Order-disorder transition and magnetic quantum oscillations in the vortex state of strong type-II superconductors

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Abstract. We present results of $\mu$SR, dHvA, and SQUID magnetization measurements on borocarbide superconductors, which show a remarkable correlation between an order-disorder transition of the vortex lattice, observed in the $\mu$SR measurements, and enhanced additional damping of dHvA oscillations in the peak-effect region. It is, therefore, concluded that an important mechanism of additional damping of dHvA oscillations in the superconducting state should be associated with enhanced scattering of quasi particles by the pair potential in disordered vortex lattices.

Investigating the response of a superconductor to the application of an external magnetic field is crucially important for understanding superconductivity at the most fundamental level. The “ideal” superconducting (SC) state of a clean metal at very low temperature under high magnetic field is at present not well understood. For example, even within the framework of the conventional BCS theory, the SC ground state of the many-electron system under the influence of Landau quantization of the underlying single electron states is currently unknown [1, 2]. In the absence of such a quantitative theory it is helpful to resort to experiments in order to guide the theory. Magnetic quantum oscillations (e.g., de Haas-van Alphen (dHvA) or Shubnikov-de Haas (SdH) effects) provide researchers with powerful probes of the low temperature quantum states of metals at high magnetic fields. dHvA oscillations have been observed in the mixed state of many strong type-II superconductors [2, 3]. Relatively old data for the nonmagnetic borocarbide superconductor, YNi2B2C [4], which is still not well understood, showed a large peak in the measured magnetization just below $H_{c2}$, the so called peak-effect (PE), reflecting the influence of enhanced pinning of vortices by defects in the crystal due to softening of the vortex lattice. The data also showed a pronounced dip in the dHvA signal, which is correlated with the position of the PE. The origin of this dip was attributed by Terashima et al. [4] to “phase smearing”, i.e., an inhomogeneous field broadening associated with displaced flux lines by random pinning centers in the PE region.
Recent measurements of dHvA oscillations in the vortex state of a similar nonmagnetic borocarbide superconductor, LuNi$_2$B$_2$C, have shown a similar behavior [5]: A large PE just below $H_{c2}$ and a rather sharp dip in the dHvA signal, which is nicely correlated with the position of the PE (see Fig.2, upper panel). In the broad field range well below the PE region the signal, after recovering from the dip, undergoes extra damping with respect to the usual thermal and disorder (Dingle) damping factors in the standard Lifshitz-Kosevich formula, which is, however, much weaker than that seen in the PE region. At present, there is no theory that accounts for this data quantitatively. At first sight, the apparent correlation between the positions of the relatively narrow PE region and the dip in the dHvA amplitude just below $H_{c2}$ indicates that the extra damping might be due to strong “phase smearing”, as originally suggested by Terashima et al. [4]. However, as will be shown below, our $\mu$SR measurements on a LuNi$_2$B$_2$C single crystal rule out this possibility, pointing to the importance of vortex-lattice disordering effects on the pair potential in the enhanced damping process.

Transverse-field (TF) $\mu$SR measurements up to 7 T were carried out on the M15 muon beam line at TRIUMF using the HiTime spectrometer, which consists of muon and positron detectors contained within a standard He-flow cryostat. The external field was directed parallel to the c-axis of the crystal. A fast Fourier transform (FFT) of the TF-$\mu$SR signal closely resembles the internal magnetic-field distribution $P(B)$ [6]. The measurements were typically done by cooling the sample in a fixed field to a temperature between 2 and 3 K, and then measuring the field dependence of the TF-$\mu$SR signal. Specifically, measurements were performed on the LuNi$_2$B$_2$C single crystal after field cooling in 3 and 7 T. Note that, due to technical reasons, the $\mu$SR and dHvA measurements could not be carried out on the same sample. Furthermore, it is not currently feasible to carry out $\mu$SR measurements below 2 K in fields above 5 T. Thus, in order to allow cross-correlation between magnetization and $\mu$SR measurements, the magnetization was also measured using a SQUID magnetometer on the same sample and at the same temperature as employed in the $\mu$SR experiments.

Results of the isothermal SQUID magnetization measurements, performed on the LuNi$_2$B$_2$C sample, are shown in the left panel of Fig.1 together with the corresponding field-dependent width, $\langle \Delta B^2 \rangle^{1/2}$, $\Delta B = B - \langle B \rangle$, of the TF-$\mu$SR probability field distribution line $P(B)$. The sharp maximum in the $\mu$SR line-width closely follows the PE in the corresponding magnetization curve. The skewness parameter of the TF-$\mu$SR line shape, defined by $\alpha = \langle \Delta B^3 \rangle^{1/3} / \langle \Delta B^2 \rangle^{1/2}$.
Figure 2. Upper panel: (a) dHvA oscillation signals, for upward and downward field-sweeps respectively, measured on LuNi$_2$B$_2$C after background subtraction, and (b) the corresponding Dingle plots (triangles and circles respectively). The gray oscillatory lines in (a) represent the extrapolated dHvA signal, based on the normal-state Lifshitz-Kosevich formula, whereas the solid straight line in (b) is the corresponding Dingle plot. The total magnetization for both field-sweeps (solid curves) are also shown in (b). The dash-dotted line in (b) represents the result of a calculation based on the random vortex distribution model with the zero-field order parameter equal to 4 meV and mean-field $H_{c2} = 8$ T. Lower panel: A modified Dingle plot (thick solid curve) obtained by combining the calculated Maki Dingle factor in the PE region with the YK Dingle factor in the entire field range below the PE region. Original data were taken from Ref.[12].

[6], is plotted as a function of the magnetic field in the right panel of Fig.1. Note, that a negative $\alpha$ is due to the presence of short-range triplet correlation in the absence of long-range order, characterizing a vortex-glass phase [7]. Thus, the onset of negative $\alpha$ (around 5 T) just below the PE region indicates that the vortex lattice is disordered in the entire PE region. Remarkably, the sharp change of $\alpha$ is seen to correlate with the appearance of the PE and the enhanced additional damping of the dHvA oscillation shown in Fig.2, upper panel. The positive values of $\alpha$ near unity in a broad field range below the PE reflect the occurrence of a well-ordered vortex lattice in this region, which is seen to correlate with the weak additional damping of the dHvA signal.

These remarkably correlated phenomena seem to arise from the same physical source—enhanced pinning-induced redistribution of vortices. However, the enhanced field inhomogeneity observed in the PE region, approximately 40 G (maximal field distribution width in the PE) is found to be much too small to attribute the additional damping of the dHvA amplitude to further broadening of the Landau levels by magnetic-field inhomogeneity. This can be seen by exploiting a model of a completely random flux lines distribution under the external magnetic induction $B_0$ and then estimating the damping of the dHvA amplitude associated with the corresponding Landau-level broadening. The effective Dingle factor can be calculated from the expression [8]: $R_D = e^{-\pi/\tau_R \omega_c}$, with $\pi/\tau_R = n_F^{1/2} (B_1/B_0) \omega_c$, $\omega_c = eB_0/m^*c$. Here $m^*$ is the quasi-particle effective mass, $n_F = E_F/\hbar \omega_c \gg 1$, and $B_1 = \left\langle [B(r) - B_0]^2 \right\rangle^{1/2}$. This
may be compared with the extra damping factor due to direct scattering of a quasiparticle by the pair potential in the random vortex distribution limit [2], which takes the form [9]:

\[ R_M = e^{-\pi / \tau_M \omega_c}, \quad \pi / \tau_M = \pi^{3/2} \Delta_0^{-2} n_F^{1/2} \omega_c, \]

where \( \Delta_0 \equiv \Delta_0 / \hbar \omega_c, \) and \( \Delta_0 \) is the self-consistent Ginzburg–Landau expression for the amplitude of the SC order parameter. The (Dingle) plot of \( \ln R_M \) for documented values of the adjustable parameters \( \Delta_0 \) and \( H_{c2} \) [5] is shown in Fig.2, left panel, to agree well with the experimental Dingle plot in the PE region. On the other hand, at the PE field position: \( B_{PE} \lesssim H_{c2}, \) where \( \Delta_0^2 \approx 0.36 n_F(1 - B_{PE}/H_{c2}), \) we have \( \tau_M / \tau_R \geq (1 - B_{PE}/H_{c2})^{-1} (B_1/2H_{c2}), \) so that for \( B_{PE} \approx 6 \) T, and \( H_{c2} \approx 7 \) T (at \( T < 3 \) K), we find: \( \tau_M / \tau_R \approx 3 \times 10^{-3} \) for \( B_1 = 40 \) G. Thus, the small ratio \( \tau_M / \tau_R \approx 3 \times 10^{-3} \) implies that the additional damping rate associated with the enhanced field inhomogeneity observed in the PE region is at least two orders of magnitude smaller than the observed damping rate shown in Fig.2, left panel.

For the ordered vortex lattice state well below the PE region several numerical simulations [10, 11, 12] of the corresponding Bogoliubov-de Gennes equations for the quasi-particles in the Abrikosov vortex lattice are available. Guided by our experimental findings we focus on the work of Yasui and Kita (YK) [12], who found a significantly smaller effective Dingle factor in their calculation in comparison with the Dingle factor derived in the random vortex distribution limit [9]. In Fig.2 the Dingle plot extracted from the experiment (upper panel) is compared to a combined plot of the calculated Maki Dingle factor [9] in the PE region and the YK Dingle factor below the PE region (lower panel). The good agreement found between the experimental and calculated Dingle plots indicates that the two markedly different damping rates indeed represent two different regions of the vortex state—a disordered phase in the PE region, and a broad ordered vortex-solid phase in the entire low-field region, as verified by the field dependence of the skewness parameter derived from the \( \mu \)SR experiment. It also provides support for the theoretical argument associating enhanced quasi-particle scattering by the pair-potential to disordering of the vortex lattice [2].

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