Motion of flux lines under an applied Lorentz force and rf penetration from ^{89}Y and ^{63}Cu NMR in $YBa_2Cu_3O_{7-\delta}$

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^{89}Y NMR spectra in $YBa_2Cu_3O_{7-\delta}$ (Y 1:2:3) demonstrate that an applied Lorentz force induces a narrowing of the line due to a decrease in the effective correlation time of flux-line (FL) motion. No effect is detected on the nuclear spin-lattice relaxation. The influence of the FL motion on the radio-frequency penetration has been investigated through the study of the amplitude of the ^{63}Cu NMR echo signal in magnetically aligned Y 1:2:3 powders.

One of the central issues in high-T_c superconductors (HTSC) is the study of the structure and of the motions of the flux-line lattice (FLL), in view of the technological applicabilities of these materials and for elucidating the microscopic phenomenology related to the superconducting state. Although some peculiarities of the magnetic field versus temperature phase diagram of the FLL in HTSC have been clarified, such as the presence of a large region where the FL motion is characterized by rather short correlation times τ_c (Ref. 1) ("liquid" phase), several aspects are still unsettled. For instance, it is not established whether or not the "solid" and "liquid" phases are separated by a real phase transition,[2] which is its driving mechanism, namely the occurrence of a crossover from a three-dimensional to a two-dimensional FLL (Ref. 3) or a melting when the average displacement of the FL from their equilibrium position is a given fraction of the lattice constant.[2] Studies of microscopic character, such as NMR, μ^+SR and neutron scattering are expected to yield enlightening insights on the motion of the FLL and recently, relevant information on the pinning energies and the correlation times have been derived.[4-9]

In this paper ^{89}Y and ^{63}Cu NMR measurements, carried out in $YBa_2Cu_3O_{6.94}$ (pressed powder pellet, $T_c = 90$ K, sample A) and in $YBa_2Cu_3O_{6.92}$ magnetically aligned powders ($T_c = 89$ K, sample B, the same as in Ref. 4), are reported. The aims of the work were to achieve information on the FL motion in the liquid phase and on the penetration of the radio-frequency (rf) field H_1 in the superconducting state. In the following it is shown how the Lorentz force associated with an electric current causes a narrowing of ^{89}Y NMR linewidth, while no effect is detected from nuclear spin-lattice relaxation measurements. Moreover, from the amplitude of the ^{63}Cu echo signal, the extent of the penetration of the radio-frequency field as a function of the temperature is derived. A discussion based on current theoretical models is given.

In order to study the effect of the Lorentz force on the ^{89}Y NMR line, a dc current was progressively injected in sample A, perpendicular to the external $H_0 \simeq 5.9$ T magnetic field, through two 0.1 cm^2 copper electrodes, up to 120 mA ($J \simeq 1.2 \times 10^4$ A/m^2). Correspondingly, the ^{89}Y NMR spectrum was recorded at constant temperature and constant current. For zero current, the value of the linewidth at low temperatures, $\Delta\nu = 18$ kHz, as well as its temperature behavior, were in good agreement with previous findings from NMR (see Refs. 4–8). In particular, in the liquid phase, for 65 K $< T < T_c$, the temperature dependence of $\Delta\nu(T)$ is well described in terms of a correlation time $\tau_{c0} \simeq 30$ μs (see Ref. 5 for a discussion on the temperature behavior of τ_c). When the current is applied, an extra narrowing of the ^{89}Y NMR line is detected (Fig. 1), indicating an increase of the characteristic frequencies involved in the FL motion.[10]

A simple description of the effect of the current can be given by considering that the effective correlation time for the drift against the Lorentz force τ_{c-} becomes longer than the one in the absence of the current (τ_{c0}), while the correspondent τ_{c+} for motions in favor of the Lorentz force becomes shorter. In this case, the hopping rate $f = \tau_c^{-1}$ probed by ^{89}Y nuclei can be written[11]

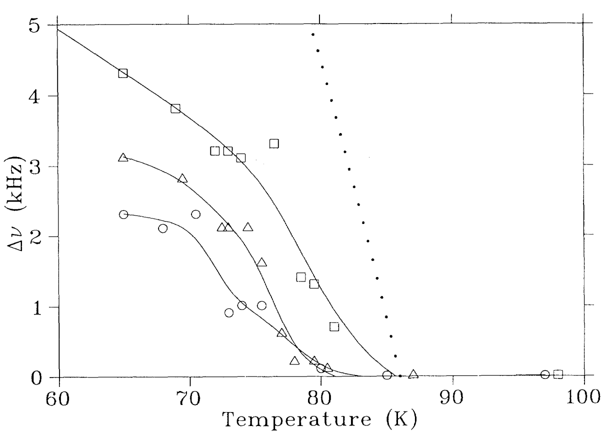

FIG. 1. ^{89}Y NMR linewidth $\Delta\nu$ vs T (the constant value $\Delta\nu_{T>T_c} = 1.1$ kHz has been subtracted) for currents $I = 0$ mA (squares), $I = 50$ mA (triangles), and $I = 100$ mA (circles). The dotted line is the behavior expected for the rigid FLL (Ref. 12). The solid lines are guides for the eye.

$$f=f_{+}+f_{-}=\frac{1}{2\tau_{c0}}(e^{\Delta U/kT}+e^{-\Delta U/kT})=f_0\cosh\left[\frac{\Delta U}{kT}\right], \quad (1)$$

where the energy contribution from the Lorentz force is $\Delta U=JH_0VL/c$, L being the characteristic hopping distance and V the volume of the FL bundle. Since in the temperature range of interest, τ_c is much smaller than the inverse of the rigid-lattice linewidth ($\Delta\nu_R(T)=18[1-(T/T_c)^4]$ kHz, see Ref. 12), the line can be approximated by a Lorentzian one[13] with a linewidth $\Delta\nu\simeq 2\tau_c\Delta\nu_R^2$. Thus, from Eq. (1) one can write

$$\frac{\Delta\nu_0}{\Delta\nu(I)}\simeq\frac{\tau_{c0}}{\tau_c(I)}\simeq\cosh\left[\frac{\Delta U}{kT}\right], \quad (2)$$

$\tau_c(I)$ being the effective correlation time in the presence of the current. In Fig. 2 the quantity $y=\tau_{c0}/\tau_c(I)$, derived for different currents at $T=73$ K, is compared with Eq. (2). A good agreement is observed and from the estimate of ΔU, which is of the order of the thermal energy kT, the quantity VL turns out to be 2.5×10^{-18} cm^4.

At low temperatures, the FL bundle is correlated over distances of the order of the FLL parameter, $a\simeq220$ Å.[14] When the temperature is increased toward T_c, the thermal fluctuations can overcome the pinning barriers, yielding much larger FL bundles,[14] whose average size, although restricted within the grain dimension, is of the order of the average London penetration depth. Therefore, one can conclude that the hopping distance L is of the order of magnitude of a, in agreement with recent findings on artificially built 2D systems (Nb films),[15] and certainly larger than a few fractions of the FLL parameter. Finally, it should be remarked that these relatively large displacements of huge FL bundles are introduced by relatively small currents. In the light of Eq. (2) the evaluation of the quantity VL was carried out at lower temperatures, where VL was found to decrease. For example, at $T=65$ K, one obtains $VL\simeq8\times10^{-19}$ cm^4.

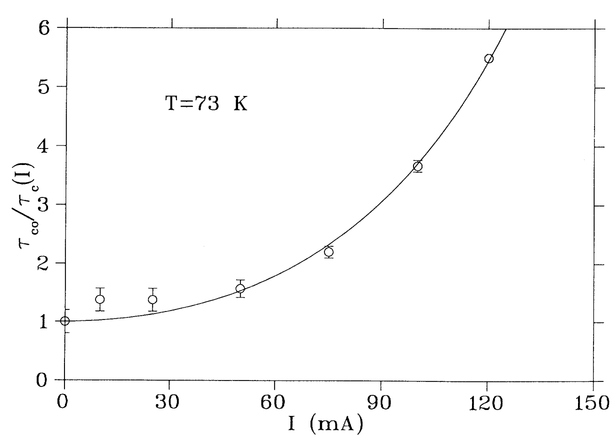

FIG. 2. Normalized characteristic correlation time of FL motion $\tau_{c0}/\tau_c(I)$ as a function of the applied dc current I, at $T=73$ K. The solid line is the best fit according to Eq. (2).

One could argue that the decrease in the effective correlation time due to the electric current, evidenced in narrowing of the ^{89}Y NMR line, could induce an extra contribution to the spin-lattice relaxation. No effect on the ^{89}Y relaxation time T_1 was observed, within experimental error (less than $\pm10\%$), at $T=65$ and 73 K, for $I=80$ mA. The lack of sizable effect on the relaxation can be qualitatively justified through an order of magnitude estimate, by taking into account the occurrence of a slow motion regime, namely $\bar{\tau}_c(I)\omega_L\gg1$, where $\bar{\tau}_c=\tau_c/2\pi$. Under this condition, the relaxation rate induced by the FL motion can be written

$$2W\simeq\frac{\gamma_{89}^2\langle\Delta B^2\rangle}{4}\left[\frac{1}{\omega_L^2\bar{\tau}_c}\right], \quad (3)$$

where $\langle\Delta B^2\rangle$ is the mean-square amplitude of the fluctuating field components perpendicular to the average direction of the applied field (at most, of the order of the rigid-lattice second moment). From Eq. (3), by using $\tau_c=10$ μs, $\omega_L=7.7\times10^7$ rad/s and $\langle\Delta B^2\rangle=100$ G^2, one has $2W\simeq10^{-4}$s^{-1}, a factor 100 times smaller than the experimental relaxation rate due to the usual electron nucleus interactions.[16]

In order to discuss under which conditions the FL motion may lead to a sizable relaxation process, it is useful to derive a more quantitative expression for W in terms of experimental variables, such as the strength of the magnetic field, and the characteristic parameters of the FLL. The contribution to the relaxation process can be obtained by integrating over the wave vector $\mathbf{q}$ the dynamical structure factor $T(\mathbf{q},\omega)$ describing the transverse fluctuations of the FL.[17] One has

$$W=\left[\frac{\gamma_{89}}{2}\right]^2\frac{V}{8\pi^3}\int_0^{q_m}T(\mathbf{q},\omega_L)d\mathbf{q}, \quad (4)$$

where for $T(\mathbf{q},\omega)$ one can use

$$T(\mathbf{q},\omega_L)\simeq\frac{kTH_0^2}{\pi Vc_{44}(\mathbf{q})}\frac{\omega_\tau(\mathbf{q})}{\omega_L^2+\omega_\tau^2(\mathbf{q})}, \quad (5)$$

as derived in a hydrodynamical approach[18] with $c_{44}(\mathbf{q})$ the tilt modulus,[19] and with a dispersion relation for the transverse fluctuations of the FL[2,18] of the form

$$\omega_\tau(\mathbf{q})\simeq\frac{c_{44}(\mathbf{q})q^2}{\gamma}, \quad (6)$$

where γ is a coefficient which accounts for the friction between the FL and the pinning centers[18] which can be estimated around $\gamma_0\simeq10^{11}$ G^{2}s/cm^2. From Eqs. (4)–(6), the contribution of FL motion to the relaxation process can be derived in terms of the magnetic field H_0 and of the isotropic cutoff wave vector q_m. In Fig. 3, the values of $2W$ are reported as a function of q_m for three different magnetic fields. The increase of $2W$ with q_m reflects the decrease of the tilt modulus and the approach of $\omega_\tau(q_m)$ toward ω_L. One notices that for $H_0=6$ T, the contribution to W is consistent with the experimental result only when $q_m<2.1\times10^5$ cm$^{-1}\simeq\pi/\lambda_{ab}$, λ_{ab} being the London

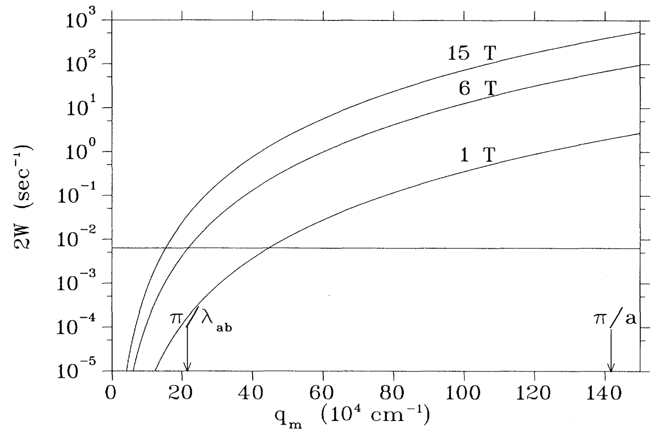

FIG. 3. Contribution of FL motion to the relaxation rate as a function of the cutoff wave vector q_m, at $T=65$ K, for $H_0=1$, 6, and 15 T. The solid horizontal line shows the experimental value of the relaxation rate at the same temperature.

penetration depth for $\mathbf{H}_0 \| \mathbf{c}$. Moreover, from the narrowing of the ^{89}Y NMR line, the q integrated effective frequency $\langle \omega_\tau \rangle_q \simeq \bar{\tau}_c^{-1}$ can be estimated to be around 10^6 rad/s. According to Eq. (6) this corresponds to $q_m \simeq \pi/\lambda_c$, $\lambda_c \simeq 7500$ Å being the London penetration depth for $\mathbf{H}_0 \perp \mathbf{c}$. From these observations one could conclude that if a hydrodynamical description of the FLL[18] is valid, in order to account for the NMR findings, the cutoff wave vector has to be $q_m \simeq \pi/\lambda_c$. The conclusion that only the modes at $q \rightarrow 0$ appear to be involved in the FL motion is supported by the observation[20] that the characteristic correlation time derived by a macroscopic probe of the ac susceptibility[21] is similar to the one derived by a microscopic probe of the muon in a μ^+SR experiment (see Ref. 9).

In Fig. 3, one can observe that an increase of the magnetic field from 6 to 15 T increases the contribution of FL motion to the relaxation process by almost one order of magnitude (for $q_m \simeq \pi/\lambda_c$), giving rise to a sizable enhancement of the relaxation rate. Thus, NMR experiments at high magnetic fields should yield quantitative information in this respect.

In the following, I report a simple experimental method, based on the ^{63}Cu(2) NMR echo signal, which allows one to extract another important parameter related to the FL motion, namely the penetration of the rf field in the sample. ^{63}Cu(2) NMR echo signals were detected on the magnetically oriented sample B, with $\mathbf{H}_0 \| \mathbf{c}$, by irradiating the central $1/2 \rightarrow -1/2$ line ($\Delta\nu^{63} \simeq 300$ kHz). Above T_c, the standard $(\pi/2)_x - \tau - (\pi/2)_y$ pulse sequence yields a measure of the full nuclear magnetization M_0 by plotting the echo amplitude $M(\tau)$ vs τ and extrapolating at $\tau \rightarrow 0$. On the contrary, below T_c the limit $M(\tau)$ for $\tau \rightarrow 0$ does not give the full magnetization. In fact, for the nuclei at a distance r from the surface of the grain, the strength of the rf field H_1 is reduced and the actual pulse sequence should be written as $\theta(r)_x - \tau - \theta(r)_y$, with $\theta(r) = \frac{1}{2}\pi |\mathbf{H}_1(r)/\mathbf{H}_{10}|$, with a reduction in both the tipping angle and the irradiated bandwidth. The law describing the decrease of the nuclear magnetization for partial irradiation depends on the line shape, the spread of the magnetization during the pulse, and the related phase shifts. Although simplified expressions, pertaining to situations where a precise offset of the resonance is known, are reported in the literature,[22] it was preferred to derive the real dependence of M on θ experimentally, by detecting the amplitude of the signal as a function of H_1 above T_c, where the whole grain is irradiated by the rf field. The decrease of $M(\theta)$ was well fitted by the $M(\theta) = M_0 \sin^3\theta$ law, which has been used below T_c to study the rf penetration. From the decrease of the amplitude for $\tau \rightarrow 0$ below T_c, after the correction due to the effect of the temperature on the population difference, one can extract information on the decrease of the rf in the superconducting phase (see Fig. 4).

In the framework of the London approximation it is possible to solve exactly the problem of the rf penetration for particular sample geometries, and to describe the penetration depth in terms of characteristic parameters of the FLL, such as the elastic modulus k_p of the restoring pinning force (see Ref. 23). However, since the solutions for the rf field are determined by the boundary conditions, the calculations for finite-size sample geometries, as a grain, are extremely complicated. Therefore, in order to analyze the data and to extract at least qualitative information on the physics involved, the crude approximation of adopting the solution for an infinite slab of thickness w, $H_1(x) = H_{10}\cosh(x/\lambda_{rf})/\cosh(w/2\lambda_{rf})$, was done. Then, the corresponding decrease of the recovered nuclear magnetization is

$$M(x) = M_0 \sin^3[\tfrac{1}{2}\pi \cosh(x/\lambda_{rf})/\cosh(w/2\lambda_{rf})] .$$

Since $\mathbf{H}_1 \perp \mathbf{H}_0$, the penetration depth of the rf field is $\lambda_{rf} \simeq (\lambda_{ab}^2 + \lambda_C^2 \cos^2\alpha)^{1/2}$ (Ref. 23), with $\lambda_C = B\Phi_0/k_p\mu_0$ and α the angle between $\mathbf{H}_0$ and the normal to the slab. In particular, when both $\mathbf{H}_0$ and $\mathbf{H}_1$ are parallel to the

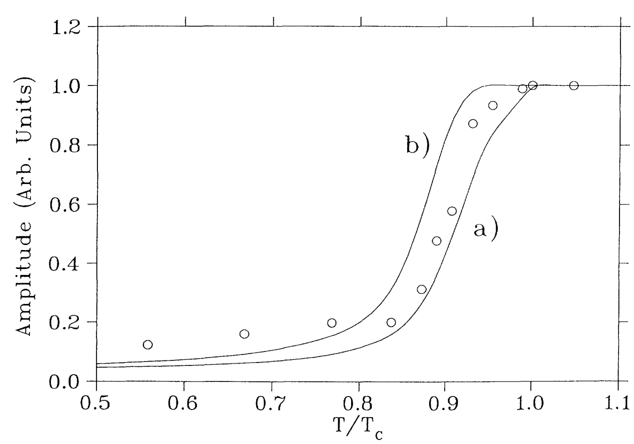

FIG. 4. Temperature dependence of the normalized nuclear magnetization below T_c compared to the theoretical behavior expected for a slab geometry: (a) with $\lambda_{rf} \simeq (\lambda_{ab}^2 + \lambda_C^2 \cos^2\alpha)^{1/2}$ and (b) with $\lambda_{rf} \simeq (\lambda_{ab}^2 + \lambda_C^2)^{1/2}$ (see text).

slab ($\lambda_{rf}=\lambda_{ab}$), for this orientation the induced ac currents are parallel to the FL and no force is applied on them.[2,23] The value of k_p for $T\rightarrow 0$ can be estimated from the pinning energy $U=500$ K (Ref. 4) and from the FL hopping distance $L\simeq a$, being $k_{p_0}\simeq 2\pi^2 U/La^2\simeq 10^6$ N/m^2. Since $\lambda_{ab}\simeq 1500/(1-t^4)^{1/2}$ Å (Ref. 4) and $k_p=k_{p_0}(1-t^2)^2$ (Ref. 24) ($t=T/T_c$), it is possible, after integrating over x and α, to extract the temperature dependence of the recovered nuclear magnetization. Line (a) in Fig. 4 shows the derived temperature dependence for a slab thickness $w=5$ μm. Although a satisfactory agreement is observed, it should be remarked that line (a) is below the experimental data (the offset at low T reflects only the finite size of the grains). This fact probably arises from the impossibility in practice of having a zero-induced Lorentz force, due to the irregularly shaped grains and the bending motion of FL. Line (b) shows the temperature behavior of the nuclear magnetization for $\lambda_{rf}\simeq(\lambda_{ab}^2+\lambda_C^2)^{1/2}$, i.e., maximum penetration depth for any orientation. It therefore represents an upper limit for the recovered nuclear magnetization. The fact that the experimental data are between lines (a) and (b) indicates that the previous estimates of U (Ref. 4) and L (this work) through NMR are of the correct order of magnitude.

In conclusion, in this report a clear effect of the Lorentz force on FL motion has been evidenced through a microscopic technique. It appears that even a small dc current can induce displacements of large FL bundles in the liquid phase. No effect of FL motion on ^{89}Y nuclear spin-lattice relaxation was detected between 65 K and T_c, in agreement with the estimate of the effective correlation time for FL motion. On the basis of a simple picture based on a hydrodynamical description, it appears that only the branch of modes in the range $0<q\leq\pi/\lambda_c$ is effective regarding NMR quantities. Finally, a qualitative agreement between the decrease of the nuclear magnetization below T_c and the predictions from the London approximation for the penetration depth is pointed out.

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