Vibrating Reed Study of the Flux Line Dynamics of \( \kappa-(ET)_2Cu[N(CN)_2]Br \)


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Vibrating reed measurements were performed on single-crystal samples of \( \kappa-(ET)_2Cu[N(CN)_2]Br \) in an applied magnetic field \( H \) oriented either parallel ("longitudinal") or perpendicular ("transverse") to the highly conducting ac-plane. Field-cooling data taken for the longitudinal orientation and \( H < 0.7 \) T revealed a peak with a low-temperature shoulder in the reed dissipation \( 1/Q \) located at temperature \( T_Q \) below the superconducting transition temperature \( T_c \) (~ 11.6 for \( H = 0 \)). The shoulder disappeared near \( H \approx 0.7 \) T, accompanied by an abrupt change in the slope of \( T_Q(H) \), corresponding to a similar change in the slope of the upper critical magnetic field \( H_{c2} \) measured by Kwok et al. The existence of the shoulder in the dissipation peak bears on a number of current explanations for the exotic superconducting properties of \( \kappa-(ET)_2Cu[N(CN)_2]Br \). The data taken for the transverse orientation fell far below estimates of \( H_{c2} \), indicating the existence of a substantial region of flux line (FL) mobility below \( H_{c2} \). The location of a peak in NMR relaxation observed by De Soto et al. lies close to \( T_Q \) for the transverse orientation.

KEY WORDS: Vibrating reed; type-II superconductors; organic superconductors; flux pinning; vortex lattice melting.

1. INTRODUCTION

Organic superconductors continue to be a subject of intense interest due to their anisotropic properties [1,2]; in particular, the zero-temperature coherence length \( \xi_0 \) can be approximately a factor of 3 to 4 less than the separation between layers of organic donor molecules. This extreme anisotropy leads to nearly two-dimensional superconducting behavior, which is expected to result in unusual flux line (FL) dynamics along particular crystal directions [3]. \( \kappa-(ET)_2Cu[N(CN)_2]Br \) is particularly interesting since it has the highest transition temperature of any organic superconductor known to date, \( T_c = 11.6 \) K at ambient pressure [4]. The interesting behavior of these materials and the expectation of various anomalies in their FL dynamics have motivated the present work, and we present our preliminary findings below.

2. VIBRATING REED TECHNIQUE

The vibrating reed method involves measurement of the flexural oscillations of a thin rectangular reed (made of single-crystal Si wafer, in this case) of length \( l \), width \( w \), and thickness \( t \), clamped at one end in a cantilever geometry [5–7]. When a vibrating reed is loaded on its free end with a superconducting sample and is subjected to applied magnetic fields and/or temperature variations, anomalies in the inverse quality factor, \( 1/Q \), and normalized resonant frequency shift, \( \Delta f/f \), of the Si reed resonances may be observed, as shown in Fig. 1.

Brandt, Esquinazi, and coworkers [5,8,9] demonstrated that vortex pinning models provided quantitative explanations of the strong resonant frequency
shifts and damping peaks of superconducting reeds induced by applied magnetic fields. The diamagnetic surface currents flowing in the reed produce a magnetic restoring force that leads to an increase $\Delta f$ in the resonant frequency $f$ compared to its normal state value (see Fig. 1). However, if the FL are imperfectly pinned to the lattice, the frequency shift is reduced and the motion of vortices in the applied field leads to additional energy losses and an increase in $1/Q$.

A maximum of vortices in the applied field leads to additional energy losses and an increase in $1/Q$. A maximum or peak in $1/Q$ is usually observed at temperatures and fields near $H_c(T)$, although the position $(T, H)$ varies significantly for different materials, and the exact mechanism of this maximum is still controversial [3,10,11].

3. EXPERIMENTAL TECHNIQUES AND SAMPLE CHARACTERIZATION

Single crystals of composition $\kappa$-(ET)$_2$Cu[N(CN)$_2$]Br were prepared by an electrocrystallization technique described elsewhere [4,12]. A small single-crystal platelet of millimeter dimensions was attached to a thin, single-crystal Si reed using either silver paint, Apiezon L-Grease, or Apiezon N-Grease, as described below. The sample ac-plane (i.e., the conducting plane containing the organic donor molecules) was oriented parallel to the reed axis.

Three crystals, “E”, “F”, and “B”, were investigated. Sample E was first glued to a Si reed using silver paint. However, during the first cooldown the sample shattered, presumably due to differential thermal contraction; a small splinter of the sample remained on the reed, enabling some data to be taken. Sample F was initially mounted with silver paint, but failed to stay on the reed upon cooldown (but was not broken). Sample F was reattached to the Si reed using Apiezon L-Grease, and measured in two series of runs separated by approximately a four-week period.

Vibrating reed resonances were excited by anchoring one end of a Si reed to the active surface of a piezoelectric bimorph transducer [6]. Typical Si reed dimensions were $1 \text{ cm} \times 1 \text{ mm} \times 80 \mu\text{m}$. The fundamental reed vibrational mode, whose frequency was in the range 700–3000 Hz, was characterized for applied fields perpendicular to the reed axis (“transverse geometry”) and parallel to the reed axis (“longitudinal geometry”). Data for $1/Q$ and $\Delta f/f$ can be taken either by sweeping temperature downward from above $T_c(H)$ at fixed field (except where hysteresis effects were studied), or by cooling the sample from above $T_c$ in zero applied field, and then sweeping field at a desired fixed temperature.

4. VIBRATING REED RESULTS

All of the samples studied exhibited two regimes of behavior, depending on the applied field strength. Our most extensive data are for sample “F.” Data for $\Delta f/f$ and $1/Q$ versus $T$ are shown in Fig. 1 for the fundamental ($f$ = 733 Hz) mode of a longitudinal Si reed (conducting planes parallel to the field) and applied field $H$ = 2.3 T. These data are typical of the VR behavior expected for a type-II superconductor [5,8,9].

The data for $\Delta f/f$ and $1/Q$ versus $T$ for the fundamental mode of a longitudinal reed carrying sample F in the low-field regime at $H$ = 0.18 T are shown in Fig. 2. A distinct, reproducible shoulder is present on the low-temperature side of the dissipation peak, although no corresponding anomaly was detected in the relative frequency shift. This feature was consistently observed in all of our measurements on other samples (with the possible exception of one data set for sample B, as discussed below) for $0 \leq H \leq 0.7$ T, although the shoulder was extremely difficult to resolve near 0.7 T. The higher-temperature peak may merge with the shoulder at fields above 0.7 T; additional measurements are under way to check the alternative possibility that the two anomalies might cross for $H \approx 0.7$ T. In particular, field-sweep experiments...