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THE MAGNETIZATION CURVE OF In_2Bi INTERPRETED ON THE BASIS OF THE BOSON METHOD

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The magnetization curve of the pure intermetallic compound In_2Bi is interpreted on the basis of the boson formulation of superconductivity. Experimental results are in fair agreement with the numerical curve calculated in an approximation with summation over 6000 reciprocal lattice vectors.

The interpretation of magnetization curves is an especially important problem in the theory of type II superconductivity. The growing interest in this problem is shown in many papers (see for example a review article [1], papers based on microscopic theories [2–9], and phenomenological studies [10–16]). The theoretical papers are generally based on the Eilenberger [17] version of Gorkov equations [18] or as regards the boson formulation of superconductivity on modern ideas of quantum field theory. The present paper gives the results of computations of the magnetization curve of a pure type II superconductor, based on the boson method and compares the results with the experimental curve measured on pure In_2Bi sample.

Intermetallic compounds such as In_2Bi, with a relatively large ratio of the mean free path to coherence length allow one to investigate superconducting properties of pure type II superconductors. From crystallographic analysis, [19] it is known that In_2Bi forms a hexagonal lattice with parameters $a = 5.469$ Å, $c = 6.579$ Å. Cylindrical samples were made from ingots of high purity In and Bi. They were melted together in a Pyrex tube under a vacuum of better than 10^{-4} mm of mercury. The magnetization measurements were carried out using the sensitive integrating method, as was described in [20]. The cylindrical sample was mounted in one of two oppositely wounded 6000-turns pick-up, coils. They were connected to the Y-axis of $X-Y$ recorder. To the X-axis was connected a voltage proportional to the external magnetic field generated by a superconducting solenoid with homogeneity better than 0.5% over the distance of the sample length. The magnetization curve was directly plotted on an $X-Y$ recorder by slowly varying the

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field of the superconducting magnet from 0 above H_{c2}. The stabilization of temperature, while the magnetic field was on, was better than 0.01 K.

Small hysteresis magnetization curves were obtained from these measurements. The experimental values of critical fields extrapolated to 0 K are: $H_c(0) = 600$ Oe, $H_{c2}(0) = 1645$ Oe. In order to compare experiment with predictions of the boson method the magnetization measurements were carried out at $T = 1.32$ K, in reduced units $t = 0.23$. From the magnetization curve shown in Fig. 1 the experimental values of G–L parameter κ and penetration depth λ_L were obtained $\kappa = 1.73$, $\lambda_L = 826$ Å.

In the boson method it has been shown [7], that in describing magnetic phenomena in type II superconductors, in addition to quasi-electrons, are very important quanta of collective excitations that is bosons, which can be interpreted as the density waves of an electronic gas, or as bound states of electrons with an opposite spin and a total momentum not equal to 0. The equations of motion for boson and fermion operators are invariant under the transformation induced by function $f(\vec{x})$, equal to half the phase of the order parameter $\vec{\Delta}(\vec{x})$, a solution of the Laplace equation

$$\vec{\nabla}^2 f(\vec{x}) = 0. \tag{1}$$

The choice of function $f(\vec{x})$ determines a given situation of the superconductor (e. g. given magnetization or the Josephson current). The ground state current is given by

$$\vec{J}(\vec{x}) = \frac{1}{4\pi\lambda_L^2 e}\int d^3y c(\vec{x}-\vec{y})\,[\vec{\nabla}f(\vec{y})-e\vec{A}(\vec{y})], \tag{2}$$

where A is the transverse component of the vector potential and λ_L is the London penetration depth. $c(\vec{x}-\vec{y})$ is the boson characteristic function, which Fourier transformation $c(\vec{g})$

$$c(\vec{x}) = \frac{1}{(2\pi)^3}\int d^3g c(\vec{g}) \exp(i\vec{g}\cdot\vec{x}) \tag{3}$$

in our calculations was approximated by Eq. (8). From the solution of the basic equations for $f(\vec{x})$ and $\vec{J}(\vec{x})$ functions the energy can be determined

$$W = \frac{1}{2e}\int d^3x[\vec{\nabla}f(\vec{x})-e\vec{A}(\vec{x})]\cdot\vec{J}(\vec{x}). \tag{4}$$

Next from thermodynamical considerations the Gibbs free energy G can be obtained. From the equilibrium condition $\partial G/\partial n = 0$, where n is the density of fluxoids, the constitutive equation describing the magnetization curve can be obtained:

$$H = B\sum_{l,m}\left[F(g)+\tfrac{1}{4}\,g\frac{\partial F(g)}{\partial g}\right], \tag{5}$$

where $B = n\phi_0$ is an induction, l, m are integers running from $-\infty$ to $+\infty$ and g is a modulus from the vector of the reciprocal lattice:

$$g = 2\pi n\sqrt{b^2l^2+a^2m^2-2ablm\cos\theta}. \tag{6}$$

The function $F(g)$ is defined in terms of the boson characteristic function $c(g)$:

$$F(g) = \frac{c(g)}{c(g)+\lambda_L^2 g^2}. \tag{7}$$

For $c(g)$ in our calculations was taken an approximate expression [7]:

$$c(g) = \frac{1}{1+0.438g^2\xi^2+0.025g^4\xi^4}. \tag{8}$$

We assumed, that flux lines form a triangular (hexagonal) lattice. The summation in Eq. (5) over the reciprocal lattice vectors was performed with more than 6000 reciprocal lattice vectors taken into account. The result of the computations is presented in Fig. 1. The

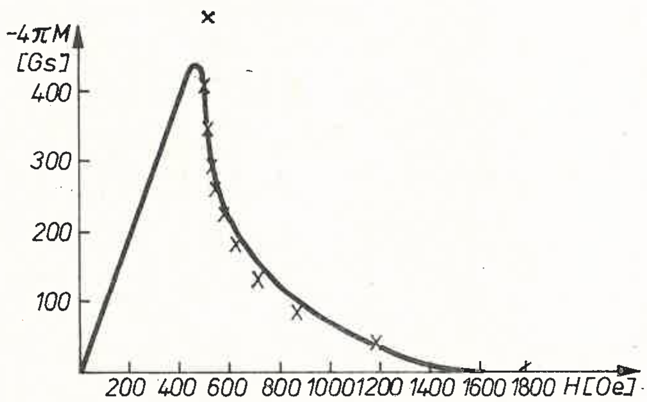

Fig. 1. Magnetization curve of a pure In_2Bi sample compared with boson method results for $\lambda_L - 580.1$ Å and $\varkappa - 1.6$. The solid line denotes experimental values at $t - 0.23$, crosses are theoretical predictions

continuous line denotes experimental results, while crosses are the theoretical predictions computed with two fitting parameters: $\lambda_L = 580.1$ Å and $\kappa = 1.6$. These values are sufficiently good compared to the experimental results presented above. The discrepancy of the values of G–L parameter κ is smaller than 10%, however for λ_L the deviation is some-what higher.

As follows from Fig. 1, the theory describing ideal type II superconductors, predicts a spontaneus transition from the Meissner state at the lower critical field H_{c1}. However, the real In_2Bi specimen shows some rounding of the magnetization curve in the neighbourhood of H_{c1}. This is mainly due to sample inhomogeneities. A better approximation of the experimental results can probably be obtained by also taking into account the energy of normal cores, which is nonvanishing for low κ-superconductors.[1]

[1] The normal cores energy can influence the shape of the magnetization curve near H_{c2}, which in the boson formulation can be determined as a field, where computed magnetization changes sign: from diamagnetic to unphysical paramagnetic values.

In conclusion we stress, that until now the boson method has been confirmed by experiments performed on Nb and V [21, 7]. Our results give the third example of the reasonable good agreement of the boson method with experiment performed on a pure In_2Bi sample.

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