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COLLECTIVE EXCITATIONS IN CHARGED SUPERCONDUCTORS BELOW T_c AND THE LONGITUDINAL ULTRASONIC SPECTRUM

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Résumé.- En plus du premier son, un deuxième maximum peut être observé dans le spectre des fréquences acoustiques des métaux supraconducteurs à températures plus basses que T_c . Il est excité par les mouvements collectifs des électrons, qui influencent aussi le son habituel. La discussion se restreint au cas des spécimens purs. En ce cas la vitesse du nouveau mode est plus grande que celle du premier son.

Abstract.- Collective modes in superconductors lead to a second peak in the ultrasonic spectrum besides the first sound maximum, which is also affected. The discussion is restricted to the case of clean samples, in which case the velocity of the new mode is larger than that of ordinary sound.

Collective excitations in charged superconductors near the critical temperature [1-4] play a role in tunnel junctions, where they govern the fluctuating part of the current-voltage characteristic

Other kinds of experiments revealing the influence of these modes involve density fluctuations of both superfluid and normal electrons by way of the longitudinal dielectric function ϵ . $\text{Im } 1/\epsilon$ (related to the scattering cross section of electromagnetic waves and charged particles) has the following property in the dirty limit: At the same frequency $\omega = \sqrt{2D\Delta}q$ (D the electron diffusion constant, Δ the pair potential), where there is a maximum in the phase correlation function of the order parameter, characterizing the propagating collective mode, $\text{Im } 1/\epsilon$ has a minimum. Both maximum and minimum disappear, when the superconductor becomes gapless. In the clean limit [5] that feature is even more pronounced, this time at $\omega = q\sqrt{2A\Delta}/6$, where $A=7\zeta(3)v^2/(6\pi^3T)$ with Fermi velocity v and temperature T . Therefore and on account of complications arising from the collision drag effect in dirty probes, the discussion is confined to clean superconductors.

ϵ is in this case (for $\omega \leq 2\Delta < T$, $vq \ll T$ and $q \ll$ Fermi momentum):

$$\epsilon(q, \omega) \approx 1 + \frac{K^2}{q^2} \left[1 - \frac{\omega}{2vq} \ln \left| \frac{\omega + vq}{\omega - vq} \right| \right] + \frac{i\pi\omega K^2}{2vq^3} \Theta(vq - \omega) + \frac{\frac{n_s}{n} \cdot \frac{\omega_p^2}{p}}{-\omega^2 + Aq^2 \sqrt{4\Delta^2 - \omega^2}} \quad (1)$$

The last term describes the contribution by the superfluid component, $n_s/n = 7\zeta(3)\Delta^2/(2\pi T)^2$ is the ratio of superfluid and total particle density, $\Delta^2 = 8\pi^2 T^2 (1 - T/T_c)/7\zeta(3)$, $\omega_p^2 = 4\pi e^2 n/m$ is the square of the electron plasma frequency. For $\omega \geq 2\Delta$ replace $\sqrt{4\Delta^2 - \omega^2}$ by $-i\sqrt{\omega^2 - 4\Delta^2}$. The remaining part of ϵ is due to the normal component and the same one is acquainted with from standard literature. $\kappa^{-2} = v^2/3\omega_p^2$ is the square of the Debye screening radius. Restricting frequencies to $\omega \ll 2\Delta \ll vq$, wavevectors to $q \ll K$ we may go ahead simplifying:

$$\epsilon(q, \omega) \approx \frac{K^2}{q^2} \left(1 + \frac{i\pi\omega}{2vq} \right) + \frac{n_s}{n} \frac{\omega_p^2}{-\omega^2 + 2A\Delta q^2} \quad (2)$$

To include the ionic motion within the frame of the jellium model, subtract Ω_p^2/ω^2 from the electronic ϵ of (2). $\Omega_p^2 = 4\pi(Ze)^2 N/M$ is the square of the ionic plasma frequency. Thus the Coulomb potential between electrons, screened by the combined motion of ions, normal and superfluid electrons, reads:

$$D(q, \omega) = - \frac{4\pi e^2}{q^2 (\epsilon - \Omega_p^2/\omega^2)} \quad (3)$$

Abbreviations: the velocity of ref. [6] $c = \sqrt{2A\Delta}$, fourth sound $c_4 = v\sqrt{\frac{n_s}{3n}}$, first sound $c_s = \Omega_p/K$ and the square of the electron-phonon coupling constant $g^2 = 4\pi e^2/K^2$. This essentially yields the phonon Green's function:

$$D(q, \omega) = \frac{g^2 \omega^2}{-\omega^2 + c_s^2 q^2 - \frac{i\pi\omega^3}{2vq} - \frac{c_4^2 q^2 \omega^2}{-\omega^2 + c^2 q^2}} \quad (4)$$

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Fig. 1 : Ultrasonic spectrum as a function of the temperature dependent scaled frequency $\omega/2\Delta$ for two values of the parameter $Aq^2/2\Delta$ (0.1 and 0.2). The other parameter appearing in formula (4) is fixed $\pi\Delta/4T = 0.1$. The two peaks on the left are ordinary sound, the small ones at higher frequencies are caused by collective excitations and only present below T_c .

The imaginary part of D is plotted in the figure : besides the first sound peak $\omega \approx c_s q$ there is a second maximum at $\omega \approx c_q$, some orders of magnitude smaller, looking like second sound [3]. The denominator of D yields the spectral equation ($x = \omega/q$) :

$$(x^2 - c_s^2 + \frac{i\pi x^3}{2v})(x^2 - c^2) = c_q^2 x^2 \quad (5)$$

Note : $c_s^2 : c_q^2 : c^2 \approx 10^{-4}$; $(1-T/T_c) : (1-T/T_c)^{1/2}$. For the range $10^{-8} \ll 1-T/T_c \ll 1$ c is largest of all three velocities ; here we get the following spectrum :

$$\omega \approx q \sqrt{c^2 + c_q^2} - iq \frac{\pi c c_q^2}{4v \sqrt{c^2 + c_q^2}}, \text{ c-sound} \quad (6)$$

$$\omega \approx c_s q \frac{c}{\sqrt{c^2 + c_s^2 + c_q^2}} - iq \frac{\pi c_s^2}{4v} \frac{c^4 (c^2 + c_q^2)}{(c^2 + c_s^2 + c_q^2)^3} \text{ 1. sound}$$

From the imaginary part of Lorentz shaped peak one may infer their height, thus finding for the ratio of the two intensities

$$\frac{I_c}{I_{cs}} = \frac{c_s^2}{c_q^2} \cdot \frac{c^3 (c^2 + c_q^2)^{3/2}}{(c^2 + c_s^2 + c_q^2)^3} \approx \frac{c_s^2}{c_q^2} \quad (7)$$

The smaller $1-T/T_c$, the better the c-signal. It may be detected by light, though Brillouin scattering

in solids is not easy. Another possibility is ultrasound with frequencies $\omega \approx 10^{10} \text{ s}^{-1}$ and wavevectors $q \approx 10^2 \text{ cm}^{-1}$. The attenuation coefficient $\alpha = 2 \text{ Im } q(\omega)$ describing the exponential decay of the energy intensity is for the c-mode $\frac{\pi\omega}{2v} \cdot c_q^2 c / \sqrt{c^2 + c_q^2}^3 \approx (\pi\omega/2v) \cdot (\pi\Delta/4T)$. For first sound in the normal state at T_c it is $\alpha_n = \pi\omega/2v$. Then (6) yields for the first sound :

$$\frac{\alpha_s}{\alpha_n} = \frac{c^2 (c^2 + c_q^2)}{(c^2 + c_s^2 + c_q^2)^2} \approx 1 - \frac{\pi\Delta}{4T} \quad (8)$$

The BCS prediction (without collective excitations) reads

$$\frac{\alpha_s}{\alpha_n} = 2/(1 + e^{\Delta/T}) \approx 1 - \frac{\Delta}{2T}$$

Due to the propagating mode α_s/α_n drops more rapidly near T_c than found by BCS. For $1-T/T_c \ll 10^{-8}$ one gets $\alpha_s/\alpha_n \approx 1 + c_q^2 c^2 / c_s^4 \approx 1 + 10^8 (1-T/T_c)^{3/2}$: the attenuation coefficient is continuous at and has a maximum below T_c , which, however, cannot be seen.

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