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EXPERIMENTAL INVESTIGATION OF MAGNETIC DOMAINS IN NON-FERROMAGNETIC METALS

I. A. PRIVOROTSKIĬ

L. D. Landau Institute of Theoretical Physics, USSR Academy of Sciences

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THE formation of magnetic domains in non-ferromagnetic metals is possible under conditions of a strong de Haas-van Alphen effect, when the amplitude of magnetization oscillation is not small in comparison with the oscillation period. It is important in this case that the magnetization **M** is uniquely determined by the value of the induction **B**, rather than by the value of the field **H**[1]. If

$$4\pi\left(\frac{\partial M}{\partial B}\right)_{\max} > 1,$$

then instability regions appear on the state diagram H = H(B) (Fig. 1). The unstable states correspond to that portion of the curve between points B_1 and B_2 which is determined from the condition of equality of the shaded areas. For a given value of H, the stable phase turns out to be the phase with the lowest value of thermodynamic potential

$$\tilde{\Phi} = -\frac{1}{4\pi}\int_0^H B\,dH.$$

States with $\partial H/\partial B > 0$ for $B_1 < B < B_2$ can be metastable states, while states with $\partial H/\partial B < 0$ are completely unstable. The thermodynamic potentials of the phases with inductions B_1 and B_2 are equal, and these phases can coexist.

The magnetic field H inside a long cylindrical sample placed inside a longitudinal external field H_0 coincides with H_0. Consequently a first-order phase transition must occur in such a sample in a longitudinal external field $H_0 = H_c$ (see Fig. 1), namely a jumpwise change in induction from B_1 to B_2.[2]

In the case of a thin plate in an external field H_0 perpendicular to it, a domain structure, i.e., the splitting into layers of successive regions with induction B_1 and B_2, is thermodynamically advantageous in the interval $B_1 < H_0 < B_2$. The phase concentrations are determined from the condition of conservation of the magnetic flux $c_1B_1 + c_2B_2 = H_0$. The average sample magnetization in the region of existence of the domain structure must also depend linearly on the external magnetic filed H_0.

The possible formation of domains under the conditions of the de Haas-van Alphen effect was predicted by Condon[3]. His experiments confirmed indirectly the existence of domains in beryllium: jumps in the magnetic moment of a cylinder in a longitudinal external field were discovered, while in the case of a plate in an external perpendicular field H_0, a linear dependence of the magnetization on H_0 was observed (Fig. 2). A detailed theory of domain structures under de Haas-van Alphen conditions, including the theory of surface tension at the phase interface and the theory of emergence of the domains to the surface, is presented in[4,5].

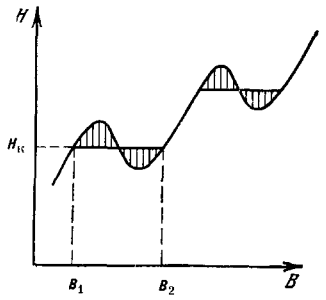

FIG. 1

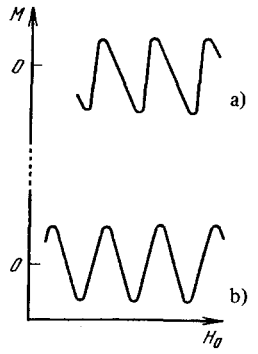

FIG. 2. Dependence of magnetization of beryllium on H_0 at T = 1.4°K and $H_0 \sim$ 30 kOe [3]. a) Cylindrical sample in a longitudinal external field; b) disc in a transverse field.

In recent work, Condon and Walstedt[6] presented a direct proof of the existence of magnetic domains in silver. They observed a splitting of the nuclear magnetic resonance frequency in a silver plate, the splitting being connected with the formation of a domain structure. The experiments were performed at helium temperatures, and splitting was observed at $T < 2.5$°K. A plate of dimensions $8 \times 8 \times 0.8$ mm was placed in a perpendicular field $H_0 \approx 99$ kOe produced by a superconducting solenoid. The surface of the plate was perpendicular to the [100] crystallographic axis.

The silver used in the experiments was a mixture of isotopes (^{107}Ag and ^{109}Ag) with approximately equal concentrations. The nuclei of ^{107}Ag and ^{109}Ag have a spin $I = 1/2$ and consequently do not possess a quadrupole moments. Resonance was observed on the ^{109}Ag nuclei in the skin layer, at frequencies $\nu = \mu B/k \approx 18$ MHz, where μ is the magnetic moment of the ^{109}Ag nucleus. The width of the resonance line was of the order of 0.1 Oe, which is significantly smaller than the observed splitting of the resonance. The values of the induction were determined to within 0.5 Gauss.

Outside the region of existence of the domain structure ($H_0 < B_1$), the induction B in the plate is equal to the external field H_0, and the resonance frequency increases linearly with H_0. Further, in the region B_1

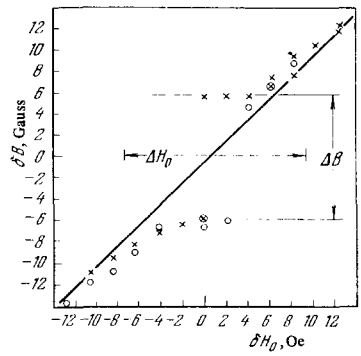

FIG. 3. Magnetic induction in a skin layer vs. the external magnetic field H_0 [6]. The resonance frequencies ν were determined by observing the signal of free precession of the spins of the ^{109}Ag nuclei after the application of radio-frequency pulses at frequencies ν_1 = 17913.7 and ν_2 = 17916.7 kHz. The apparatus used made it possible to measure the differences $\nu - \nu_1$ and $\nu - \nu_2$. The corresponding experimental points are denoted by circles and crosses. The dashed lines show that for the given value of H_0 there were two resonance frequencies, but one of these could not be measured with sufficient accuracy because of the small amplitude of the signal. The solid line with slope 1 is drawn for comparison.

$< H_0 < B_2$, two resonance frequencies independent of H_0 and corresponding to values of induction B_1 and B_2 were observed. The amplitudes of the signals at these frequencies depend linearly on H_0 in correspondence with the linear dependence of the phase concentration on H_0. When $H_0 > B_2$ the resonance splitting vanished and re-appeared subsequently in a new cycle of de Haas-van Alphen oscillations. The oscillation period ΔH_0 was equal to 16.7 Gauss, while $\Delta B = B_2 - B_1 \approx 11$ Gauss. Under the assumption that

$$M = M_0 \sin \frac{2\pi (B - H_k)}{\Delta H_0},$$

the parameter

$$4\pi \left(\frac{\partial M}{\partial B}\right)_{\max}$$

was computed. This parameter must in this case be equal to

$$\frac{\pi \Delta B/\Delta H_0}{\sin (\pi \Delta B/\Delta H_0)} \approx 2.6.$$

The results of the experiments are shown in Fig. 3.

The observed picture agrees fully with theory and is evidence of the fact that the depth of the skin layer is large in comparison with the domain dimensions, for otherwise the distortion of the domain structure near the surface, at a depth of the order of the domain width, would smear out the resonance. In addition, the distinct separation of the resonance frequencies means that the domain dimensions are large in comparison with the width of the transition region (the domain wall) in which the change of the induction from B_1 to B_2 occurs. It is also curious that the presence of splitting at T = 2.2°K depends on whether the sample is heated or cooled to that temperature, i.e., the supercooling effect predicted by theory was observed.

Thus, the existence of domains in non-ferromagnetic metals is now firmly established. Further investigation of this phenomenon, and in particular the discovery of domain structures in other metals, as well as the investigation of the form of the domains inside the sample and on its surface, are undoubtedly of great interest. One hopes that the exceptionally beautiful and accurate work by Condon and Walstedt will attract attention to this difficult but very curious problem.

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