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2D DE HAAS-VAN ALPHEN EFFECT IN THE SUPERCONDUCTING STATE

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Abstract

We present a theory of the dHvA effect in the superconducting mixed state within the framework of the Gorkov's scheme near H_{c2} in a 2D, extremely type-II superconductor. The mean square order parameter is calculated over the entire flux lattice. The calculated superconducting magnetization oscillations are of the same order of magnitude as the normal electrons ones. Reentrance of the superconducting state above $H_{c2}(T)$, is found to occure within an accessible range of fields and temperatures, which is a dramatic manifestation of the two-dimensionality of our model.

The behavior of type-II superconductors under very high magnetic fields has become a subject of considerable interest recently [1,2,3] especially in the light of the very recent reports [4,5] of the observation of dHvA oscillations in 123 oxide superconductors. The aspect which makes the superconducting state so unusual and exciting at a high magnetic field is the enhancement of the single electron density of states in certain field regions. Cooper-pairing in these regions is reinforced and this may compete with the destructive nature of the magnetic field with respect to the superconducting order [2]. In a 2D electron system the density of states is singularly enhanced at the Landau levels,while the introduction of the third dimension smears out this sinularity.

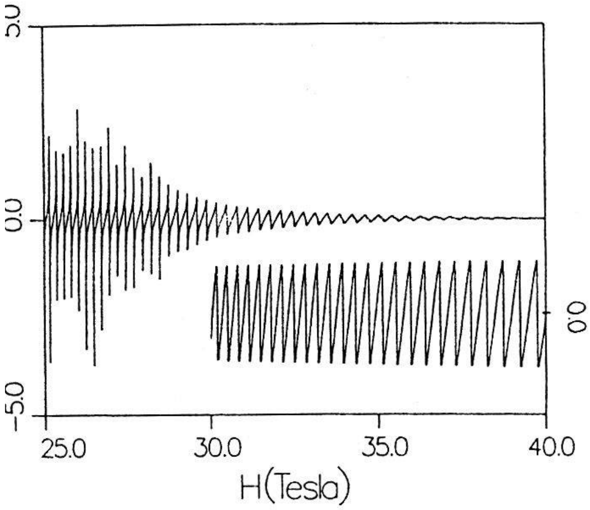
We consider a pure,2D electron gas (in the $x-y$ plane) under a perpendicular magnetic field H (along the $z-$axis). For the sake of simplicity we assume a simple BCS pairing ineraction,V,which is independent of the magnetic field. Near the upper critical field $H_{c2}(T)$ at an arbitrary temperature $0 < T < T_c$,the order parameter $\Delta(\vec{r})$ is small and the superconducting free energy can be expanded in $\Delta(\vec{r})$. Using a novel semiclassical approach [6] the superconducting free energy per unit flux area can be written in the following Landau-like form [6] :

$$f_s \equiv \frac{F_s}{N\pi a_H^2} = \eta[-\tilde{\alpha}\Delta_0^2 + \frac{\tilde{B}}{(\pi k_B T_c)^2}\Delta_0^4] = -\eta(\pi k_B T_c)^2\frac{\tilde{\alpha}^2}{4\tilde{B}}$$

where $\tilde{\alpha}$ is the dimensionless condensation energy,η is the 2D density of states,Δ_0^2 is the mean square order parameter over the entire Abrikosov lattice,and N is the total number of flux lines threading the superconductor. Note that $\tilde{B}$ is proportional to the Abrikosov lattice geommetrical factor, β_A, while the other factors are independent of the flux lattice . Thus the free energy f_s for $\tilde{\alpha} > 0$ is inversely proportional to β_A,as in the classical Abrikosov theory. This implies immediately that the triangular flux lattice yields the minimum free energy.

The formalizm outlined here enables us to compute any observable which is a functional of the superconducting order parameter near the upper critical field. In particular,one may calculate the average supercunducting magnetization ,$m_s \equiv \partial f_s/\partial H$. We have found that the superconducting and the normal parts of the magnetization oscillations are of the same order of magnitude (see Fig.(1)). It should be noted here that under a strong magnetic field the chemical potential in systems, where the number of electrons is fixed ,is not field independent [8].

Fig. 1.



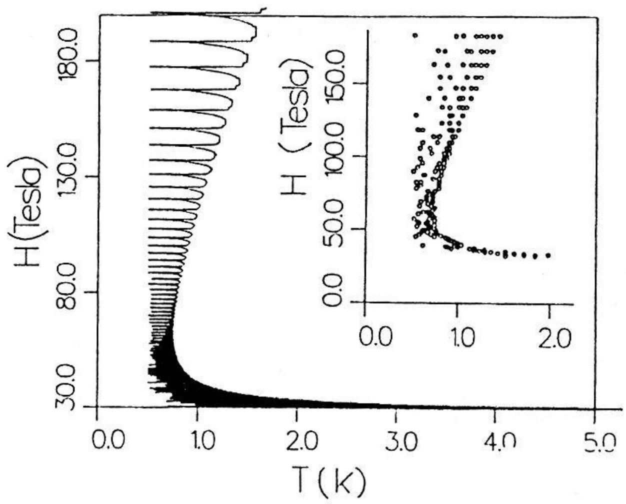


Fig.(1):The superconducting magnetization oscillations in the limit of fixed number of electrons. The selected values of the parameters ,i.e. $T_c = 87K$, $E_F = 2029K$, may characterize $Bi_2Ca_1Sr_2Cu_2O_{8+x}$. The mass ratio $m_c/m_0 = 2$ (second spin splitting zero). The temperature is $T = 1K$. Inset: The normal magnetization for similar parameters.

Fig.(2): The phase diagram around the critical point for reentrance superconductivity for the second spin splitting zero: $m_c/m_0 = 2$ where the number of electrons fixed. Inset: The same phase diagram in the case when the chemical potential is fixed.

The oscillations enhance dramatically under the resonance (spin splitting zero) condition,when m_c/m_0 becomes close to an integer. The possibilty of controlling experimentally such a resonant condition is unique to highly 2D electron systems;it can be done by tilting the magnetic field with respect to the axis normal to the conducting planes [3] . The corresponding phase diagram is shown in Fig.(2). The critical point for the back bending of the phase boundary is within an accessible range of fields and temperatures. This is a dramatic manifestation of the two-dimensional dHvA effect since the critical temperature for the back bending in three dimensions is several orders of magnitudes lower [2,3].

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