Shubnikov-de Haas oscillations in the heavy fermion α-YbAlB$_4$

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Abstract.

Shubnikov-de Haas oscillations were measured in α-YbAlB$_4$ at fields up to $B = 16$ T. Quantum oscillations were used to directly extract the quasiparticle mean free path by fitting to the Dingle decay yielding a mean free path $\sim 550$ Å. We also describe a novel fitting procedure used to extract a low frequency oscillation from the non-oscillatory background magneto-resistance.

1. Introduction:

When crossing a quantum phase transition the correlation structure of the ground state changes. For this reason quantum critical points (QCP) are a central topic in the study of strongly correlated electron systems. Tuning to the vicinity of a QCP has become a reliable experimental heuristic for discovering new electronic states of matter [1].

The YbAlB$_4$ [2, 3, 4, 5] systems α-YbAlB$_4$ and β-YbAlB$_4$ (see Figure 1A inset) have received considerable interest in this context. β-YbAlB$_4$ is the first example of a Yb-based heavy fermion superconductor [3] around a QCP that occurs at exactly zero magnetic field [4]. Superconductivity in β-YbAlB$_4$ is suggested to be unconventional on the basis that superconductivity is only found in the clean limit and pairing involves highly renormalized quasiparticles [5]. In contrast, α-YbAlB$_4$ has been found to be a Fermi liquid at zero magnetic field in measurements to $T = 0.01$ K [6].

However, in several respects α-YbAlB$_4$ closely resembles β-YbAlB$_4$. At temperatures greater than the putative Kondo lattice coherence temperature ($T^* = 8$K [4, 6]) both the specific heat and magnetization of α and β are almost identical suggesting almost identical local moment properties. This is consistent with the local isomorphism of the Yb sub-lattice whereby up to nearest neighbour the Yb-Yb bond distances and angles are almost the same. Therefore, a detailed comparison of the low energy excitations in α and β polymorphs should yield information on the relevant parameter to realize quantum criticality in β-YbAlB$_4$.

By comparing the electronic structure of α and β polymorphs we can extract differences in the strength and/or symmetry of the hybridization between $f$-moments and conduction electrons ($c$) that will have important implications for a microscopic approach to this problem. Such differences have been considered theoretically by Tompsett et al. [7] and it was found that the boron heptagon that surrounds and strongly hybridizes with the Yb ion (in both α and β
polymorphs) is distorted in the structure of the α polymorph; this leads to a more significant anisotropy of the $c-f$ hybridization within the $ab$ crystal plane.

An experimental investigation of electronic structure has been carried out for $\beta$-YbAlB$_4$ by quantum oscillation measurement of the Fermi surface [8]. In this paper we present a partial result of a Shubnikov-de Haas study of $\alpha$-YbAlB$_4$. Here we use the Dingle relation for the decay of quantum oscillations to determine the quasiparticle mean free path and verify the high quality of the crystals used. We then describe the analysis of a particularly low frequency oscillation and show how the oscillatory component was extracted from the non-oscillatory background magneto-resistance.

2. Methods
Single crystals of $\alpha$-YbAlB$_4$ were synthesized according to the method of Macaluso et al. [2]. Crystals of $\alpha$-YbAlB$_4$ grow as long needles along the $c$-axis. Therefore, electrical contacts were made to apply current ($I$) parallel to the $c$-axis ([0,0,1]) and resistivity measurements were made using a current of approximately 50 $\mu$A, having checked that Joule heating effects were absent. In this article we present measurements made with fields applied parallel to the [1,1,0] and [0,0,1] crystal axes.

3. Results
Figure 1A shows the quantum oscillation spectrum measured for the magnetic field $B \parallel [1,1,0]$ crystal axis. The spectrum shows several frequencies and we analyze the Dingle decay to characterize the quality of our samples. To fit the Dingle decay we need to extract amplitude of some frequency; for this we choose the peak at $F = 0.91$ kT as it is well separated from other frequencies so can be easily filtered in the Fourier domain.
Figure 2. A: Resistivity $\rho(B \parallel c \parallel I)$ measured at constant temperature $T = 30$ mK, together with the fit to the non-oscillatory background $\rho_{\text{MR}}(B)$. B: Oscillatory component of the resistivity $\rho_{\text{osc}}(B) = \rho(B) - \rho_{\text{MR}}(B)$.

Figure 1B shows the result for the amplitude of $F = 0.91$ kT, plotted on the appropriate Dingle scale for Shubnikov-de Haas oscillations. The approximately linear decay on this scale is consistent with the expected decay of a single oscillatory component without interference. The gradient of this line is $-\pi B_D/l$, where $B_D = (2\hbar F/e)^{1/2}$, $l$ is the mean free path and we have assumed the orbit has a circular cross section to convert from the real space area to circumference.

From this fitting we obtain quasiparticle mean free path $550\pm20$ Å and because of the assumption of a circular orbit this is a lower bound for the sample measured. This is comparable to the mean free path (900 Å) measured for $\beta$-YbAlB$_4$ [8], which shows that $\alpha$-YbAlB$_4$ can be synthesized at a similar level of purity to $\beta$-YbAlB$_4$ and furthermore suggests that the measured differences with respect to superconductivity and quantum criticality [4] should reflect the intrinsic behaviour of the system rather than the effects of disorder in either polymorph.

Figure 2A shows resistivity measured with $I \parallel B \parallel c$ at a constant temperature of 30 mK. From the raw data it is clear that the resistivity has an oscillatory component. We now consider how to extract this from the non-oscillatory background magneto-resistance.

The total resistivity is assumed to be of the form $\rho(B) = \rho_{\text{MR}}(B) + \rho_{\text{osc}}(B)$, where $\rho_{\text{MR}}(B)$ is the background magneto-resistance, $\rho_{\text{osc}}(B)$ is the quantum oscillatory component and is assumed to be essentially periodic in $1/B$. $\rho_{\text{MR}}(B)$ is expected to have a polynomial dependence on $B$, it is then usually adequate to fit the entire resistivity to some polynomial and then subtract this fitted polynomial. If the polynomial order is sufficiently low and the oscillation frequency is sufficiently high then the projection of the oscillation onto the polynomial fit is essentially zero and as such the oscillatory component is extracted intact. For the data in Figure 2A the number of periods observed is clearly small (< 5) over the entire $B$ range so the usual criteria for making a simple polynomial fit to the background does not apply; even a small polynomial order will interfere with the oscillation.

A particular difficulty is that the oscillation is periodic in $1/B$ while the background is expected to be polynomial in $B$, therefore a fit in $B$ does not weight all parts of the oscillation.
equally. To overcome this problem we used a robust local regression technique well known in the field of applied statistics (LOWESS) [9] using the ‘locfit’ implementation by Loader [10].

We briefly describe the procedure as we are unaware any previous application of this technique in the context of quantum oscillations, we apply the fit in $1/B$ so define $x = 1/B$; the data is first weighted around the fit location ($x_0$) using a weighting function $W(x)$ which has the property that it is zero beyond some cut-off distance ($x_c$) from the fit location i.e. $W(|x - x_0| > x_c) = 0$, the locally weighted data is then regressed to a polynomial $^1$ in the usual least squares way. The weighting function we used is the common tri-cube model $W(x) = (1 - |x/x_c|^3)^3$ $|x/x_c| < 1$, $W(x) = 0$ $x/x_c ≥ 1$ [9]. The advantage of this procedure is that it acts as a high pass filter in $1/B$ without requiring a model for $\rho_0(B)$. In our application of this procedure we use a cutoff that corresponds to an oscillation frequency ($1/x_c = F_c < 2T$).

Figure 2A shows the background produced in this way, the apparent tendency to saturate at higher fields is likely an artifact appearing at the end of the fit range (in $1/B$). Figure 2B shows the oscillatory component extracted in this way. $\rho_{osc}$ is periodic in $1/B$ with frequency $F = 10.4T$ and decays at low field as expected. The oscillation has significant anharmonicities, given the difficulty in removing the background we do not ascribe significance to these.

4. Conclusion
We measured quantum oscillations in $\alpha$-YbAlB$_4$ at fields up to $B = 16$ T. For $B || [1,1,0]$ we used the Dingle decay relation to extract the quasiparticle mean free path as 550 Å. From this we conclude that high purity single crystals of $\alpha$-YbAlB$_4$ can be prepared similarly to $\beta$-YbAlB$_4$. We also measured resistivity for $B || [0,0,1]$, in this configuration we found a low oscillation frequency $F = 10.4T$ and we described the technique used to remove the non-oscillatory background.

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$^1$ we used a quadratic which does not have oscillatory character (c.f. order $\geq 3$) as the second derivative is constant