Optical response and Higgs mode excitation in s-wave superconductors using terahertz vortex beam

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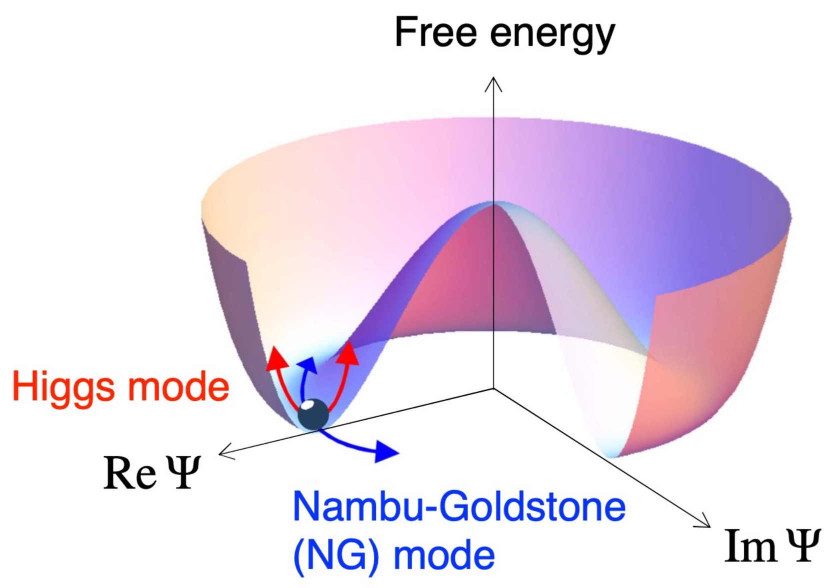
Introduction



[1] R.Shimano and N.Tsuji, Annu. Rev. Condens. Matter Phys. **11**, 103 (2019).

Higgs mode is the amplitude mode of the order parameter . Its excitation cost is about 2Δ. ($\Delta \sim k_B \sim 10^{12}$Hz)

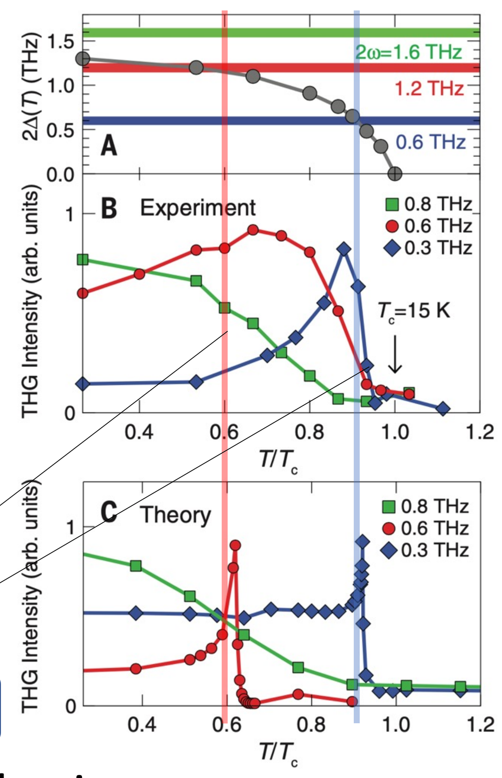
→ One needs intense terahertz light

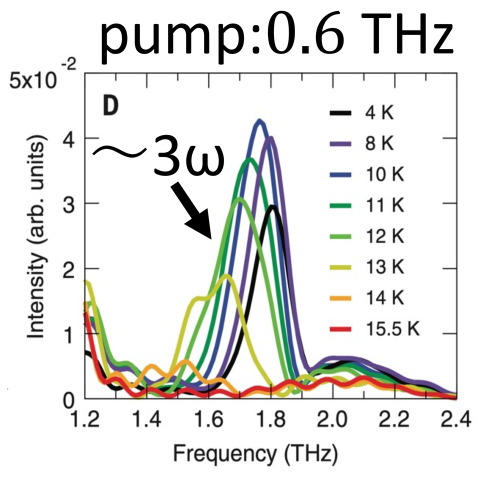
※Terahertz light is beginning to be used in condensed matter research.

$$f = -2aH^2 + \frac{1}{2m}(\nabla H)^2 + \frac{e^2\Delta_0^2}{2m}\boldsymbol{A}^2 + \frac{e^2\Delta_0}{m}\boldsymbol{A}^2 H$$

$$j = -\frac{\partial F}{\partial \boldsymbol{A}} = -\frac{e^2}{m}\boldsymbol{A}\Delta_0^2 - \frac{2e^2\Delta_0}{m}\boldsymbol{A}H$$

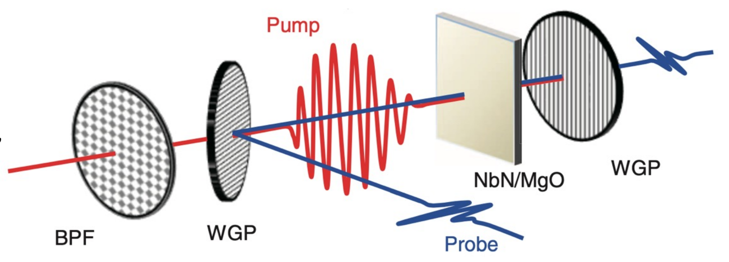
→ Third Harmonic Generation





peaks appear at ω = Δ

The current response is observed using pump-prove spectroscopy.



[2] R.Matsunaga, YI.Hamada, K.Makise, Y.Uzawa, H.Terai, Z.Wang, R.Shimano, Phys. Rev. Lett. 111,057002(2013)

Dirty limit is necessary. There is another major excitation in SC, quasi-particle excitation. And the contribution of quasiparticle is much larger than that of Higgs mode. In dirty limit, the contribution of Higgs mode is same as that of quasiparticle.

mode	channel	clean → dirty
Higgs	dia ($\boldsymbol{A}^2$)	$(\Delta/\epsilon_F)^2$
	para ($\boldsymbol{p}\cdot\boldsymbol{A}$)	$(\epsilon_F\gamma/\Delta^2)^2 \to (\epsilon_F/\gamma)^2$
Quasiparticles	dia ($\boldsymbol{A}^2$)	1
	para ($\boldsymbol{p}\cdot\boldsymbol{A}$)	$(\epsilon_F\gamma/\Delta^2)^2 \to (\epsilon_F/\gamma)^2$

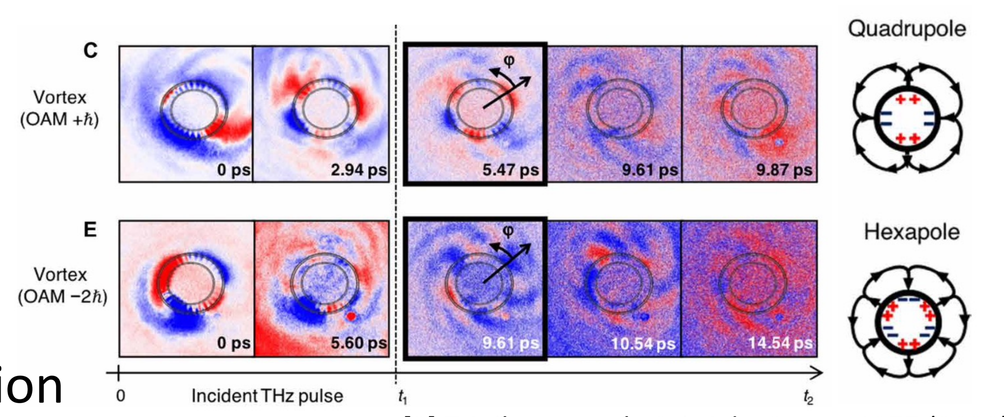
Table1 taken from Rev [1]

Background and Purpose

Previous experiments have revealed nonlinear coupling between Higgs mode and the Gaussian beam. The goal of my research is to reveal linear coupling between Higgs mode and light. I assume terahertz vortex beam as light and consider current as the response of linear coupling.

Terahertz vortex beam

$$\boldsymbol{E} \propto \boldsymbol{e}_\lambda \left(\frac{\rho}{w}\right)^{|m|} L_p^{|m|}\left(\frac{2\rho}{w^2}\right) e^{im\phi} e^{-\frac{\rho^2}{w^2}}$$



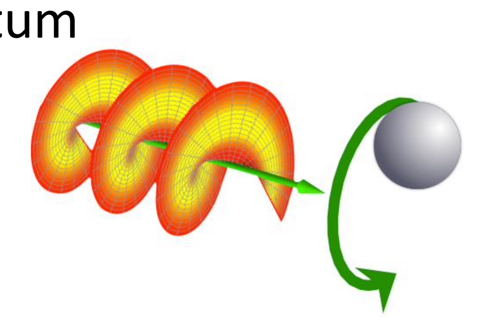
When metamaterials is irradiated the vortex beam, multipole are excited.

$\lambda = \pm 1$ → Circular polarization

[3] T.Arikawa et al., Sci. Adv. **6**, eaay1977 (2020)

$$-i\hbar\frac{\partial}{\partial\phi}[e^{im\phi}] = m\hbar$$ → Orbital Argument Momentum

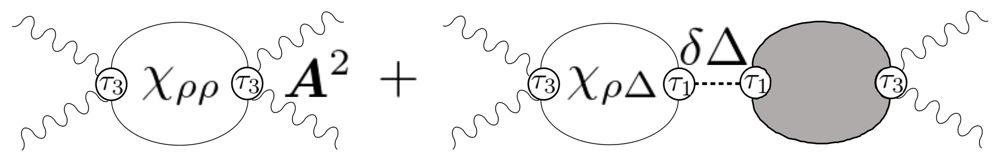
If lights can break inversion symmetry, we can see the Higgs mode in linear coupling. Light that breaks inversion symmetry is the vortex beam. As shown in the above equation, the vortex beam has angular momentum mh.



The vortex beam

Calculation

The Gaussian beam



third order current response

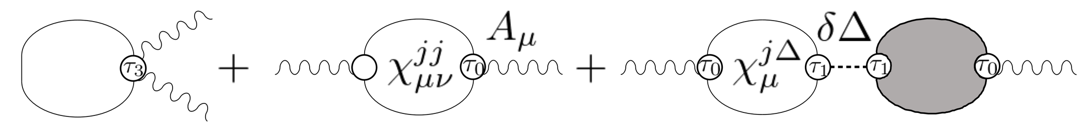
$$S[A] = \frac{e^2}{2m^2c^2}T\sum_{\omega_m}\left[A^2(-i\omega_m)\left\{-\chi_{\rho\rho}(i\omega_m) - \frac{\chi_{\rho\Delta}(i\omega_m)\chi_{\Delta\rho}(\omega_m)}{X_{\Delta\Delta}(i\omega_m)}\right\}A^2(i\omega_m)\right]$$

→ $j_\mu \propto A^3$

※These calculations and diagrams show only the diamagnetic contribution. The paramagnetic contribution, which is the constant term, is neglected.

Difference of order

The vortex beam



first order current response

$$S[A] = \frac{2e^2}{c^2}T\sum_{\omega_m}\left[\tilde{A}_\mu(-i\omega_m)\left\{\frac{n}{m} - \chi^{jj}_{\mu\nu}(i\omega_m) - \frac{\chi^{j\Delta}_\mu(i\omega_m)\chi^{\Delta j}_\nu(i\omega_m)}{X_{\Delta\Delta}(i\omega_m)}\right\}\tilde{A}_\mu(i\omega_m)\right]$$

→ $j_\mu \propto \tilde{A}$ ※ $X_{\Delta\Delta}(i\omega_m) = \frac{2}{V} - \chi_{\Delta\Delta}(i\omega_m)$

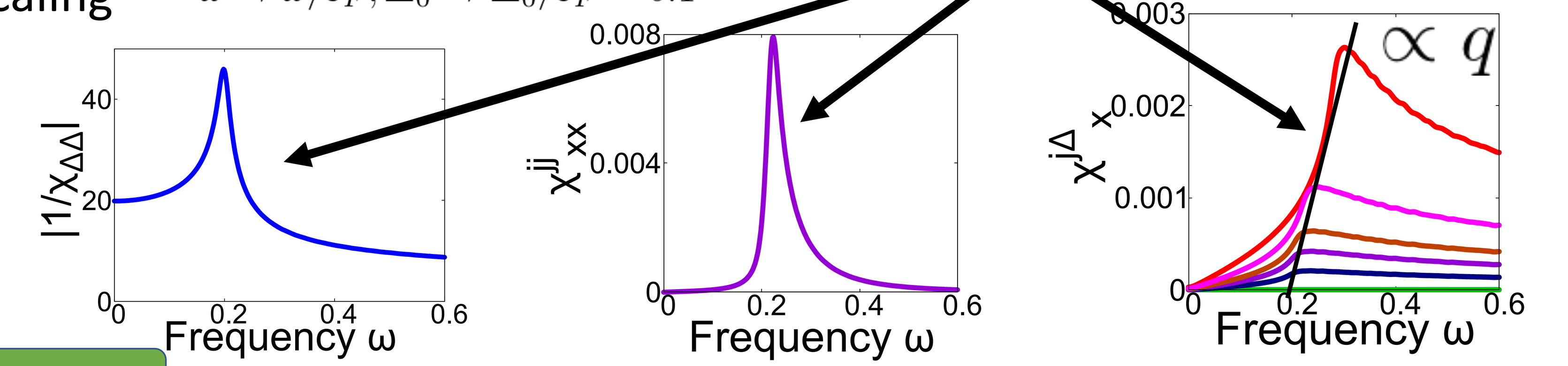
Higgs mode and terahertz vortex beam are linearly coupled. So, the action has first order.

Parameter $\omega \to \omega/\varepsilon_F, \Delta_0 \to \Delta_0/\varepsilon_F = 0.1$

Response function

Peak is around $\omega = 2\Delta_0$

Scaling $\omega \to \omega/\varepsilon_F, \Delta_0 \to \Delta_0/\varepsilon_F = 0.1$



Current

$$j_\mu(i\omega_m,\boldsymbol{q}) = e^2\left[\left\{\frac{ne^2}{m} + \chi^{jj}_{\mu\nu}(i\omega_m,\boldsymbol{q}) + \frac{\chi^{j\Delta}_\mu(i\omega_m,\boldsymbol{q})\chi^{\Delta j}_\nu(i\omega_m,\boldsymbol{q})}{X_{\Delta\Delta}(i\omega_m,\boldsymbol{q})}\right\}\tilde{A}_\nu(i\omega_m,\boldsymbol{q})\right]$$

Vector potential

[4] A. A. Peshkov, D. Seipt, A. Surzhykov, S. Fritzsche, Phys. Rev. **96**, 023407 (2017)

$$\tilde{A}_\perp(i\omega,\boldsymbol{q}) = \boldsymbol{A}_\perp^{\rm OV} - i\frac{c}{2e}\boldsymbol{q}\cdot\varphi = \boldsymbol{A}^{\rm OV} - \frac{\boldsymbol{q}(\boldsymbol{q}\cdot\boldsymbol{A}^{\rm OV})}{\boldsymbol{q}^2 - (\omega/v_p)^2},\ \boldsymbol{A}^{\rm OV}(i\omega_m,\boldsymbol{q}) = v_{pm}(q_\perp)e^{i(m+\lambda)\phi_q}\boldsymbol{e}_{q\lambda}$$

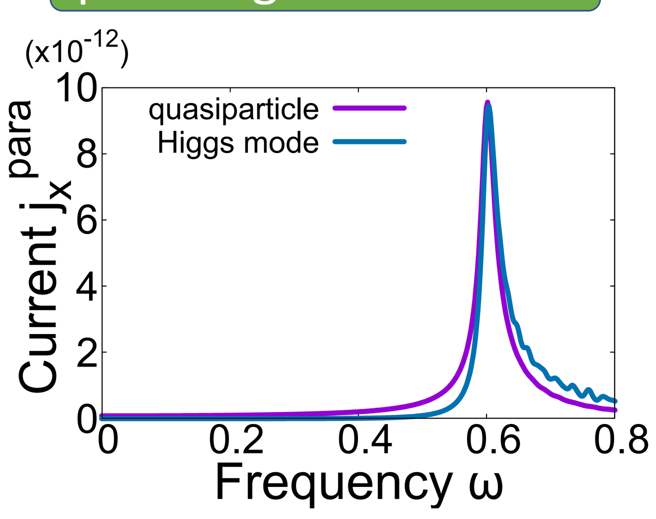
$\boldsymbol{A}^{\rm OV} = \boldsymbol{A}_\perp^{\rm OV} + \hat{\boldsymbol{z}}A_z$ → $\nabla_\perp\cdot\boldsymbol{A} \neq 0$ L_β^m is Laguerre function

$$v_{pm}(q_\perp) = \frac{(-i)^m w_0}{4\pi}e^{-\frac{q_\perp^2 w_0^2}{4}}\left(\frac{q_\perp w_0}{2}\right)^m \sum_{\beta=0}^{p}(-1)^\beta 2^{\beta+\frac{m}{2}}{}_{p+m}C_{p-\beta}L_\beta^m\left(\frac{k_\perp^2 w_0^2}{4}\right)$$

In the votex beam, a component of the vector potential also appears in the direction of the light propagetion. Therefore, surface plasmons are excited when thin film superconductivity is considered. The OAM of terahertz vortex beam is translated to the phase fluctuation. As follows below,

$$\boldsymbol{q}\cdot\varphi \propto \boldsymbol{q}\cdot\boldsymbol{A}_\perp^{\rm OV}$$
$$\to \boldsymbol{q}\cdot\varphi \propto \nabla\cdot\boldsymbol{A}_\perp^{\rm OV} \propto (m+\lambda)v_{pm}e^{i(m+\lambda)\phi}$$

paramagnetic current



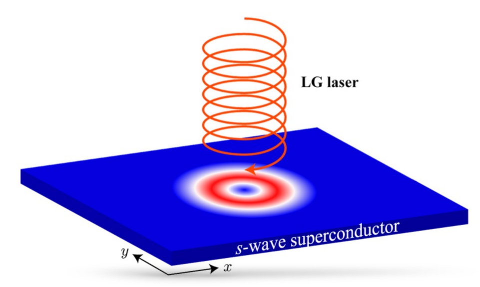
The contribution of Higgs mode is multiplied by 2,500 compared to quasi-particle. Higgs mode is not so visible.

Future Work

We will take account of the following effects.

1. Phase fluctuations.
2. Rashba spin-orbit coupling(SOC) effect.

The SOC may enhance the linear coupling of terahertz votex beam with Higgs.



References

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[2] R.Matsunaga, YI.Hamada, K.Makise, Y.Uzawa, H.Terai, Z.Wang, R.Shimano, Phys. Rev. Lett. 111,057002(2013)
[3] T.Arikawa et al., Sci. Adv. **6**, eaay1977 (2020)
[4] A. A. Peshkov, D. Seipt, A. Surzhykov, S. Fritzsche, Phys. Rev. **96,** 023407 (2017)