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Temperature and magnetic field properties of Condon domain phase in Be

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Abstract

The temperature and magnetic field behavior of non-uniform diamagnetic phase in Be is analyzed theoretically. It is shown, that in the model of slightly corrugated cylinder-like Fermi surface sheet relevant for dHvA oscillations in Be, the parameters of Condon domain (CD) phase, e.g. the magnetic induction splitting between two adjacent domains and the range of existence of non-uniform phase in every period of dHvA oscillations, reveal strong dependencies on temperature, magnetic field and purity of the sample. In particular, we show that the maximum of magnetic induction splitting $\sim 15\,\mathrm{mT}$ can be achieved in Be at relatively moderate values of magnetic field $\mu_0 H \sim 5$–$7\,\mathrm{T}$ and Dingle temperature $T_{\mathrm{D}} = 2\,\mathrm{K}$ in contrast to the case of noble metals, e.g. Ag, where for observation of the splitting of the same order of values the extremely high magnetic field $\mu_0 H \sim 35\,\mathrm{T}$ and extremely pure samples with $T_{\mathrm{D}} = 0.1\,\mathrm{K}$ are needed. The last circumstance can make it favorable to investigate experimentally the predicted temperature and magnetic field properties of CD phase in Be.

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1. Introduction

Many thermodynamic quantities of an electron gas are characterized by the oscillatory behavior in external magnetic field, as a result of the oscillations of the density of states when successive Landau levels sweep through the Fermi level due to change of magnetic field [1]. At high magnetic field and low temperature the instability of strongly correlated electron gas due to magnetic interaction between electrons results in diamagnetic phase transition (DPT) [2] with formation of Condon domains (CDs) [3]. The stratification of the sample into diamagnetic domains is a macroscopic manifestation of quantum effects, related to the quantization of electron orbits. The instability of an electron gas appears under condition $a = \mu_0 \max\{\partial M/\partial B\} > 1$, where a is the amplitude of the differential magnetic susceptibility, or reduced amplitude of dHvA oscillations [2], and B is magnetic flux density, and is extensively studied, both theoretically and experimentally [3–16]. The direct observation of laminar domain structure in Ag [5] confirms the striking similarity between intermediate state of type-I superconductor and DPT at the conditions of strong dHvA effect. Magnetic interaction of strongly correlated electron gas results in non-linear dependence of local diamagnetic moments on external magnetic field and temperature [9], which contributes to the magnetization reversal and gives rise such an exotic phenomenon as diamagnetic hysteresis [10,14].

The temperature and magnetic field behavior of non-uniform phase in Ag [13], estimated on the basis of the Lifschitz–Kosevich–Shoenberg formalism [2] shows a good agreement with experiment [5]. However, in case of Be due

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to negligibly small curvature of the extreme cross-sections of it cylinder-like Fermi surface sheet [2], the standard approach, giving the satisfactory results for free or almost free electron gas which is a good approximation for noble metals, fails to describe the DPT and cannot be applied for investigation of properties of CDs [6]. The results of [6] show the serious disagreement of muon-spin rotation spectroscopy (μSR) data in Be with the phase diagrams, calculated in the framework of standard Lifschitz–Kosevich formula, and necessity to take into consideration the actual 3D Fermi surface geometry for Be. Although, the power-law model developed in Refs. [6–8] is consistent with the previous experiments on observation of Condon instability [6] at low range of quantizing magnetic field (till ~3 T), unfortunately, it gives the overestimated values of critical magnetic field ≈ 10 T for non-uniform phase in contradiction to recent data on independent observation of Condon instability in Be [10,16], which demonstrate the existence of the non-uniform diamagnetic phase in essentially narrow interval of quantizing magnetic field (≈ 0–6 T) depending on estimated Dingle temperature $T_D \approx 2$ K. This discrepancy between experimental data and existed models of DPT has stimulated the development of the model of slightly corrugated cylinder-like Fermi surface sheets [12] which gives a good agreement with the observed phase instability in Be [10,16] over all the range of external magnetic field, temperature and Dingle temperatures relevant to DPT.

Motivated by recent experiments on observation of DPT in Be [15] which allow for the first time to construct the phase diagram and compare it with the existent DPT models, we present here the theoretical investigation of temperature and magnetic field properties of the CD phase in Be. Due to relatively high amplitude of dHvA oscillations in Be [2] we expect strong influence of temperature, magnetic field and impurities of the sample on formation of non-uniform phase and compare our results with available data on investigation of CDs.

In particular, we show that the magnetic field dependencies of the parameters of CD phase in Be, such as the magnetic induction splitting between two adjacent domains and the range of existence of non-uniform phase in every period of dHvA oscillations, are characterized by a set of bell-shape curves which is a direct consequence of the bells-like diamagnetic phase diagrams $T = T(\mu_0 H, T_D)$ [12]. The maximums of these functions appear periodically on the scale of inverse magnetic field with the period inversely proportional to the discrepancy of the two fundamental frequencies, corresponding to two extreme cross-sections of the cigar-like Fermi surface sheets of Be.

2. Model

The temperature and magnetic field behavior of the CD phase, as well as the effect of impurities on the CDs formation, is governed by the reduced amplitude of dHvA oscillations $a = a(T, \mu_0 H, T_D)$.

The equation

$$a(\mu_0 H, T, T_D) = 1 \tag{1}$$

defines the critical surface in three dimensions $\mu_0 H - T - T_D$, which in case of Be consists of bell-shape sheets, arranged periodically when plotted against the reciprocal of the magnetic field strength with inverse period related to the discrepancy of the two fundamental frequencies of extreme cross-sections cigar-like Fermi surface relevant for dHvA oscillations [12]. Above this surface the uniform diamagnetic phase exists, but below it the CD phase appears in the part of the period of dHvA oscillations. The reason of using the model of slightly corrugated cigar-like Fermi surface, developed in Ref. [12], is a good agreement of calculated phase diagrams with the recently observed Condon instabilities [10,15,16].

The formation of non-uniform phase can be characterized by two main parameters, the average magnetic induction splitting δb, defined as the difference, calculated at the center of dHvA period, between the values of magnetic induction in two adjacent domains and the range of existence of CDs Δ in every period of dHvA oscillations, defined as a part of dHvA period occupied by non-uniform phase (see Ref. [9]). By definition, $\delta b, \Delta \leqslant 2\pi$, where 2π is period of dHvA oscillations in reduced units [2]. It was shown also [9] that the characteristics of the non-uniform phase, e.g. δb and Δ, depend on the temperature T, magnetic field $\mu_0 H$ and Dingle temperature T_D through the reduced amplitude of dHvA oscillations $a = a(\mu_0 H, T, T_D)$:

$$\delta b = 2a \sin\frac{\delta b}{2},$$
$$\Delta = 2\left(\sqrt{a^2 - 1} - \cos^{-1}\frac{1}{a}\right). \tag{2}$$

Eqs. (2) can be considered as definition of the function $\delta b = \delta b(\Delta)$ (or *vice versa*) in parametric form with parameter a. Thus, the magnetic induction splitting δb and the range of existence of CDs Δ appear to be dependent on each other at wide range of applied field $\mu_0 H$ and temperature T [13]. In particular, near the point of DPT Eq. (1) the simple relationship between the range of existence of CD structure Δ and the magnetic induction splitting δb is fulfilled, e.g. $\Delta = (\delta b)^3/36$.

The measured, or absolute, values of the range of existence of CD structure Δ_{CD} and magnetic induction splitting δB are defined as follows:

$$\Delta_{CD} = \frac{\Delta}{k} = \Delta\frac{(\mu_0 H)^2}{2\pi F_0}, \tag{3}$$

$$\delta B = \frac{\delta b}{k} = \delta b\frac{(\mu_0 H)^2}{2\pi F_0}, \tag{4}$$

where $F_0 = (F_h + F_w)/2$ is average fundamental frequency ($F_h = 970.9$ T and $F_w = 942.2$ T are two fundamental