Predicted plasma oscillations in the $Bi_2Sr_2CaCu_2O_8$ high-temperature superconductor

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It is shown that the frequency of the longitudinal plasmon with an electric field polarized perpendicular to the CuO layers is lower than the superconducting gap and the plasmon decay rate should be extremely small.

Recently, a giant superconducting effective-mass anisotropy $m_c/m_a \cong 3000$ has been measured in $Bi_2Sr_2CaCu_2O_8$ Bi-based 2:2:1:2 using torque magnetometry.[1] Here m_c and m_a are the London effective masses for Cooper-pair motion along the c direction and in the a-b plane (CuO plane), respectively. This leads to anisotropy in the penetration depth $\lambda_c/\lambda_a = (m_c/m_a)^{1/2} \cong 55$, where λ_c and λ_a are the London penetration depths corresponding to screening currents flowing along the c direction and in the isotropic a-b plane, respectively.

Using a typical value $\lambda_a \cong 250$ nm (Ref. 2), we can calculate a giant value $\lambda_c = (m_c/m_a)^{1/2}\lambda_c \cong 14$ μm. This leads to an extremely low plasma frequency, $\omega_{\text{pl}} = c/(\lambda_c\sqrt{\epsilon}) \simeq 4$ meV, lower than the superconducting gap $2\Delta(0)$ at low, $T \ll T_c$, temperatures. Here c is the light velocity and $\epsilon \simeq 4.5$ (Ref. 3) is the background dielectric constant. The electric field of these plasma oscillations is polarized in the c direction. The BCS theory gives $2\Delta(0) = 3.52T_c \simeq 30$ meV and experimental data even more.[4]

In conventional superconductors, $2\Delta(0) \ll \omega_{\text{Fl}}$ and plasmons destroy the Cooper pairs.[5] But, for the layered and extremely anisotropic Bi-based 2:2:1:2 with weak coupling between conducting CuO planes, the attenuation of the plasmons will be negligible. The predicted slow decay may encourage experimenters to look for plasmons in their samples.

It is well known that the London electrodynamics describe the electromagnetic response for frequencies ω up to the superconducting gap $\omega < 2\Delta$. No special treatment connected with the mechanism of superconductivity is necessary for considerations of the consequences of London electrodynamics for all superconductors. The existence of plasmons connected with fluctuations of the density "superfluid" electrons n is a simple consequence of the London electrodynamics if the plasma frequency is low enough:

$$\omega_{\text{pl}} = (4\pi n e^{*2}/m_c\epsilon)^{1/2} = c/(\lambda_c\sqrt{\epsilon}) < 2\Delta(0) ,$$

$$1/\lambda_c^2 = 4\pi n e^{*2}/m_c c^2 , \quad |e^*| = 2|e| ,$$

where e^* and m_c are the charge and mass of Cooper pairs. Plasma waves connected with the Cooper-pair motion were predicted for thin wire[6] (one-dimensional superconductors) and for thin films[7] (two-dimensional superconductors) without any connections with the mechanisms of the superconductivity. Moreover, for small spheres (zero-dimensional superconductors), plasma resonances were observed experimentally[8] for many high-T_c superconductors (HTS); let us mention that the existence of such plasma oscillations is not directly connected with the mechanism of HTS. The suggestion in this paper is that similar plasma oscillations can exist in bulk (three-dimensional) superconductors, and it is worthwhile to understand plasmons of Cooper pairs in Bi-based 2:2:1:2 and Ta-based 2:2:1:2. The experimental observation can be performed, for example, using high-resolution electron-energy-loss spectroscopy for electrons reflected by a clean a-b surface of a 2:2:1:2 crystal. The electric field of these plasma oscillations is oriented in the c direction, perpendicular to the a-b surface of a HTS crystal, and these resonances cannot be excited by electromagnetic waves falling perpendicularly to the a-b surface. Namely, this is the reason that considered plasma oscillations are not discovered by chance during the contemporary intensive far-infrared (FIR) investigations of HTS.

Thin HTS layers with thickness $d \ll \lambda_c$ are also intensively investigated. Let us mention that the plasma frequency for a thin layer is just the same as that for a bulk material. For thin 2:2:1:2 layers, the polarization, geometry, and plasma frequency are of the same order as intersubband plasmons in a two-dimensional electron gas (2DEG) in semiconductors and can be observed by the same FIR techniques.[9] (For an introduction to the physics of the two-dimensional electron gas, see the well-known review of Ando, Fowler, and Stern.[10] Another possibility is the use of a grating coupling[11] of the FIR electromagnetic field with the plasma oscillations and the standard FIR transmission spectroscopy.

We hope that thin c-oriented 2:2:1:2 films will be the most appropriate systems for observation of c-polarized plasma oscillations because the attainable quality of bulk crystals is not as high as that of thin films.

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