Surface Josephson plasma waves in layered superconductors and THz detectors

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We predict the existence of surface waves in layered superconductors in the THz frequency range, below the Josephson plasma frequency ω_J. This wave propagates along the vacuum-superconductor interface and dampens in both transverse directions out of the surface (i.e., towards the superconductor and towards the vacuum). This is the first prediction of propagating surface waves in any superconductor. These predicted surface Josephson plasma waves are important for different phenomena, including the complete suppression of the specular reflection from a sample (Wood's anomalies) and a huge enhancement of the wave absorption (which can be used as a THz detector and for improving THz gratings).

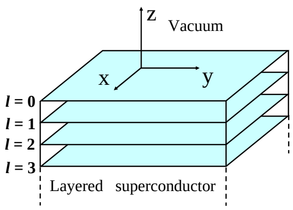
Surface Josephson plsma waves

Problem setup

$$\text{p-waves} = \begin{array}{l}\vec{E} = \{E_x, 0, E_z\} \\ \vec{H} = \{0, H, 0\}\end{array}$$

$$H^{\text{vac}},\ E_x^{\text{vac}},\ E_z^{\text{vac}} \propto \exp(-i\omega t + iqx - k_{\text{vac}} z),$$

$$q > \omega/c, \ \text{ine the vacuum}, \quad z < 0$$



$$H,\ E_x,\ E_z \propto \exp(-i\omega t + iqx - klD),$$

$$\text{inside the superconductor}, \quad z < 0$$

Damped waves in the vacuum

Maxwell equations

$$q\, H^{\text{vac}} = -(\omega/c) E_z^{\text{vac}},$$

$$k_{\text{vac}}\, H^{\text{vac}} = -(i\omega/c) E_x^{\text{vac}},$$

$$iq\, E_z^{\text{vac}} + k_{\text{vac}}\, E_x^{\text{vac}} = -(i\omega/c) H^{\text{vac}}$$

Dispersion equation

$$k_{\text{vac}} = \sqrt{q^2 - \omega^2/c^2}$$

E/H at the surface from the vacuum side

$$\frac{E_x^{\text{vac}}}{H^{\text{vac}}} = \frac{ic}{\omega}\sqrt{q^2 - \omega^2/c^2}$$

Damped waves in the superconductor

From coupled sine-Gordon equations

$$\left(1 - \frac{\lambda_{ab}^2}{D^2}\partial_l^2\right)\left(\frac{\partial^2 H^l}{\partial t^2} + \omega_r \frac{\partial H^l}{\partial t} + \omega_J^2 H^l\right) - \alpha\, \omega_J^2\, \partial_l^2 H^l - \left(\frac{c^2}{\varepsilon}\right)\frac{\partial^2 H^l}{\partial x^2} = 0$$

Damping — Josephson currents — Charge neutrality breaking

Dispersion relation

$$\frac{\omega^2}{\omega_J^2} = 1 + \frac{\lambda_c^2 q^2}{1 - (4\lambda_{ab}^2/D^2)\sinh^2[k(q,\omega)D/2]} - 4\alpha \sinh^2[k(q,\omega)D/2], \quad \lambda_c^2 = \frac{c^2}{\omega_J^2 \varepsilon}$$

$$\frac{E_x}{H^{\text{vac}}} = \frac{i\omega\lambda_{ab}^2}{cD}\left[1 - \exp(-kD)\right]$$

E/H at the surface from the superconductor side

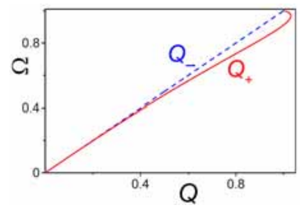
Surface waves

$$Q_-(\Omega) = \Omega;$$

$$Q_+(\Omega) = \Omega\left[1 + \frac{\beta^2\Omega^2(1-\Omega^2)}{4\alpha}\right.$$

$$\left.\times\left(1 + \frac{1-\Omega^2}{2\alpha} - 2\sqrt{\frac{(1-\Omega^2)^2}{16\alpha^2} + \frac{1-\Omega^2}{4\alpha}}\right)\right]^{1/2}$$

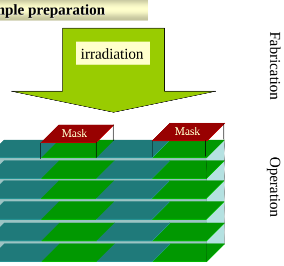
$$Q = cq/\omega_J,\ \Omega = \omega/\omega_J,\ \beta = 2\lambda_{ab}^2\omega_J/cD$$



Spectra of two branches "±" of the surface Josephson plasma waves for the parameters $\alpha = 0.1$ and $\beta = 1.4$, standard for Bi2212.

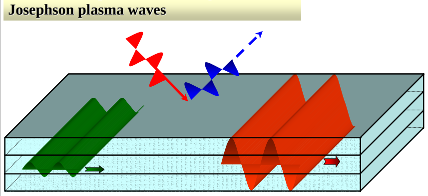
Exciting surface waves by applying external wave

Sample preparation



$$\omega_J^2(x) = \omega_J^2\left[1 + 2\mu\cos\left(\frac{2\pi x}{a}\right)\right], \quad \mu \ll 1$$ Modulations

3D schematic picture of exciting surface Josephson plasma waves



One of the ways to excite surface waves is via externally applied electromagnetic waves on a sample having spatially modulated parameters.

Exciting surface waves by applying external wave

$$q_1 = (\omega/c)\sin\theta + 2\pi/a$$

Due to interaction with modulations

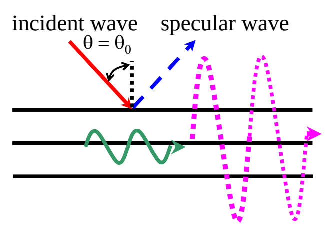
$$H_{\text{forced}} \exp\left\{iq_1 x - i\omega t - k_-\left(\frac{\omega\sin\theta}{c}, \omega\right) Dl\right\}$$

$$\Omega\sin\theta_0 + \frac{2\pi c}{a\omega_J} = Q_+(\Omega)$$ Resonance condition

Surface wave

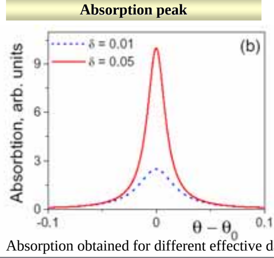
$$H_{\text{surf}} \exp\left\{iq_1 x - i\omega t - k_+(q_1, \omega)\, Dl\right\}$$

$$H_{\text{surf}}^{\text{vac}} \exp\left\{iq_1 x - i\omega t - \left(q_1^2 - \frac{\omega^2}{c^2}\right)^{1/2} z\right\}$$



Schematic diagram showing the mechanism of excitation of the surface waves along the superconductor-vacuum interface. To zero-order approximation, with respect to the amplitude μ of the spatial modulations in a superconducting sample, an incident wave (shown as a solid red arrow) reflects as a specular wave (the straight dashed blue arrow), producing a damped wave (green wave) inside superconductors. To first order approximation, the very intense surface wave (dotted magenta wave) can be excited at a certain resonant angle between the incident wave and sample surface.

Absorption peak



Absorption obtained for different effective dampings

$$H_{\text{surf}}^{\text{vac}} = H_{\text{in}}^{\text{vac}} \frac{2\mu q_0^2}{(1-\Omega^2)(q_1^2 - q_0^2)} \cdot \frac{1}{\mathcal{R}}$$

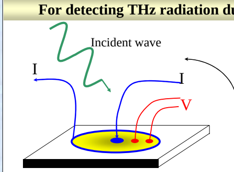
$$\mathcal{R} = X + iY = \frac{2Q_+(\Omega)\cos\theta_0(\theta - \theta_0)}{\beta\Omega\sqrt{Q_+^2(\Omega) - \Omega^2}} + \frac{i\omega_r\alpha\Omega^3}{\omega_J(1-\Omega^2)^3}$$

$$\text{Absorption}(\theta) \propto \sigma_\perp E_z^2 + \sigma_\parallel E_x^2 \propto \frac{1}{X^2(\theta) + Y^2}$$

An electromagnetic wave with $\omega<\omega_J$ incident at an angle θ with respect to the sample surface generates modes (due to interaction with modulations) having longitudinal wave vectors $q_m=\omega/c \sin\theta +2\pi m/a$, with integer m. Almost all of these modes for $m \neq 0$ are weak, because μ ¿ 1. However, one of these modes (e.g., for m=1) can be excited with large amplitude at resonance, i.e., when the wave vector $q_1=(\omega/c)\sin\theta+2\pi/a$ is close to the wave vector $q_+=\omega_J Q_+(\Omega)/c$ of the surface wave. In resonance, the mode with $q=q_1$ is actually the surface Josephson plasma wave discussed above.

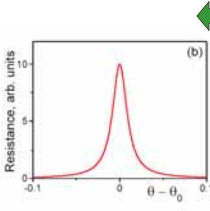
Application of surface waves

For detecting THz radiation due to absorption peak



Tilting the sample to reach the angles where the surface wave can be excited. At these angles peak of absorption and resistance occurs

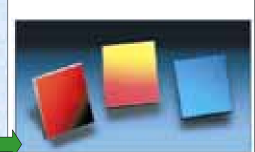
The resonance in the absorption can be observed by measuring the dependence of the surface impedance on the angle θ. Alternatively, the peak in absorption produces a temperature increase, resulting in a sharp increase of the DC resistance or even the transition of the sample to the normal state at $\theta=\theta_0$.



The excitation of the Josephson plasma waves could be potentially useful for the design of THz detectors, an important current goal of many labs worldwide. The simplest design could be a spatially modulated Bi2212 sample fixed on a precisely rotated holder and attached by contacts to measure its resistance. Spatial modulations in the sample could be fabricated by either using ion irradiation of the sample covered by periodically modulated mask, or even mechanically. When rotating the sample, the incident THz radiation can produce a surface wave at certain angles. This results in a strong enhancement of absorption associated with increasing of temperature in the sample and, thus, its resistance. The relative positions of the resonance peaks (the set of angles) allows to calculate the angle and the frequency of the incident THz radiation, while the relative heights of the resistance peaks can be used to estimate the intensity of the incident radiation.

Another promising application of the THz surface Josephson plasma waves could be an improvement of grating arrays, which is one of the usual application of the Wood's anomalies associated with resonance enhancement of surface waves.

For improving diffraction of THz waves due to Wood's anomalies



References:
[1] S. Savel'ev, V. Yampol'skii, F. Nori, Phys. Rev. Lett. **95,** 187002 (2005); cond-mat/0508716