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Acoustic Studies of High Temperature Superconductors

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Abstract. Acoustic studies of superconductors have a long tradition. The most notable of such studies was the early experimental confirmation of the temperature dependent ultrasonic attenuation in superconductors, predicted by the Bardeen, Cooper and Schrieffer (BCS) theory. This confirmation placed ultrasonics in the forefront of methods used for various features of superconductors. Among those, in particular, were measurements of the superconducting energy gap and of its anisotropy. Accordingly, the advent, three decades later, of high temperature superconductivity brought about a flurry of activity in acoustic measurements of this new state of solids. These studies include frequencies from less than 1 Hz to the GHz range, thus covering a much broader range than what is traditionally referred to as ultrasonics. In this paper a very brief review of the background is followed by a discussion of the highlights of low and high frequency stress wave propagation studies on high temperature superconductors. Emphasis is given to investigations of the dynamics of superconducting vortex line lattices.

1. INTRODUCTION

The use of stress waves as a means to study the superconducting state of matter has a long and distinguished history. Even before the advent of the Bardeen, Cooper and Schrieffer (BCS)¹ theory of superconductivity in 1957, experiments by Bömmel² on lead and by Mackinnon³ on tin first established that the ultrasonic attenuation decreases rapidly as a function of decreasing temperature, when a metal becomes superconducting.

In a normal metal, or in a superconductor above the transition temperature, T_c , the ultrasonic attenuation, α_n , due to conduction electrons, has the form

$$\alpha = K \frac{N m v_F \nu^2}{\rho v^3} l_e \quad (1)$$

or equivalently

$$\alpha = K \frac{N m v_F \nu}{\rho v^2} q l_e \quad (2)$$

where K is a numerical constant that depends on the polarization (longitudinal or transverse) of the waves, m is the electron mass, N is the density of electrons, v_F is the Fermi velocity, ν is the sound frequency, q is the wave vector of the sound, l_e is the electron mean free path, v is the sound velocity and ρ is the mass density (this expression is valid for $q l_e < 1$).

Below T_c the BCS theory predicted that as a consequence of the opening of a superconducting energy gap, $\Delta(T)$, and the change of normal electrons into pairs, the ultrasonic attenuation, α_s , (for $h\nu \ll \Delta$, where h is Planck's constant) is related to α_n as follows

$$\frac{\alpha_s}{\alpha_n} = \frac{2}{\exp[\Delta(T)/k_B T] + 1} \quad (3)$$

Here k_B is Boltzmann's constant, T is the absolute temperature and $\Delta(T)$ is the temperature dependent superconducting energy gap. Thus, the ratio α_s/α_n is given by twice the Fermi function of $\Delta(T)$. This prediction was confirmed experimentally⁴ very shortly after the BCS theory appeared and was subsequently followed by a study of the energy gap anisotropy⁵. These and related studies established ultrasonics as an important and powerful method for investigating various features of superconductors. Among the ultrasonic studies that followed these early successes, it is useful to distinguish several categories. One of these categories addressed measurements of sound velocity and thus elastic constants, while another was concerned with attenuation. Since the elastic constants and wave velocities are directly related to the second derivatives of the Gibbs free energy with respect to strain, such measurements constitute an important probe of phase transitions. In the case of the superconducting transition these measured quantities provide a direct check on the theoretical predictions.

Attenuation studies are themselves divided into two main groups: 1) Measurements of the energy gap (and thus of the order parameter), which apply, in principle, to all superconductors; 2) Measurements of the mixed state of type-II superconductors aimed at an understanding of the properties of flux lines (vortices) and of the lattices that they form.

In this brief review it is obviously impossible to cover the hundreds of publications on acoustic studies of high temperature superconductors (HTCS) which appeared in the last ten years. While it is difficult to choose a subset of the most representative papers, a decision had to be made and here a small number of publications were selected in an attempt to illustrate some of the highlights. Hopefully, this review will encourage interested reader to search the literature for the many other important contributions to this field.

2. GENERAL BACKGROUND

With reference to Eq. 3, measurements of α_n and α_s provide a means to determine the energy gap $\Delta(T)$. While Eq. 3 assumes implicitly an isotropic gap, measurements along different crystallographic directions in single crystals allow one to determine anisotropies of $\Delta(T)$ when present⁵.

Some of the earliest acoustic studies of HTCS consisted of attempts to reproduce the type of results concerning the energy gap obtained on the low T_c superconductors. These attempts, however, were not successful, because in this case the use of Eq. 3 has proven ineffective. This can be readily appreciated by considering some quantitative implications. Indeed, looking at Eqs. 1 and 2 it is noted that the attenuation is proportional to the electron density, N , which is typically two orders of magnitude smaller in HTCS than in common metals. This results in a corresponding reduction of α_n and the total change in attenuation below the superconducting transition is generally smaller than available experimental resolutions. In addition, when $T_c > 40\text{K}$ and in many of the most interesting HTCS cases $T_c \sim 100\text{K}$, the contributions of phonon-phonon interactions to the attenuation become quite significant. This, together with all the other attenuation sources, such as crystal defects, make it very difficult to separate the very small electronic contribution from the other mechanisms. Thus, not surprisingly, to-date there appear to have been no reliable, direct ultrasonic measurements of $\Delta(T)$ in HTCS, on the basis of Eq. 3.

In general, therefore, the bulk of ultrasonic studies of HTCS was focussed on some early observations of relaxation peaks and subsequently on the static and dynamic properties of the flux line lattice

(FLL) in the presence of a magnetic field. In this context, to discuss further ultrasonic studies of HTCS, it is useful to recapitulate very briefly the effects of a magnetic field on the superconducting state. In particular, it is noted that superconductors are divided into two groups, namely type I and type II, according to their response to a magnetic field. Type I superconductors are characterized by the expulsion of the magnetic field and by full diamagnetic behavior for all field values below H_c , at which the solid reverts to the normal state (the Meissner effect). H_c is a thermodynamic critical field at which the solid undergoes a first order phase transition. Type II superconductors remain diamagnetic up to a lower critical field H_{c1} , analogously to type I. For field values in excess of H_{c1} , magnetization penetrates the solid in the form of quantized flux lines. Each such line carries a flux $\phi_0 = hc/2e$, where h is Planck's constant, c is the speed of light and e is the electron charge. The total number of flux lines is equal to the total magnetization divided by ϕ_0 , i.e., the number is proportional to the applied field in excess of H_{c1} . This process is completed at a field value H_{c2} , where the entire solid becomes normal. The superconducting phase in the range between H_{c1} and H_{c2} is called the mixed state. The criterion of whether a superconductor is type I or II is provided by the value of the Ginzburg-Landau parameter $\kappa = \frac{1}{\sqrt{2}} \frac{\lambda_L}{\xi_0}$ where $\lambda_L = (mc^2/4\pi ne^2)^{1/2}$ is the London penetration depth (m is the mass of the electron, n is the density of superconducting electron pairs and the other symbols were defined above) and the coherence length $\xi_0 = 2\hbar v_F/\pi\Delta(0)$. Superconductors whose $\kappa < \frac{1}{\sqrt{2}}$ are type I, while those with $\kappa > \frac{1}{\sqrt{2}}$ are type II. All known high temperature superconductors (i.e., superconductors with transition temperatures in excess of about 40K) are type II. All subsequent discussions here of the behavior of superconductors in the presence of a magnetic field involve, therefore, the mixed state containing flux lines.

3. MATERIALS

Known high temperature superconductors are multicomponent oxides with a superconducting transition temperature, T_c , in excess of about 40K. Some of the best known and most extensively studied among these compounds are: $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4-y}$ ($T_c \sim 40\text{K}$), $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ ($T_c \sim 90\text{K}$) and $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_6$ ($T_c \sim 100\text{K}$).

It is well established that in these compounds electrons form Cooper pairs, in analogy with "conventional," low temperature superconductors. There is no general agreement, however, regarding the mechanism responsible for this pairing in HTCS. In particular, it appears that in this case the electron pairing is most likely mediated by elementary excitations other than phonons, which constitute the "glue" in conventional superconductors.

Among the special features, as well as sources of difficulties in characterizing HTCS is the extreme sensitivity of their superconducting properties to the details of composition and particularly their oxygen content. Coupled with the fact that the superconducting coherence length is very short ($\sim 10\text{\AA}$) in these materials, sample inhomogeneity is a source of serious concern. These issues have rendered comparisons of experimental results obtained in different laboratories very difficult, even when nominally the same types of samples were used.

Structurally, the HTCS compounds are usually orthorhombic, with very small differences in length of the a and b axes, and large c/a ratios. They are characterized by quasi two-dimensional copper-oxygen planar elements resulting in elastic and other anisotropies for the in-plane and normal to the plane properties. The structural and compositional complexities mentioned constitute a great challenge in studying these at once scientifically fascinating and technologically very promising materials.

The earliest acoustic studies of HTCS were conducted on sintered ("ceramic") samples, which were the only ones available in the initial stages of the field. These samples consisted typically of randomly oriented crystallites $1-3\ \mu\text{m}$ in diameter. For wavelengths significantly in excess of these dimensions (i.e. frequencies below $\sim 10^8\ \text{Hz}$) the medium could be considered isotropic. Within these parameters, both wave velocity and attenuation were measured on several compounds and provided the first

information on elastic properties and on some damping mechanisms of these materials. This approach obviously made it impossible to obtain information about anisotropy. Early attempts to remedy this situation consisted in preparing so-called sinter-forged samples that develop strong preferred orientations of the grains. Generally, a uniaxial symmetry is thus developed with the *c*-axes of the crystallites well aligned and the *a*–*b* axes randomly rotated. This method yielded partial information on anisotropies.

As sample preparation and especially crystal growth methods evolved to the point that single crystals of various HTCS compounds became available, many of the basic studies shifted to this type of specimens. Before long various anisotropies in sound velocity and in damping were found and documented, opening the way to new interpretations. Throughout this period and in most cases to this day, however, the dimensions of these single crystals remain quite small, sample thickness seldom exceeding $\sim 10^{-1}$ cm and often remaining well below this value. This feature severely restricted the use of conventional ultrasonic methods in the low MHz frequency range. It was possible, however, to use very short duration (~ 10 nanoseconds) pulses, at frequencies in the GHz region, to measure velocity and attenuation on very small samples. At the same time many important studies were carried out using vibrating reed (frequencies $\sim 10^3$ Hz) or even torsion pendulum (frequencies $\sim 10^{-1}$ Hz) methods. Another complication appeared when it was realized that most single crystal samples were extensively twinned. This feature, perhaps as much as any other, except for variations in oxygen content, appears to be responsible for frequent and sometimes large discrepancies in experimental results obtained, in earlier times, by various researchers using single crystals with different twin contents. With increasing awareness of the above issues, discrepancies attributable to them have become rare.

While the availability of single crystals of many HTCS compounds opened the way to basic studies for which such samples are essential, many fundamental as well as technologically important properties were and continue to be investigated on sintered samples and polycrystalline thin films.

4. EXAMPLES OF VELOCITY MEASUREMENTS

Among the early ultrasonic velocity measurements at GHz frequency, one notes the work of Golding et al.⁶, carried out on a single crystal of $\text{YBa}_2\text{Cu}_3\text{O}_7$ with $T_c \sim 87.3\text{K}$ and having dimensions $0.36 \times 0.27 \times 0.222 \text{ mm}^3$. ZnO films sputtered on two adjacent faces of the crystal (one face perpendicular to the *c*-axis and another to the *ab* plane) served as transducers. A pulse-echo method was used with pulse durations limited by the small dimensions of the sample to about 20 nsec. The temperature interval covered was 0.01 K to 300 K.

In this study a small discontinuity in the sound velocity was observed at T_c for propagation parallel and perpendicular to the *c*-axis. To analyze further these results, the authors used the expression:

$$\Delta v_i/v_i = \frac{1}{2} \frac{\Delta C_p T_c}{c_{ij}} A_i^2$$

where $A \equiv (1/T_c)(dT_c/d\varepsilon_{ij})$, $\Delta C_p = C_p(T_c^+) - C_p(T_c^-)$, C_p is the specific heat at constant pressure, c_{ij} is the relevant elastic constant and $dT_c/d\varepsilon_{ij}$ is the strain derivative of T_c . Using their measured values of $\Delta v_c/v_c = 30 \times 10^{-6}$ and $\Delta v_{ab}/v_{ab} = 30 \times 10^{-6}$, together with a published value of $\Delta C_p = 50 \text{ mJ/g/K}^2$, the authors obtained $|A_c| = 1.41$ and $|A_{ab}| = 1.79$. In addition, the authors determined the sound velocity of longitudinal waves at 80 K. For the propagation parallel and perpendicular to the *c*-axis they obtained, respectively, the values $5.4 \times 10^5 \text{ cm/s}$ and $6.1 \times 10^5 \text{ cm/s}$. With the use of the x-ray density $\rho = 6.35 \text{ g/cm}^3$, the pseudo-tetragonal (i.e. assuming that the *a* and *b* axes are equal) elastic moduli $C_{33} = 1.45 \times 10^{12} \text{ dynes/cm}^2$ and $C_{11} = 2.34 \times 10^{12} \text{ dynes/cm}^2$ were obtained. It is noted that because of extensive microtwinning of the sample it was not possible to obtain separate values of velocity along the *a* and *b* directions. In these experiments the authors

noted that the velocity jump for propagation in a direction perpendicular to the c -axis (i.e. in the ab plane) is much broader than for propagation along the c -axis. This is attributable to inhomogeneity in oxygen content, which is the most likely source of a distribution of T_c values, i.e. of the transition broadening. Since oxygen diffuses at different rates along the c and ab axes, different degrees of inhomogeneity in composition may be encountered by waves propagating along the two directions. Another interesting feature reported in this work is the observation of a positive slope of the velocity as a function of temperature, below about 3 K. In this region the velocity was found to vary as $\ln T$, which is typical of solids containing two-level tunneling systems (TLS). In the case of HTCS these systems are usually thought to consist of motions of oxygen atoms. The tunneling density of states of TLS found in this single crystal is somewhat smaller than in ceramic samples. Nonetheless, this observation suggests that the tunneling systems are an intrinsic feature of $\text{YBa}_2\text{Cu}_3\text{O}_7$ and not a phenomenon associated with intergranular interfaces.

Other measurements of the discontinuity in the sound velocity for propagation along the c -axis have been subsequently reported by several research groups. Measurements at 15 MHz were carried out by Saint-Paul et al.,⁷ for a crystal of $\text{YBa}_2\text{Cu}_3\text{O}_7$ with T_c of 89 K. A discontinuity, $\Delta v/v$, for this mode, of 50×10^{-6} was observed. Measurements by Kim et al.⁸ at 53 MHz for c -axis propagation and at 9 MHz for propagation in the ab -plane have been reported. In both directions the discontinuities appear to be less than 50×10^{-6} , and the uncertainty in the results is appreciable.

In a different context, velocity measurements were carried out by McKenna et al.⁹ on sintered (ceramic) samples of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, in the temperature range 0.25 K to 3 K, at frequencies of 5, 10, 20 and 25 MHz. Samples with two values of δ , namely 0.03 and 0.15, having T_c values of 90 K and 82 K respectively, were used. The purpose of these measurements was to gain information on the interactions of TLS, with electrons and with phonons in HTCS at low temperatures, for $T \ll T_c$. Such information is important for determining the characteristics of the energy gap and thereby distinguishing among different classes of mechanisms responsible for the superconducting transition.

The model of TLS that accounts well for their behavior in glasses and disordered solids^{10,11} predicts that $\Delta v/v$ as a function of temperature has the form

$$\Delta v/v = P \ln(T/T_0). \quad (4)$$

Here P is a parameter that depends on the density of states of the TLS, on the coupling parameter between phonons or electrons and TLS, and on the mass density and sound velocity of the material. T_0 is an arbitrary reference temperature. At very low temperature, in materials that contain TLS $\Delta v/v$ initially rises with increasing temperature according to Eq. 4, goes through a maximum, and then decreases with increasing temperature. This behavior constitutes a characteristic "signature" of TLS.

The model enables one to determine the dominant relaxation mechanism for the TLS from the temperature dependence of the maximum in $\Delta v/v$, as a function of ultrasonic frequency^{9,11}. An analysis of relaxation times for various mechanisms shows that the temperature of the maximum, T_m , varies with frequency as $T \propto \omega^{1/3}$ for TLS interactions with phonons and as $T_m \propto \omega^0$ (frequency independent) for interaction with electrons. The former is characteristic of dielectric glasses and of disordered, conventional superconductors for $T \ll T_c$, while the latter is a feature of metals, or more generally, of solids containing an appreciable density of conduction electrons.

The measurements discussed here consisted of determining the dependence of T_m in the HTCS samples described above, as a function of frequency, from 5 to 25 MHz. The results showed clearly the $T_m \propto \omega^0$ behavior. Since T_m was in the range 0.5 K to 1 K, i.e. $T/T_c \sim 10^{-2}$, the condition $T \ll T_c$ was amply satisfied. Consequently, if the samples were conventional superconductors one would expect essentially all unpaired electrons to be frozen out and the TLS relaxation to be due to

phonons, with $T_m \propto \omega^{1/3}$. The fact that the experiments yielded $T_m \propto \omega^0$ clearly showed that in HTCS an appreciable concentration of unpaired electrons remains even for $T \ll T_c$. This, in turn, indicated that theoretical models of HTCS should be restricted to those providing for the presence of unpaired electrons at $T \ll T_c$.

5. ATTENUATION MEASUREMENTS

Numerous reports have appeared on ultrasonic attenuation measurements in HTCS, above and below T_c . Generally, the results below T_c are either featureless, or show what appears to be a relaxation peak. In some cases such peaks were observed to shift to higher temperatures as the frequency of the waves increased, confirming qualitatively the relaxation nature of the process involved. In many instances it was found that the peaks are not directly related to the superconducting state. This was evidenced in several ways. For example: (1) the peaks shifted to temperatures above T_c for sufficiently large frequency increases; (2) the peaks persisted at approximately the same temperature when the composition of the material was changed beyond the range of occurrence of superconductivity.

As mentioned earlier, there appear to be no direct measurements of attenuation changes that would yield the value of the energy gap, $\Delta(T)$, on the basis of Eq. 3.

An indirect approach to extract $\Delta(T)$ from attenuation and velocity measurements on melt-textured samples of the high HTCS $\text{YBa}_2\text{Cu}_3\text{O}_7$ was reported by Levy et al¹². (Although this study was done in the mixed state, and thus should appear in the next section, it is included here to maintain continuity in the discussion of searches for $\Delta(T)$.) These measurements were carried out near the lower critical field H_{c1} . The magnitude of the velocity change was assumed to be proportional to the repulsive force between vortex lines. The changes in attenuation at H_{c1} per unit vortex line were attributed to a relaxation process involving the motion of the vortex lines, whose cores "capture" superconducting pairs, while simultaneously leaving behind normal electrons, as they move back and forth. A model was presented which assumed that the relaxation time of the quasiparticles is controlled by electron-phonon interactions involving shear thermal phonons. A BCS relation was used for the collision drag portion of the electron-phonon interaction. An attempt was then made to extract the temperature dependence of the superconducting energy gap $\Delta(T)$ from this relation. While the results yield the value $\Delta(0) = 1.76 k_B T_c$, which is consistent with the predictions of the BCS theory, the procedure is indirect and involves several assumptions that remain to be proven.

6. STUDIES OF THE MIXED STATE

Type-II superconductors in the mixed or vortex state (the terms "vortex" and "flux line" are used interchangeably), i.e. in the presence of magnetic fields in excess of H_{c1} , display energy dissipation whenever a force (electrical or mechanical) causes a displacement of vortex lines. This dissipation is, naturally, of great technological and scientific interest; the former primarily because it limits the current carrying capacity of such superconductors, and the latter because many features of interaction mechanisms, pinning of vortices and the nature of the various FLL states are not completely clear and current views are sometimes controversial. In fact, the static and dynamic properties of the FLL display a rich and varied behavior and many of its aspects lend themselves particularly well to studies by acoustic means. More common approaches to such studies use a Lorentz force in resistive measurements in a magnetic field, which show the familiar broadening of the superconducting transition, frequency dependence of the a-c susceptibility and magnetic relaxation. As a brief reminder, it is noted that a flux line or vortex "line" extends radially from its axis over a distance of the order of the London penetration depth λ and that its core radius, r_0 , is of the order ξ_0 , the correlation length. In "conventional" (low T_c) type-II superconductors the Ginzburg-Landau parameter, $\kappa_s = \lambda/\xi$, is $1 < \kappa \leq 10$ and the transition temperature $T_c \lesssim 20\text{K}$. For HTCS (all known examples of which are type-II), $\lambda \gg \xi$, $\kappa \sim 100$ and $T_c \sim 100\text{K}$. So, while the basic rules of FLL

formation are about the same in low T_c and HTCS, the dynamical properties turn out to be quite different. As mentioned previously, the application of an electrical or mechanical force to the flux lines results in dissipative displacements, unless this motion can be prevented by pinning or blocking. In conventional superconductors such pinning is accomplished quite successfully by various materials preparation techniques that introduce appropriate defects and/or inhomogeneities. In HTCS, the situation could be thought of as analogous, except for two basic issues. (1) the ratio of binding energy U between a flux line and a pinning defect, to the thermal energy $k_B T$ is $U/(k_B T_c) \sim 100$ for low T_c , and $U/(k_B T_c) \sim 10$ or even less for HTCS. (2) For a binding potential to be fully effective, one needs to have pinning inhomogeneities in the properties of the medium that are of a spatial extent comparable to the core radius, i.e., of the order of ξ . Now, $\xi_{Low T_c} \gg \xi_{High T_c}$ and for high T_c , $\xi \sim 10^{-7}$ cm. It is obvious from points (1) and (2) that thermal fluctuations can help "dislodge" a flux line much more easily in high T_c than in low T_c superconductors. It follows that the dynamical behavior of FLL in HTCS is different from that in low T_c cases. In particular, at the higher temperatures and small ξ , large random displacements of the flux lines can occur which result in considerable disordering. Various conjectures and models have thus been proposed for the state of FLL in HTCS. Among these models one finds "melting", vortex glass, and vortex entanglement, all of which are characterized by the absence of long range order.

Here attention is directed to the study of FLL dynamics in HTCS by measurements of mechanical wave propagation. The experimental studies in this area (see, for example, Ref. 14 and 21-26) carried out to date fall into two categories: low frequencies, ν , in the range $10^{-1} \lesssim \nu \lesssim 10^3$ Hz, and high frequencies $\nu > 10^6$ Hz. The coupling of elastic waves to FLL occurs, in general, by pinning due to elastic anisotropies of both the crystal lattice and the FLL. Thus, elastic waves in the solid cause displacements of the FLL relative to the crystal lattice. The FLL displacements, in general, are not exactly in phase with the crystal strains, and both attenuation and wave velocity changes occur due to the presence of the FLL.

The use of acoustic wave propagation, and in particular of ultrasonic methods, offers very important advantages in the study of FLL. Especially noteworthy is the fact that acoustic methods can be limited to very small displacements of flux lines, which permits one to measure purely viscous damping, rather than hysteretic behavior. By the same token, at larger amplitudes of vibration, hysteretic effects can also be studied. At low frequencies torsional pendulum techniques have been used in the range of $\sim 10^{-1}$ Hz, and vibrating reeds at $\sim 10^3$ Hz. Both approaches are restricted to essentially one mode each and to a narrow range in frequency. By contrast, ultrasonic techniques allow real bulk measurements, and especially the possibility of studying longitudinal as well as transverse modes for chosen directions of magnetic field, which can provide information on anisotropic behavior of flux line motion. The acoustic measurements have yielded a number of results that have been variously interpreted as due to thermally activated depinning phenomena, to melting of the FLL, to critical behavior indicative of phase transitions, and possibly other mechanisms.

A model developed by Pankert¹³ for interactions of ultrasound with vortices provided a basis for interpreting much of the subsequent work in this area. He used the premise that the propagation of sound in the mixed state is affected by the FLL because of its coupling to the crystal lattice through pinning centers. As a result, the elasticity of the crystal and dissipation of sound are altered by those of the FLL. Pankert calculated the change of sound velocity and dissipation in the thermally activated flux flow (TAFF) regime, valid above the reversibility line. Experimental data obtained by a number of workers¹⁴ were consistent with the main theoretical results of Pankert's model in that temperature range.

In recent experiments Haneda and Ishiguro¹⁵ observed generation of ultrasonic waves in the mixed state of HTCS, induced by the motion of vortices subjected to an *ac* magnetic field. In a polycrystalline sample of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, under a *dc* magnetic field, a pulse of *ac* magnetic field was generated

with a coil attached to one end of the sample. Application of the pulse resulted in the generation of acoustic waves, which were detected by a quartz transducer attached to the other end of the sample. Furthermore, the echo of the acoustic signal was detected by the coil as an *ac* magnetic field induced by the returning acoustic wave. These effects arise because an *ac* electromagnetic field excites vortex oscillations and the motion of vortices and sound waves are coupled through pinning mechanisms. Thus, these measurements may provide new means to study the pinning dynamics of vortices.

In the interest of gaining a balanced perspective on the use of mechanical vibrations in studies of HTCS, it is important to review the vibrating reed technique (KHz frequencies) and the torsion pendulum method (Hz frequencies), in addition to ultrasonic studies.

The vibrating reed technique proved to be particularly important in the study of the properties of FLL. In this method the superconducting sample, in the shape of a long, thin strip, is made to vibrate in a fluxural or torsional mode in a static magnetic field. The presence of the FLL results in a change of the resonance frequency and an increase in damping of the vibration.

The vibrating reed method applied to the study of FLL was first developed for measuring the pinning forces^{16,17}. The main emphasis in this work was on determining the Labusch parameter¹⁸, i.e. the slope of the pinning force as a function of the FLL displacement. Observations of hysteretic frequency changes as a function of increasing and decreasing magnetic fields were subsequently used to determine the critical current density. The Labusch parameters and the critical current density taken together can then be used to infer the pinning range. It is particularly noteworthy that the vibrating reed methods (as, in fact, ultrasonic methods) involve very low probing currents; this allows one to study FLL dynamics in the limit of currents tending to zero.

Many of the studies based on the vibrating reed method, including effects of temperature, magnetic field, vibration amplitude and angle between magnetic field and prominent crystal orientation features were interpreted as showing that FLL motion takes place by a thermally activated linear diffusion process^{19,20}. An extensive review of the vibrating reed technique application to the study of HTS may be found in reference 21.

An example of an interesting use of the torsion pendulum method in studies of HTS is the work by Farrell et al.^{22,23} This work was carried out on a twin-free single crystals of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$, thus limiting the likelihood of FL pinning, which occurs predominantly at twin boundaries. The striking results of the first study²² consisted of the observation of very sharp damping peaks with corresponding changes in the frequency. The temperature at which these peaks occurred was a function of the applied magnetic field: the higher the magnetic field the lower the temperature of the peak. Each peak was attributed to melting of the FLL lattice for a given value of magnetic field (i.e. FL density). A detailed analysis of these results in terms of theoretical models of FLL melting and a comparison with models of FLL motion by thermally activated diffusion, clearly favors the FLL melting hypothesis. Further work²³, using the same technique, was directed to measuring the damping peaks as a function of temperature for different values of the angle between the direction of the magnetic field and the *c*-axis of the single crystals. In this case again good agreement was found between the predictions of a model based on FLL melting and the experimental results. In particular, it was shown that the angular dependence of the melting temperature, T_M , (corresponding to the damping peak temperature) is consistent with control of T_M by the electron effective mass anisotropy determined by an independent experiment.

In general, acoustic measurements of FLL behavior carried out to date show typically one or two absorption peaks, together with a phase shift (or equivalently, a wave velocity change). A striking feature of these results is that for a frequency range approximately from 10^{-1} Hz to 10^7 Hz the absorption peaks are usually clustered within a small temperature range of about 20 K (down from the transition temperatures of ~ 90 K). Moreover, when the experiments performed by various groups are examined together, it turns out that there is no systematic dependence of the temperature

at which absorption peaks occur on the sound frequency of the measurements. In fact, many of the low frequency peaks are found to occur at higher temperatures than the high frequency ones. Table I summarizes the type of results obtained. These results indicate that the processes observed by acoustic measurements are not of the traditional, thermally activated relaxation type. The temperature of the absorption peak and of the phase shift (velocity change) is generally found to have a strong dependence on the magnitude and direction of the applied magnetic field. This is consistent with the large anisotropy of the FLL in high T_c superconductors. This behavior, together with the weak dependence of the absorption peak temperature on frequency, suggest a phase transition process. Whether this transition corresponds to "melting" of the FLL or to other types of disordering, or to unpinning of the flux lines, has not yet been conclusively demonstrated. This situation is due mainly to the fact that existing theoretical models provide some latitude in the choice of numerical values of the parameters. When this is combined with experimental uncertainties, one finds that comparably good fits of the data are often obtained for two or more different models. Clearly, more experimental studies on well-characterized materials are needed before a full understanding of flux line lattice dynamics in high T_c superconductors is obtained.

Table I

Material	Frequency	Magnetic Field (T)	Absorption Peak Temperature (K)
YBCO	$\sim 10^{-1}$ Hz	1-2.3	86-84
($T_c \sim 90$ K)	2 kHz	5	73
BISCO	1.26 kHz	0.42	~ 60
($T_c \sim 83$ K)	5.7 kHz	5	~ 60
	6.9 kHz	5	~ 70
BPSCCO	3 MHz	3	~ 65
($T_c \sim 110$ K)			

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