de Haas-van Alphen effect in single crystal MgB_2

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Abstract

We present an experimental study of the de Haas-van Alphen effect in single crystals of MgB_2, using a piezoresistive torque technique. Three quasiparticle orbits were observed. Two originate from a single warped Fermi surface tube along the c direction, and the third from a cylindrical section of an in-plane honeycomb network. The quasiparticle effective masses on these orbits were determined and compared to band structure calculations. From this we deduce that the electron-phonon coupling strength λ, is a factor ~ 3 larger for the c-axis tube orbits than for the in-plane network orbit, in accord with recent microscopic calculations.

Key words: MgB_2;Quantum Oscillations;Fermi-surface;

The occurrence of superconductivity at T_c=39 K in MgB_2 has provoked extensive recent research. In addition to the obvious interest in its high T_c, experiments have revealed other unusual features, notably the possible existence of two distinct superconducting gaps [1], that may be associated with two different bands [2].

A first step in obtaining a microscopic theory of superconductivity in MgB_2 is a comprehensive understanding of the electronic band-structure. A powerful probe of the electronic structure is the de Haas-van Alphen (dHvA) effect. Here we report measurements of the dHvA effect in single crystal samples of MgB_2.

The single crystals used in this work were grown in Tokyo by high pressure synthesis, as described in Ref. [3]. Two crystals (denoted A and B) from the same batch were studied in parallel in Cambridge and Bristol using a piezoresistive cantilever technique.

Measurements were conducted as the field direction was rotated from the c-axis ($\theta = 0^\circ$) towards the a-axis ($\theta = 90^\circ$). In Fig. 1 we show the change in the cantilever resistance as a function of field for sample B for the field applied close to the c-axis ($\theta = 16^\circ$) and close to the plane ($\theta = 69^\circ$). The frequencies present were deduced by FFT analysis and by directly fitting the raw data to the standard Lifshitz-Kosevich (LK) expression [4] for the oscillatory torque of a 3D Fermi

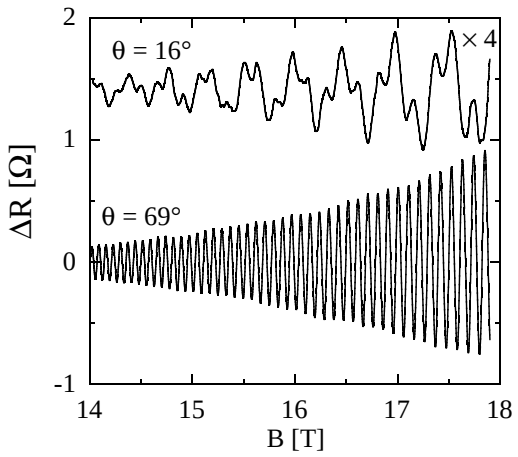

Fig. 1. Raw torque vs field data at two angles. The $\theta = 16^\circ$ data has been multiplied by 4 and offset for clarity. A bridge off balance of ΔR=1Ω is equivalent to a torque of $\sim 10^{-10}$Nm

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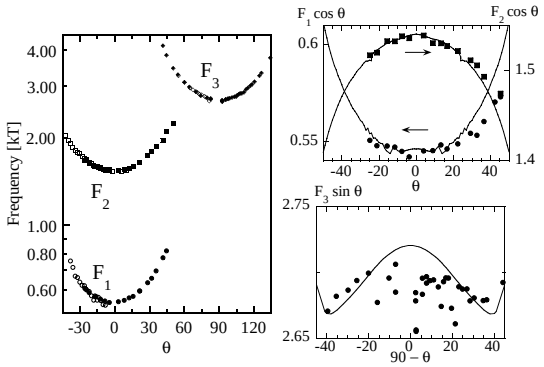

Fig. 2. Left Panel: Observed frequencies vs angle θ as the field is rotated from the c-axis ($\theta = 0$) towards the a-axis, Right Panel:Comparison of observed frequencies with calculations - solid line (Ref. [5]).

liquid. The angular dependence of the observed frequencies is shown in Fig. 2. For $\theta \lesssim 45^\circ$ two frequencies are visible (F_1 and F_2). The detailed angular dependence of F_1 and F_2 strongly suggest that they correspond to the minimal and maximal areas of a single warped cylinder directed along the c-axis. Comparison to band-structure calculations indicates that these orbits arise from the *smaller* of the two tubular quasi-2D hole sheets centered about $\Gamma - A$ line arising from quasi-2D $p_{x,y}$ B bands. For $\theta \gtrsim 45^\circ$ only a single frequency (plus weak second harmonic) is visible (F_3) which we attribute to an orbit on the 3-D, electron-like, in-plane tubular network whose median plane contains the A,H and L symmetry points.

A detailed comparison of $F_n(\theta)$ with band structure is made in the right panels of Fig. 2, where the predominate $1/\cos(\theta)$ dependence of the frequencies has been divided out. The theoretical data have been shifted to coincide with the experimental data. It can be seen that the agreement with the calculations of Harima [5] is good and generally within the scatter of the data.

Three different groups have reported detailed calculations of the expected dHvA frequencies [5–7]. All three give roughly similar values and are generally around 200-300 Tesla greater than our experimental values (Table 1). We note that although this is a significant proportion of the smaller frequencies it amounts to only ~ 0.2 % of the area of the hexagonal Brillouin zone.

Table 1
Summary of results for both samples (A and B) along with results of band-structure calculations (Th) [6].
$\lambda_{\rm exp} = m^B_{\rm exp}/m_{\rm band} - 1$ and $\Delta F = F_{\rm Th} - F^B_{\rm exp}$.

Orbit	$F^A_{\rm exp}$ [T]	$F^B_{\rm exp}$ [T]	$F_{\rm Th}$ [T]	ΔF [T]	ℓ^B [Å]	$m^B_{\rm exp}$ [m_e]	$m_{\rm band}$ [m_e]	$\lambda_{\rm exp}$	$\lambda_{\rm Th}$
1	535	546	728	+180	380	0.553	0.241	1.29	1.24
2	1530	1533	1756	+221	580	0.648	0.312	1.08	1.25
3	2688	2685	2889	+205	680	0.441	0.315	0.40	0.47

The masses of the quasiparticles on each orbit were determined by measuring the thermal damping of the dHvA signal between 0.36 K and 12 K, and fitting these amplitudes to the LK expression. The results along with the calculated bare band masses [5–7] are shown in Table 1. All the measured masses are significantly less than unity. The enhancement on F_1 and F_2 is significantly greater than on F_3. If we attribute all this enhancement to the standard electron-phonon mechanism we can deduce the average value for the electron-phonon coupling constant (λ) on each orbit. It can be seen that the values of $\lambda_{\rm exp}$ on the quasi-2D sheet (F_1 and F_2) are approximately 3 times larger than on the 3D sheet (F_3), indicating a marked difference in electron-phonon coupling on these sheets. Our values for λ are in very good agreement with the theoretical values [6,2], providing strong evidence that the electron-phonon mechanism is the only significant source of mass enhancement in this material.

In summary, we have obtained detailed data for the Fermi surface parameters of MgB_2, which are in good agreement with the most recent band structure calculations. We have shown direct evidence that the electron-phonon interaction is large on the quasi-2D B $p_{x,y}$ band and much smaller on the electronlike 3D B p_z band (in-plane honeycomb network). This supports microscopic theories of superconductivity that invoke two bands with very different properties [2]. At present we have not observed evidence for orbits arising on the other pieces of the predicted Fermi surface (i.e., the larger of the two tubular quasi-2D (B $p_{x,y}$) hole sheets and the holelike quasi-3D (B p_z) sheet). Whether this is due to the relatively short mean free path (ℓ) of our crystals (Table 1) or the actual absence of these sheets of Fermi surface awaits further investigation. A more complete analysis of the results is given in Ref. [8].

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