STATISTICAL THEORY OF PINNING ON POINT DEFECTS

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The statistical treatment of pinning on point defects is given including the correlations of the number of defects in neighbouring volumes (the interaction of these volumes with the fluxoid is taken as the elementary interaction causing the pinning). For higher defect densities, the agreement with the experiments on niobium is better than with the previous theory. This method of correlations seemed suitable for studying the effect of “cutting-off” the small elementary interactions and for the replacement of the Gauss distribution function by the Poisson distribution function for the number of defects in the elementary volumes. Both these efforts give negative results with respect to the experiments; so far we are therefore not able to explain quantitatively the large increase of the pinning force at small defect densities and small magnetic fields, as well as its decrease to zero always for fields smaller than $H_{c2}$. The attractive interaction between the flux lines in type II superconductors with small Ginzburg-Landau parameter could give a qualitative explanation of the enhancement of the pinning at small defect densities.

1. INTRODUCTION

The magnetic field penetrates into type II superconductors (i.e. superconductors with Ginzburg-Landau parameter $\kappa > 1/\sqrt{2}$) in form of flux lines (fluxoids, flux tubes), producing a two-dimensional periodical structure in the plane perpendicular to the field. Each flux line carries a quantum of flux,

$$\Phi_0 = \frac{hc}{2e} \approx 2 \times 10^{-7} \text{ G cm}^2.$$

The penetration of magnetic field begins in relatively low magnetic fields and by applying an electrical current, the whole fluxoid lattice is driven into motion — unless there is any force in the superconductor holding the equilibrium with the Lorentz force. These so-called pinning forces are caused by the interaction of flux lines with different inhomogeneities and irregularities of the crystal lattice (dislocations, precipitations of other phases, phase and grain boundaries, point and line defects, clusters).

The initial study of pinning was very difficult, because of the impossibility of creating defects of one sort with defined properties.

For the majority of physical properties of type II superconductors, we can take the fluxoids as consisting from a normal kernel with diameter $\xi$ (the coherence length); about this kernel the superconducting current shields the magnetic field in distance $r \geq \lambda$ (the penetration depth). The magnetic field reaches maximum in the midst of

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the kernel, the order parameter \( A \) (the effective Ginzburg-Landau wave function of the superconducting electrons \( \psi \)) is zero.

There are many effects which can cause an attractive or repulsive interaction between the fluxoid and the defect \([1-7]\).

The specific volumes in the superconducting and normal state are different, therefore the fluxoid "feels" the elastic strain of the defect (its energy is different in the case, when it is "in" the defect or not). Similarly, the elastic constants in the superconducting and normal state are different. The elastic energy of the fluxoid changes therefore in the neighborhood of the defect. This so-called "(di)elastic" interaction is very important for the pinning and is also responsible for the pinning on point defects.

Precipitations of other phases and dislocation networks can change the local superconducting parameters (mean free path, phonon spectrum, density of states) and in such a way the basic parameters determining the self energy of the fluxoid with respect to its position (e.g. the \( A \lambda \)-interaction).

The force between the free surface of the superconductor and the flux line can be interpreted as the force between the flux line and its image \([8]\). The "magnetic" interaction between flux lines and the phase and grain boundaries can be treated in an analogous way \([9]\).

Other possible interactions causing pinning are: The interaction of the flux lines with permanent magnetic moments of impurities (paramagnetic interaction), the interaction of the defect with the dislocations of the flux line lattice etc.

But, the knowledge of the interaction energies between flux lines and defects gives not enough information to the calculation of the volume pinning force \( p_v \), because the (repulsive) interaction between the flux lines is much larger than the interaction flux line-defect. It means that each distortion of a flux line by the elementary interaction fluxoid-defect results in a collective response of the whole flux line lattice, which can be described by its elastic properties.

The calculation of the relation between the elementary interaction force \( p \) (the maximum force between the flux line and the defect) and the macroscopic volume force \( p_v \) is therefore of a very principal interest and prime importance.

The rigid flux line lattice could not be pinned by homogeneous distribution of defects, because their interactions with the fluxoids would cancel mutually. For the ideal flexible flux line we would have \( p_v \sim p \). But, this picture is unrealistic, because of the mentioned elastic properties of the flux line lattice and because of the self energy of the fluxoid (some kind of line tension). The real situation is somewhere between these cases of total rigidity and ideal flexibility.

The most important work in this direction was made by Labusch \([10]\). He considered the interaction of the fluxoids (density \( B/\Phi_0 \)) with randomly distributed "obstacles" (density \( N/cm^2 \)) and obtained in the so-called "lattice" approximation (i.e. the flux lines form an almost perfectly periodic lattice in a relatively large volume — this is true almost in the whole region of fields between \( H_{c1} \) and \( H_{c2} \)) a