# Observation of de Haas–van Alphen oscillations in a YBaCuO high-$T_c$ superconductor in megagauss magnetic fields

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Oscillations of the magnetization of oriented polycrystalline samples of the high-$T_c$ superconductor $YBa_2Cu_3O_{7-\delta}$ have been measured at low temperatures (4.2 K) in magnetic fields up to 300 T. The magnetic fields were generated by an MK-1 implosion magnetic-field generator through compression of magnetic flux by a cylindrical detonation wave. Fourier analysis of the magnetization signals in fields $B>B_{c2}$ reveals oscillations with frequencies of 3.8, 10, 13, and 20 kT. © *1995 American Institute of Physics.*

Despite the numerous studies of the properties of high-$T_c$ superconductors, the nature of the normal state of this class of compounds remains an open question. Certain suggestions regarding the existence of a Fermi surface in high-$T_c$ superconductors have been offered on the basis of analyses of experimental results on positron annihilation and angle-resolved photoemission spectroscopy.[1] However, difficulties in the interpretation of these data have made it impossible to draw unambiguous conclusions. Measurements of the de Haas–van Alphen effect yield direct information on the Fermi surface and may shed some light on the nature of the normal state of high-$T_c$ superconductors. This effect is seen in oscillations of the magnetic susceptibility which are periodic in the reciprocal of the magnetic field. It is a consequence of a quantization of electron states in a magnetic field. The frequency ($F$) of the oscillations in the magnetic susceptibility is proportional to the area of the extremal cross section of the Fermi surface, $A_{\text{ext}}$, perpendicular to the field direction:

$$F=\hbar c A_{\text{ext}}/2\pi e.$$

Analysis of possibilities for experimentally observing oscillations in the magnetic susceptibility leads to the conclusion that the experimental conditions would have to meet some fairly stiff requirements. In the first place, a necessary condition for observation of the effect is that an electron in the metal undergoes a cyclic motion. This condition can be met only if the mean free path $l$ is larger than the cyclotron orbit in the plane perpendicular to the magnetic field. In other words, the quantizing field can be no lower than the value $H_l$ (which depends on $l$), at which the length scale of the orbit is comparable to the mean free path. If we adopt $l=10$ nm for the high-$T_c$ superconductors, we find that the fields required are more than 50 T, depending on the value assumed for the effective mass

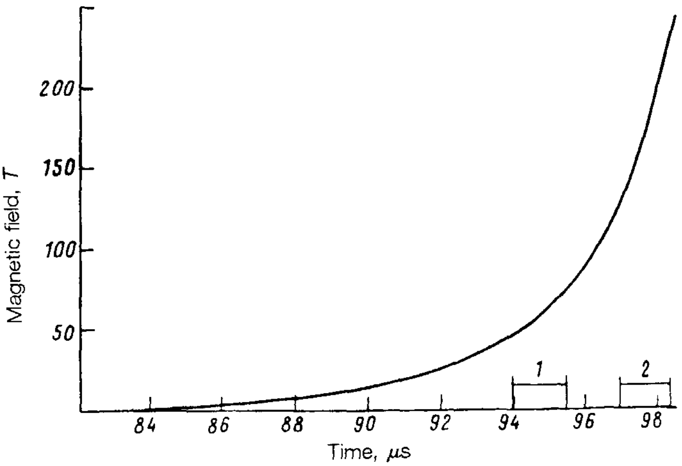

FIG. 1. Time evolution of the magnetic field in the MK-1 generator during compression of the magnetic flux by a detonation wave. Intervals 1 and 2 have the minimum noise level.

$m$. In addition, the temperature must be low enough to satisfy the condition $kT \ll \hbar\omega_c$, where $\omega_c = eH/mc$ is the cyclotron frequency. In other words, the thermal broadening of the Landau levels must be small in comparison with the distance between levels. Low temperatures are also necessary so that the mean free path with respect to scattering by phonons will be sufficiently large—comparable to the size of the cyclotron orbit. Measurements of the de Haas–van Alphen effect are usually carried out in the normal state, in which the field penetrates the sample completely. A basic requirement here is that the magnetic field be uniform over the volume of the sample. Major difficulties confront efforts to satisfy these conditions in high-$T_c$ superconductors, since the fields required to put these superconductors in the normal state at low temperatures exceed 100 T.

Nevertheless, the de Haas–van Alphen effect can be observed in the superconducting state,[2] despite the circumstance that the magnetic field penetrates into the superconductor in an exceedingly nonuniform way, because of the vortex structure. Observation of de Haas–van Alphen oscillations in the superconducting state becomes possible because this is a purely quantum-mechanical effect, analogous to the Aharonov–Bohm effect. The distribution of magnetic flux within the orbit is unimportant, since the quantization of the phase integral does not depend on the flux distribution inside the integration contour, being determined exclusively by the integrated flux linking the cyclotron orbits, $(2e/\hbar)\oint A ds = 2\pi n$.

At fields below the upper critical field (in the superconducting state), this condition thus means that the number of Abrikosov vortices linking each cyclotron orbit must remain very nearly constant. If this condition is to be satisfied, the cyclotron orbit must be penetrated by a sufficiently large number of quanta. For $YBa_2Cu_3O_{7-\delta}$ in a perpendicular field of 50 T, the cyclotron orbit is estimated to be $\sim 100$ nm in size. This figure corresponds to $\sim 10$ flux quanta within the orbit; that number is clearly insufficient to support

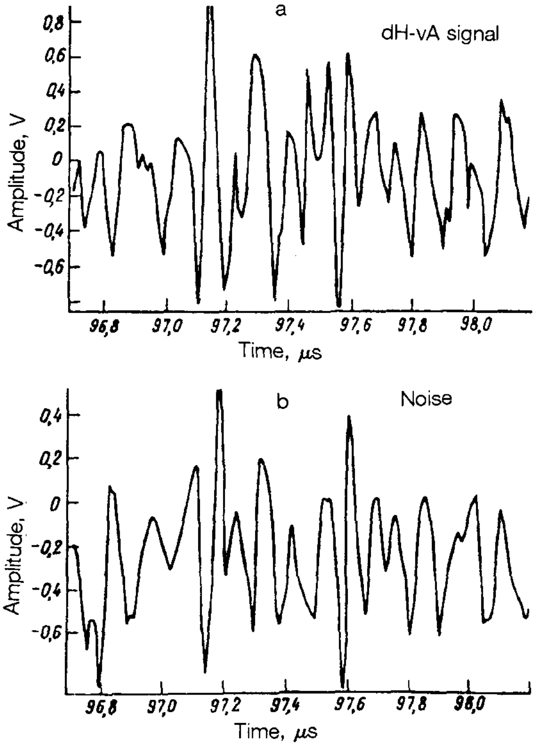

FIG. 2. Oscilloscope traces of the signals in the time interval 96.8–98.2 μs (140–230 T). a—Magnetization signal from a YBaCuO–glass measurement pair; b—noise signal from a glass–glass pair.

the proposition that the flux remains constant. This factor can explain the unstable nature of the oscillations in the experiments of Ref. 3, carried out on YBaCuO samples in fields up to 50 T. In Ref. 4, the de Haas–van Alphen effect was measured in fields up to 100 T, but no information was given on the state of the sample (normal or superconducting). We believe that a reliable interpretation of experimental results requires that the sample be in the normal state. In other words, in order to observe the de Haas–van Alphen effect in fields perpendicular to the layers, we need fields above 100 T.

It is currently possible to produce static magnetic fields up to 25–30 T in the laboratory with the help of a hybrid magnet. Pulsed fields up to 70–80 T can be produced by discharging a capacitor through specially designed coils. The only way to produce the fields above 100 T required for studying the de Haas–van Alphen effect in high-$T_c$ superconductors is to compress the magnetic flux by means of a detonation wave. We have used an MK-1 implosion magnetic-field generator to produce magnetic fields up to 300 T. In the MK-1, the magnetic field is produced by discharging a capacitor bank and then compressing the magnetic flux by means of a detonation wave. The rise time of the pulsed field is $\approx 20$ μs. We have used the same generator previously[5] to measure the upper critical field $B_{c2}(T)$ for YBaCuO. We found $B_{c2}(4.2\ \mathrm{K}) \approx 160$ T.

Measurements in such strong pulsed fields impose certain limitations on the test samples.[4] Single crystals of YBaCuO with sizes on the order of 10 μm were immersed in liquid epoxy resin, and the mixture was slowly polymerized, over 8–12 h, in a static

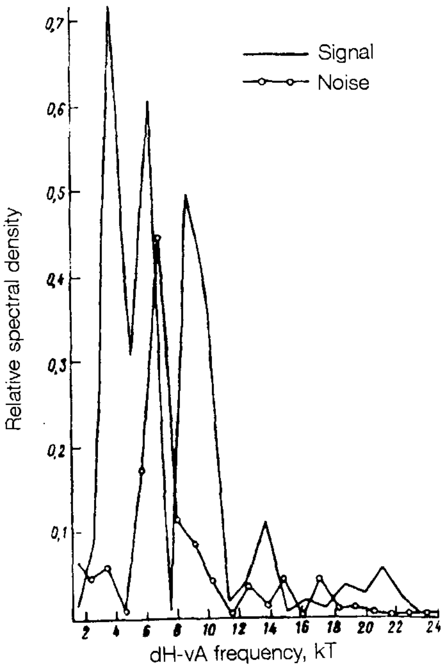

FIG. 3. Spectral densities of the magnetization and noise signals found through Fourier analysis of the spectrum in Fig. 2.

magnetic field of 8 T. The $c$ axis of the resulting samples ($d = 1$ mm, length of 4.5 mm) was oriented along the field within an angle on the order of 2°. The samples contained superconducting single crystals in a concentration amounting to about 17% of the volume. This figure is below the percolation threshold of 31%. The magnetic field can thus easily penetrate between grains during the pulse. The test sample for these measurements was graciously furnished by professor Müller from Los Alamos National Laboratory.

The de Haas–van Alphen effect was measured with the help of two pairs of coils, wound in opposite directions and balanced highly precisely in terms of capacitance and inductance over a broad frequency range. These coils were wound either directly around the YBaCuO sample or on glass cylinders. The diameter of the coils was 1 mm, the number of turns was 30, and the conductor was PÉTV-2 wire, 70 $\mu$m in diameter. The glass–glass and glass–YBaCuO coil pairs were positioned on a holder made of a glass-fabric-based laminate. The pairs of coils were positioned symmetrically with respect to the axis of the ultrahigh-field generator. A glass–glass unit was used to record the noise signal. The measurement unit was cooled with liquid helium. The magnetic field was measured with probes. Figure 1 shows the experimental time evolution of the magnetic field as it is amplified by compression by the cylindrical detonation wave.

To analyze the de Haas–van Alphen signal, we selected two time intervals, 94.0–94.7 and 96.8–98.2 $\mu$s, which corresponded to the field intervals 50–85 T ($B < B_{c2}$) and 140–230 T ($B > B_{c2}$). These particular intervals had the lowest noise level. (The noise had typical frequencies of 5–7 MHz and was observed on oscilloscope traces obtained from both the measurement units and the magnetic-field probes. A possible source of this noise is the explosion of the jacket of the metal–insulator cascade.) Figure 2 shows oscilloscope traces of the de Haas–van Alphen signal from a YBaCuO–glass pair (a), along with the noise signal from a glass–glass pair (b), for the interval 140–230 T. The signals for the selected time intervals were subjected to Fourier analysis. In the interval 50–85 T, we did not observe any clearly defined peaks of the de Haas–van Alphen effect, above the noise level. Figure 3 shows a spectrum for the interval corresponding to fields of 140–230 T. Shown here are spectral densities of both the signal and the noise. In the spectrum of the signal we can distinguish four peaks, corresponding to frequencies of 3.8, 10, 13, and 20 kT. The peak at 6 kT coincides with a peak of the noise signal. The peak at 3.8 kT corresponds to the calculated frequency of 3.7 kT and has been seen in previous experiments.[4] The formation of a frequency peak at 10 kT also follows from the theory. This frequency corresponds to an extremal cross section of the barrel type and has not previously been seen experimentally. The amplitudes of the peaks at 13 and 20 kT are just barely above the noise level. Further measurements will be required to draw clear conclusions about the nature of these peaks.

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