COMMENTS

Comments are short papers which criticize or correct papers of other authors previously published in **Physical Review B.** *Each Comment should state clearly to which paper it refers and must be accompanied by a brief abstract. The same publication schedule as for regular articles is followed, and page proofs are sent to authors.*

Comment on "Excitation of Josephson plasma and vortex oscillation modes in $Bi_2Sr_2CaCu_2O_{8+\delta}$ in parallel magnetic fields"

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This Comment suggests a different interpretation for magnetoabsorption resonances in Bi compounds in magnetic fields very close to the ab plane observed by Matsuda *et al.* The observed resonances are related with the Josephson-vortex oscillating mode governed by weak pinning of pancakes, but not with the Josephson-plasma mode as was suggested by Matsuda *et al.* [S0163-1829(99)04846-8]

Matsuda *et al.*[1] observed the magnetoabsorption resonances in Bi compounds in magnetic fields very close to the ab plane. A linear dependence of the resonance magnetic field on the small angle ϑ between the field and the ab plane has been observed. The authors claimed that they observed Josephson-plasma resonances, but at the same time they compared their results with a theoretical formula which yields zero frequency in the limit of the parallel magnetic field ($\vartheta \rightarrow 0$). However, the plasma frequency cannot go to zero when it is extrapolated to a parallel field[2] (see also discussion in Refs. 3 and 4). In the present Comment I argue that the observed resonances may be interpreted as a pinned vortex mode and derive an expression for the resonance frequency which yields a linear ϑ dependence of the resonance field revealed in the experiment.

If the magnetic field is strictly parallel to the ab plane, it penetrates into the sample in the form of infinite Josephson vortices, but at any finite ϑ the vortex is a chain of pancakes connected with Josephson strings of finite length $L_J = s/\sin\vartheta$ where s is the period of the layered structure. The fact that the frequency goes to zero in the limit $\vartheta \rightarrow 0$ means that mostly pancakes, but not Josephson strings, are pinned. If pinning were very strong, the oscillating mode would be an oscillation of the Josephson string of length L_J with fixed ends. Then the string displacements are $u(x) \propto \cos kx$ where $k = \pi/L_J$ assuming that the axis x is parallel to vortices and the origin $x=0$ is in the middle of the Josephson string. Bearing in mind that the wave along the Josephson vortices in the limit of a high magnetic field is a usual transverse electromagnetic wave with spectrum $\omega = ck$, one obtains the frequency $\omega = \pi c/L_J \approx \pi\vartheta c/s$, which is huge for any reasonable ϑ. This means that pinning of pancakes is weak and the Josephson string oscillates in the potential well formed by pancake pinning without essential flexure. Then the oscillation with the resonance frequency $\omega_r = \sqrt{K/M_J}$ is governed by a harmonic-oscillator equation

$$M_J \ddot{u} + Ku = 0, \tag{1}$$

where u is the displacement and M_J is the mass of the Josephson string of length L_J, and K is the pining constant which characterizes the pinning force on the pancakes and therefore does not depend on the string length L_J.

The Josephson-vortex mass M_J of a string of length L_J is related to the electric energy. The electric energy per unit area of one layer is $\varepsilon V^2/8\pi s$, where ε is the high-frequency dielectric constant,

$$V = \frac{\hbar}{2e}\frac{\partial\varphi}{\partial t} = -\frac{\hbar}{2e} v_L \nabla\varphi \tag{2}$$

is the voltage, $\nabla\varphi = 2\pi s H/\Phi_0$ is the space gradient of the phase difference between superconducting CuO layers, H is the magnetic field, and $v_L = \dot{u}$ is the vortex velocity in the ab plane. Multiplying the electric-energy density $\varepsilon V^2/8\pi s$ by the area $L_J \times 2\pi/\nabla\varphi$ of the Josephson string, and assuming that the obtained energy corresponds to the kinetic energy $\frac{1}{2} M_J \dot{u}^2$ of the string, one obtains the Josephson-string mass

$$M_J = \frac{\varepsilon \Phi_0 H L_J}{4\pi c^2}. \tag{3}$$

Finally, the resonance frequency is given by

$$\omega_r^2 = \frac{K}{M_J} = \frac{4\pi c^2 K}{\varepsilon \Phi_0 H L_J} = \frac{4\pi c^2 K}{\varepsilon \Phi_0 H s}\theta. \tag{4}$$

The resonance frequency does not depend on Josephson coupling since neither mass nor pinning constant depends on it. Indeed, the mass is related to the electric energy determined by capacity of interlayer junctions. Also the Josephson coupling cannot essentially affect the pinning constant K because the latter is related to pinning of pancakes, but not of

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Josephson strings themselves. Pinning of pancakes is possible even if there is no Josephson coupling at all and layers are connected only magnetically as was discussed by Clem.[5] However, the Josephson coupling determines the Lorentz force driving Josephson strings. The driving force was omitted in our analysis since we looked for only the frequency of the resonance, but not its amplitude, and therefore considered free oscillations. But excitation of the vortex oscillation surely requires a finite Josephson coupling. We should note also that the term ''Josephson string'' is not exact in our limit: there are no isolated Josephson strings since they strongly overlap and the magnetic field is nearly homogeneous. In this case the term ''Josephson string'' refers to a single-quantum magnetic-flux tube related to one pancake vortex.

Equation (4) yields that $\omega_r^2 \propto \theta/H$ like the theoretical expression used in Ref. 1 [see Eq. (5) therein], but the other factors in the two expressions are different. According to our Eq. (4), the resonance frequency is governed by the pinning constant K. In contrast, according to Matsuda *et al.*, the resonance frequency depends on the anisotropy parameter determined by the interlayer Josephson coupling. Matsuda *et al.* borrowed their Eq. (5) from Bulaevskii and co-workers.[6,7] Bulaevskii *et al.*[6] calculated the spectrum of the sliding vortex mode and obtained a finite gap despite the vortex mode being a Goldstone mode which may not have a gap in absence of pinning. They claimed that this gap was the Josephson-plasma resonance frequency. Later they admitted that their original result was wrong [see the paragraph after Eq. (50) in Ref. 7]. Nevertheless, Bulaevskii *et al.*[7] believed that even though their derivation was incorrect, one may use their final formula after deleting its *main* term, but retaining the *small* correction term linear in ϑ. But such a procedure does not make their formula correct, as our analysis above has shown.

Thus the Josephson-plasma-mode interpretation of magnetoabsorption resonances in the parallel field in Ref. 1 is based on comparison with an incorrect expression, and, moreover, obtained for the vortex mode. I should stress that though in a magnetic field tilted to the c axis motions of charges and vortices are coupled, the plasma and the vortex modes remain to be clearly discernible collective modes, in contrast to the different claims on this issue.[1,7] The characteristic features of two modes are that for the plasma mode ω_r^2 is proportional to the *maximum* current j_0, which determines the Josephson supercurrent $j_0 \sin\varphi$ [see Eq. (5) below], whereas for the vortex mode ω_r^2 is proportional to the real *critical* current j_c governed by vortex pinning. In wide junctions usually j_0 essentially exceeds j_c. An attempt to explain the magnetoabsorption resonances in terms of the pinned vortex mode was done by Kopnin *et al.*[8] But it was done for perpendicular fields assuming that the mode is governed by surface pinning. Meanwhile later experiments showed that the resonance frequency did not depend on sample thickness, and this is an evidence in favor of bulk pinning. Also other features of the model by Kopnin *et al.*[8] require a modification in order to use it for interpretation of magnetoabsorption resonances in *perpendicular* fields. This will be done elsewhere. The present Comment addresses the vortex mode in high (about a few T) *parallel* fields governed by a bulk pinning force.

Now I shall discuss shortly recent experiments relevant to the problem of magnetoabsorption resonances in high perpendicular magnetic fields and in absence of a field.

Experiments on the c-axis critical current in a Bi compound by Yurgens *et al.*[9] have shown that magnetic-field dependence of the critical current is similar to that of ω_r^2($\omega_r^2 \propto 1/H$), and they considered it as a confirmation of the Josephson-plasma interpretation. In order to check it quantitatively, one should estimate the value of the maximum current density j_0 using the expression connecting it with the Josephson-plasma resonance frequency:

$$j_0 = \frac{\varepsilon \Phi_0}{8\pi^2 c s}\,\omega_{pl}^2 . \tag{5}$$

If ω_{pl} is the magnetoabsorption-resonance frequency ω_r, then for frequency 45 GHz, $\varepsilon = 20$ (this value was taken from Ref. 3), and $s = 16$ Å, the maximum current density must be $j_0 \approx 280$ A/cm^2. At $T = 25$K Matsuda *et al.*[10] observed the 45 GHz resonance for the resonance field $H \approx 1.25$ T. For these temperature and field in some samples Yurgens *et al.*[9] observed a critical current of about 0.06 mA (see Fig. 6 in their paper). For mesa area 20×30 μm^2 this corresponds to the current density not more than 10 A/cm^2. Thus Yurgens *et al.*[9] measured not the maximum current, but the critical current governed by vortex pinning, which is quite natural to expect for a wide Josephson junction. Therefore the proportionality of the measured c-axis critical current to ω_r^2 confirms not Josephson-plasma, but vortex-mode interpretation.

As was explained in Refs. 2 and 4, the main problem for Josephson-plasma interpretation in perpendicular fields was the observed strong dependence on the magnetic field: $\omega_r^2 \propto 1/H$. In order to explain this in terms of Josephson-plasma oscillation, one must assume that even in the vortex-solid state the vortex lines deviate from straight lines so strongly that the London region totally disappears: the whole bulk is occupied by extended ''vortex cores'' in which the interlayer Josephson coupling is essentially depressed. If this assumption is correct the London penetration depth for currents along the c axis must grow strongly with the magnetic field: $\lambda_c = c/\sqrt{\varepsilon}\omega_{pl} \propto \sqrt{H}$. This is not confirmed by recent measurements of the microwave losses for the c-axis currents at frequency 10 GHz.[11] The losses which should be proportional to the surface resistance $\sim \rho_{fl}/\lambda_c$ linearly grow with the magnetic field[12] as in conventional superconductors in which the penetration depth weakly depends on the magnetic field, and the flux-flow resistance ρ_{fl} is proportional to vortex density because vortex cores do not overlap for fields not close to H_{c2}. The surface resistance would grow much slower than linearly, or even would decrease, if the vortex cores essentially overlapped and λ_c were proportional to $\sqrt{H}$.

Kosugi *et al.*[13] observed an enhancement of the resonance field due to columnar defects and concluded that columnar defects tend to align pancake vortices so that the vortex line segments of length about 50 interlayer distances are confined inside columnar defects (according to Morozov *et al.*[14] this number is about 15). A simple geometric estimation shows that in this case the extended vortex cores must not occupy more than 1/50 (or 1/15) of the whole bulk, and, correspondingly, the relative difference between the observed and the zero-field Josephson-plasma frequency ∼200 GHz should be about 1/50 (or 1/15). Meanwhile, Kosugi *et al.* observed resonances with frequencies 30 and 45 GHz dependent on the magnetic field. This is also an argument against the Josephson-plasma interpretation of magnetoabsorption resonances in high perpendicular magnetic fields.

But recently Gaifullin, Matsuda, and Bulaevskii[3] reported observation of a *zero-field* resonance for a temperature very close to the critical point where the resonance frequency must be quite low. In this case the Josephson-plasma interpretation looks quite reasonable. However, it is not necessary that *all* observed magnetoabsorption resonances in *all* experimental conditions have the same physical origin. Up to now there is no evidence that the resonance observed in Ref. 3 for fields not more than 15 mT belongs to the same branch as resonances observed at fields about 1 T.

In summary, the interesting experiment by Matsuda *et al.*[1] yields an evidence that the magnetoabsorption resonances in Bi compounds in nearly parallel magnetic fields might be a vortex-oscillation mode governed by pinning. At the present moment there is no consistent interpretation of the parallel-field resonances in terms of the Josephson-plasma resonance. Recent experiments in high perpendicular magnetic fields also do not confirm this interpretation. Up to now only the zero-field resonance observed close to the critical temperature[3] may be consistently interpreted as the Josephson-plasma resonance. In total, further efforts in experiment and theory are necessary for a final judgment on the origin of observed resonances in various experimental conditions.

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