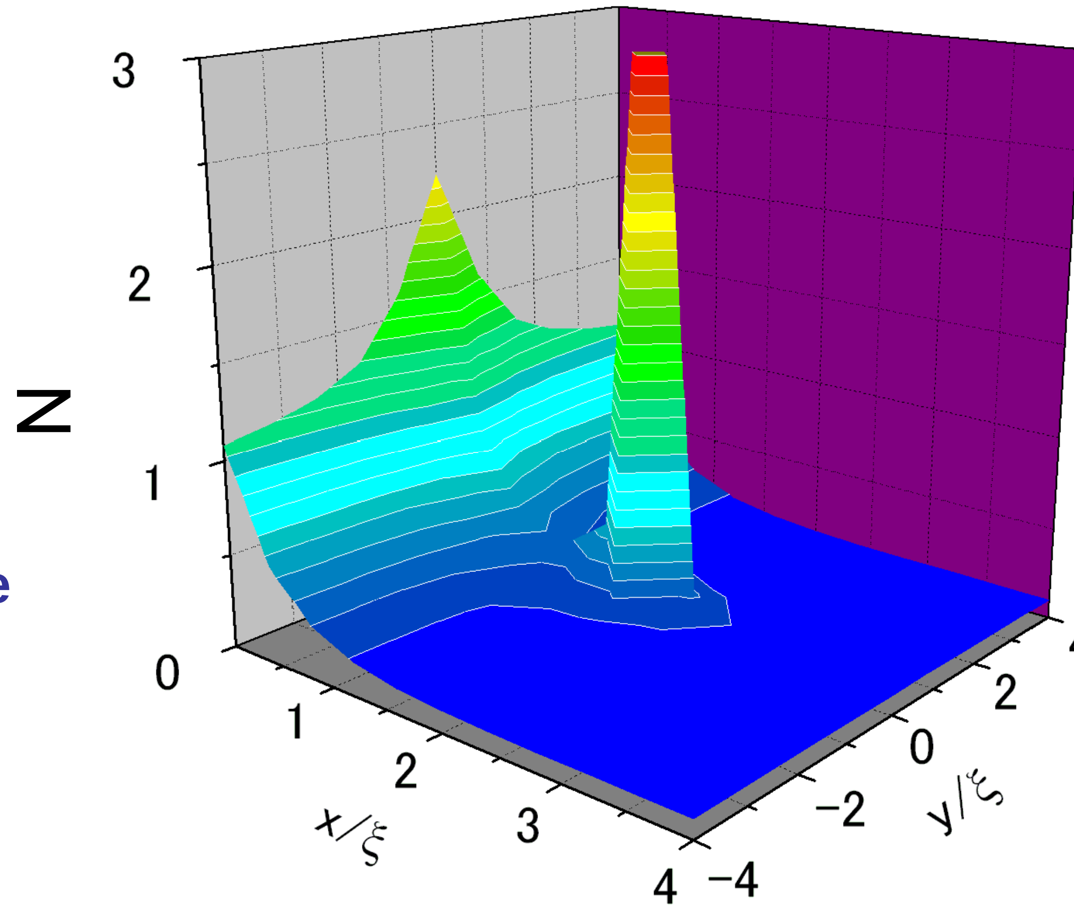
$$v\nabla\hat{b} - 2\omega\hat{b} - \hat{b}\Delta\hat{b} + \Delta^{\dagger} = 0$$

$$\Delta = \Delta_0 e^{i\theta}\psi\sigma_1$$

$$\psi = \arg(r - r_V) - \arg(r - \overline{r}_V)$$

Spatial dependence of DOS at zero energy, boundary x=0

Vortex is placed x=2 ξ



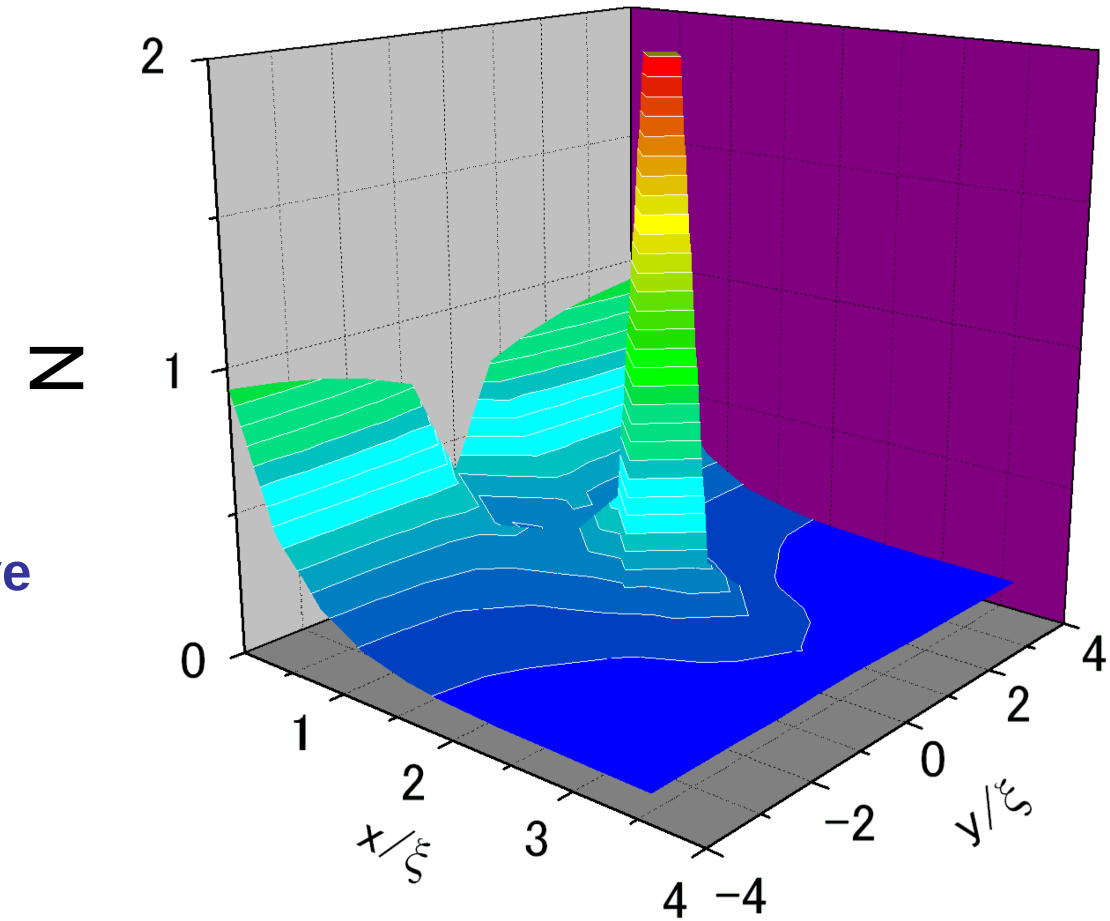
The vortex and the p-wave state have the same chirality.

A sharp peak appears at the shadow region

Spatial dependence of DOS at zero energy, boundary x=0

Anti-vortex is placed x=2 ξ

The vortex and the p-wave state have the opposite chirality.



A gap structure appears at the shadow region

Density of states at the surface in a magnetic field

$$N = 2\,\mathrm{Re}\left\langle \frac{1}{1+(1-2\tilde{\varepsilon}_n c)e^{-i\theta}} \right\rangle - 1, c = \frac{1}{\tilde{\varepsilon}_n + \sqrt{\tilde{\varepsilon}_n^2 + 1}}$$

Expanding in A at zero energy gives

$$N = 1 - \frac{ev_F}{c\Delta} A_x + ...$$

$$B_z = -\frac{\partial A_x}{\partial y}$$

Linear term survives

Applying magnetic field in a certain direction leads to the zero energy peak of the surface DOS, while applying it in the opposite direction leads to the gap structure

Conclusions

We have studied the density of states in chiral p-wave superconductor in the presence of an Abrikosov vortex in front of a specular surface, based on the quasiclassical theory of superconductivity.

When the chirality of the vortex is the same as (opposite to) that of the superconductor, the zero energy peak (gap) of the DOS at the shadow region emerges

This is because linear term in vector potential in the DOS survives

We can tune the magnitude of triplet even parity and triplet odd parity pairings by magnetic field

- For a chiral superconductor, it is expected to observe a suppression of the zero-energy DOS at the surface, when a weak magnetic field is applied parallel to the chirality.
- Inverting the field, however, leads to an enhancement of the DOS.
- In this way chirality could be detected.

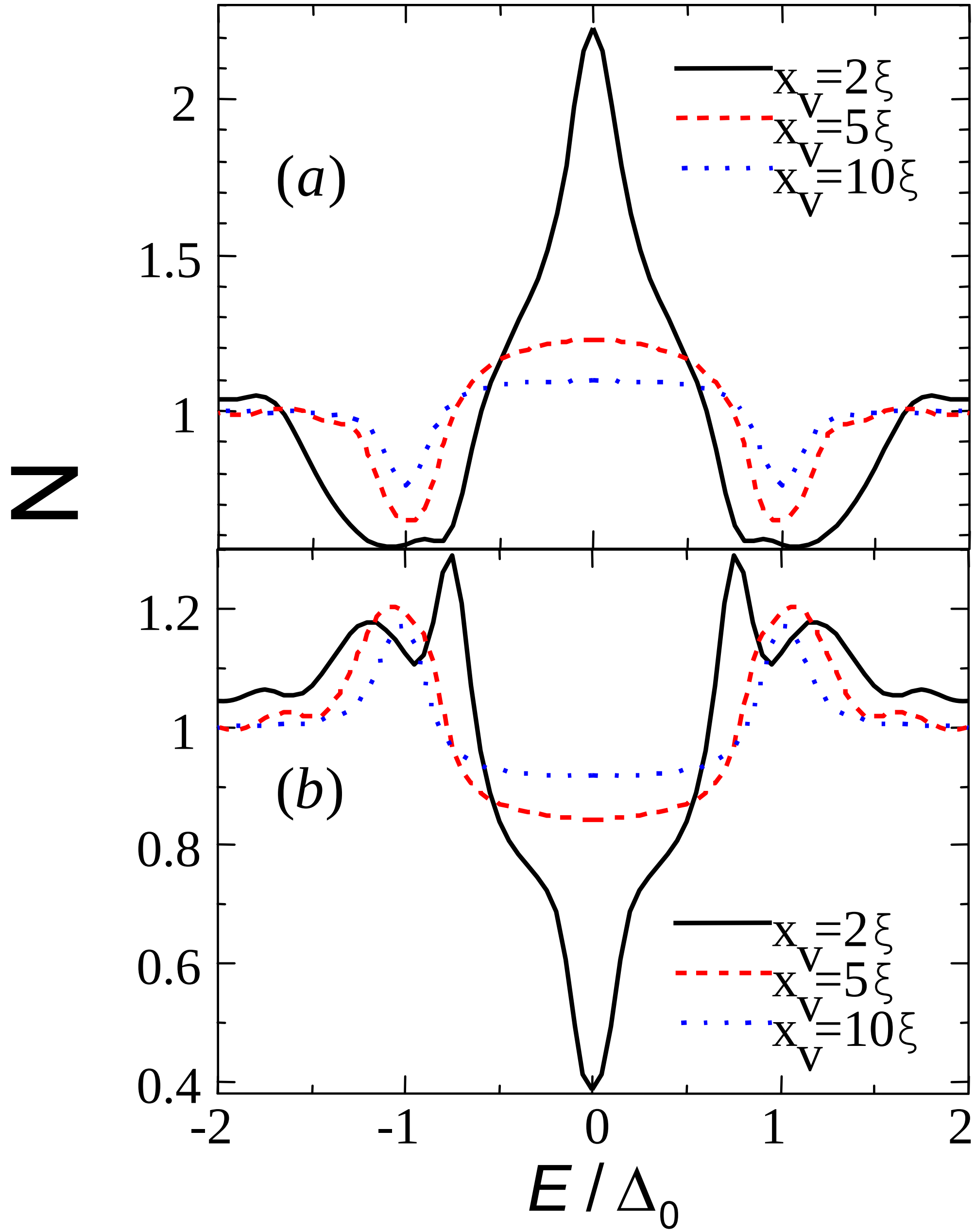
LDOS at x = y = 0 for different vortex to boundary distances x_V as a function of energy.

(a) p-wave state and Abrikosov vortex have the same chirality

(b) p-wave state and Abrikosov vortex have the opposite chirality.

Dos at x=0

$$d = \begin{pmatrix} 0 \\ 0 \\ k_x + ik_y \end{pmatrix}$$



Anomalous Green's functions at the shadow (x=y=0) with azimuthal angle θ

triplet even parity f_{ep}
triplet odd parity f_{op}

Relative manitude of triplet even parity and triplet odd parity pairings changes