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ON DETERMINATION OF THE MAGNETIC FIELD PENETRATION DEPTH IN OXIDE SUPERCONDUCTORS BY POLARIZED NEUTRONS REFLECTION

D.A.Korneev, L.P.Chernenko

The $R_+(k_\perp)$, $R_-(k_\perp)$ reflection coefficients are calculated for $YBa_2Cu_3O_7$ film sprayed on $SrTiO_3$ ($k_\perp$ is a normal to the surface component, of a wavevector of neutrons) using the quantum mechanical model describing the reflection of neutrons from the surface of a thin superconducting film. The dependence of $S(k_\perp) = R_+(k_\perp)/R_-(k_\perp)$ on the depth of magnetic field penetration into a superconductor Λ, on the external magnetic field H, and on a film thickness d is analysed. The possibility is motivated of carrying out experiments on determination of Λ under condition compared favourably with those under which the experiments with ceramic samples of high temperature superconductor have been conducted.

The investigation has been performed at the Laboratory of Neutron Physics, JINR.

Об определении глубины проникновения магнитного поля в оксидные сверхпроводники методом отражения поляризованных нейтронов

Д.А.Корнеев, Л.П.Черненко

На основе квантово-механической модели, описывающей процесс зеркального отражения нейтронов от поверхности тонкой сверхпроводящей пленки, рассчитаны спинзависящие коэффициенты отражения $R_+(k_\perp)$, $R_-(k_\perp)$ для пленки $YBa_2Cu_3O_7$, напыленной на подложку из $SrTiO_3$, где $k_\perp$ – нормальная к поверхности компонента волнового вектора нейтронов. Проанализирована зависимость функции $S(k_\perp) = R_+(k_\perp)/R_-(k_\perp)$ от глубины проникновения магнитного поля в сверхпроводник Λ, величины внешнего магнитного поля H и толщины пленки d. Обоснована возможность постановки эксперимента по определению Λ в условиях, выгодно отличающихся от условий экспериментов с керамическими образцами высокотемпературных сверхпроводников.

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Recently the results[1] on determination of the magnetic field penetration depth in $YBa_2Cu_3O_7$ obtained by polarized neutron reflection have been published. The polarized neutron reflection method compared with the other ones[2,3] has demonstrated a significant divergence (by 10 times) from estimation of Λ. As yet, the reasons of such divergence are not clear.

It should be noted that basically, under definite conditions, the polarized neutron reflection at low energies allows one to determine the dependence of a magnetic field value on a depth. The possibility of interpreting the obtained results in the frame of the problem of neutron reflection from a medium surface should be referred to such conditions. The high density and substance magnetization homogeneity along the surface (the absence of pores, multiphase states and other inhomogeneities) is the most essential requirement. Thus, it follows that the whole of the sample must be in the Meissner phase. The density of superconducting ceramics differs from the crystallographic one. Hence, those ceramics bear a significant structure inhomogeneity. This fact to some extent may reduce the evidence of the Λ estimations on the base of experiments on polarized neutron reflection from the surface of mass samples. Besides, microscopic divergences from ideal planeness, i.e. surface undulations of a ceramic sample $YBa_2Cu_3O_7$ at the experiment[1] have led to the fact that the uncertainty $\Delta\theta$ represents 25% of the mean value of a grazing angle θ. Clearly the great value of a parameter $(\Delta\theta/\theta)$ reduces the sensitivity of the method and it is connected with some hypotheses of the surface quality.

Below we analyse the chance of carrying out an experiment to determine Λ by means of polarized neutron reflection under more clear conditions using a thin film of identical composition; the film is made by spraying on monocrystal base. It goes without saying that high homogeneity of a film and the quality of its surface provided by a monocrystal base should essentially improve the reliability of the Λ estimation for the following reasons: firstly, due to the adequacy of a real reflection process and a model forming the data handling basis; secondly, because of an increase of a method sensitivity through a decrease of $(\Delta\theta/\theta)$. It is known from[4] the pattern of magnetic field distribution in a thin superconducting film differs from the one in a half-infinite sample in the case that a penetration depth is comparable to a film thickness d. According to[4] the dependence of induction on a coordinate z normal to a film surface is of the from

$$B(z) = H \cdot \frac{Ch((2z-d)/\Lambda)}{Ch(d/2\Lambda)}, \qquad (1)$$

where H is the value of an external magnetic field parallel to a film surface. In order to handle experimental data on polarized neutron reflection from a superconducting film surface the method of calculation of values R_+ and R_- is essential. Here R_+ and R_- are reflection coefficients of neutrons polarized "up" and "down" the field H,respectively. We consider the induction B(z) in a film is inhomogeneous and it is described by the equation (1). The film is applied on the base of the known composition.

The calculation method developed in [5] allows one to estimate reflection coefficients $R_+(k_\perp)$ and $R_-(k_\perp)$ ($k_\perp$ — is a normal component of a wavevector of incident neutrons to the surface) and thus, to determine the value of expected discrepancy between $R_+(k_\perp)$ and $R_-(k_\perp)$ according to Λ, d, H; it also permits to judge a sensitivity of the method with relation to the change of $(\Delta\theta/\theta)$.

The total effective potential of a medium is written in the form of:

$$U = 4\pi \frac{\hbar^2}{2m} N(b_n \pm b_M(z)), \quad (2)$$

where m is a neutron mass, N is a number of nuclei in a unit of volume, b_n is a mean length of coherent neutron-nucleus scattering, and $b_M(z)$ is calculated by the formula

$$b_M(z) = \frac{2.31 \cdot 10^{-10}}{N}(B(z) - H). \quad (3)$$

In (3) the dimensions of quantities are as follows: b_M — Å; N — $Å^{-3}$; B,H — gausses.

So, a superconductor without ferromagnetic ordering in the external field can be thought of as a magnetized medium with some effective "magnetic" length of neutron scattering related to the induction and external field by the formula (3); in this case the total neutron scattering length has two values of opposite polarizations in an incident beam:

$$b^{\pm}(z) = b_n \mp b_M(z).$$

In the table given below we present the values being used hereafter and calculated on the basis of tabulated and crystallographic data:

	Film ($YBa_2Cu_3O_7$)	Base ($SrTiO_3$)
b_n (Å)	$0.631 \cdot 10^{-4}$	$0.42 \cdot 10^{-4}$
N($Å^{-3}$)	0.0747	0.0837
b_M (Å)	$3.06 \cdot 10^{-9}$ (B(z) - H)	0.0
k_o ($Å^{-1}$)	$7.7 \cdot 10^{-3}$	$6.64 \cdot 10^{-3}$
λ_o (Å)	814	946

where B and H are being measured in gausses; $k_0 = (2\pi/\lambda_0)$ is the value of a normal component of a wavevector of incident neutrons obtained if:

$$\frac{\hbar^2 k_o^2}{2m} = U_n .$$

In brief, the principle of the method is that a continuous potential is substituted for a discrete quasipotential:

$$U(z) = \frac{\hbar^2}{2m} \sum_{i=1}^{n} b_z(z_i)\, \delta(z - z_i) . \tag{4}$$

The neutron interaction in $z = z_i$ is proportional to the value of $b_z(z_i)$, which is a mean value of a neutron scattering length on the whole plane of $z = z_i$. A neutron wave function is chosen at each section between z_i and z_{i-1} as a sum of plane waves moving in both directions (a positive and a negative one) with corresponding amplitudes: $A^{(i)}(\vec{k}_\perp)$ and $A^{(i)}(\overleftarrow{k}_\perp)$. By this means the substitution of the written wave function into a Schrödinger equation with a quasipotential (4) reduces it to a system of bounded algebraic equations in relation to $A^{(i)}$. Using this method one may find all $A^{(i)}(\vec{k}_\perp)$ and $A^{(i)}(\overleftarrow{k}_\perp)$ $(i = 1, 2, ..., n+1)$ for any model dependence of $b_z(z_i)$, and thus find out a wave function in an inhomogeneous medium, reflection coefficients $R(k_\perp) = |A^{(1)}(\overleftarrow{k}_\perp)|^2$ and transmission coefficients $T(k_\perp) = |A^{(n+1)}(\vec{k}_\perp)|^2$ of neutrons (here n is a number of points where a potential (4) is given). A continuous potential corresponding to a discrete one is defined for a homogeneous medium (b_z = const, $\Delta z = z_{i+1} - z_i$ = const) by the following expression:

$$U = 4\pi \frac{\hbar^2}{2m} \left(\frac{b_z}{\Delta z}\right) . \tag{5}$$

The latter expression may serve as a determination of a potential for a one-dimensional homogeneous problem. A particular recalculation of "three-dimensional" scattering lengths in "one-dimensional" ones is done taking this simple condition as the base: the potential of one- and three-dimensional problem must agree very closely.

The results of experiments on the polarized neutron reflection are accepted to be presented in the following form:

$$S_\theta(k) = \frac{N_\theta^+(k)}{N_\theta^-(k)} , \tag{6}$$

where $N_\theta^+(k)$, $N_\theta^-(k)$ are the intensities of the narrowly collimated

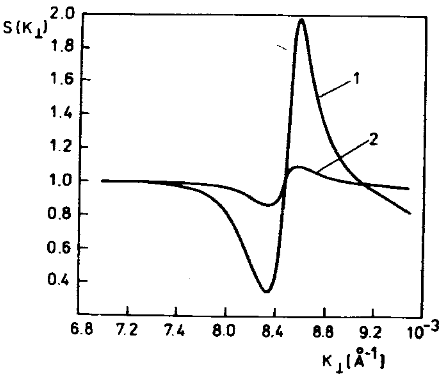

Fig.1. S($k_\perp$) *for cases: 1 – Λ = 200 Å; 2 – Λ=1000 Å, when the field* H=420 *gausses for a film 1000 Å thick.*

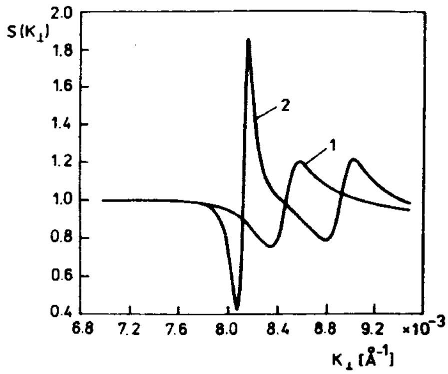

Fig.2. S($k_\perp$) *for cases: 1 –* d = *=1000 Å; 2 –* d *=1500 Å, when the field* H=*105 gauses and* Λ=*200 Å.*

neutron beam reflected at a grazing angle θ, k is a wavevector of incident neutrons. It should be noted that $k_\perp = k \cdot \theta$. Signs – and + show that neutrons have been registered with the help of a spin-flipper being switched on and switched off, respectively. A spin-flipper is the device reversing the polarization vector $\vec{P}$ about the vector $\vec{H}$ in an incident beam. In the general case P = P(k). The probability f of the polarization reverse with a spin-flipper is also the function k, i.e. f = f(k).

Now we turn our attention to the discussion of calculated values of $S(k_\perp) = R_+(k_\perp)/R_-(k_\perp)$ for a model superconducting film with the values of neutron-optical parameters given in the Table.

Figures 1÷ 3 show calculation results of the $S(k_\perp)$ for an ideal reflectometer, i.e. $(\Delta\theta/\theta)=0.$; $(\Delta k/k)=0.$; P = 1.; f =1.

Figure 1 presents $S(k_\perp)$ for a film with a thickness of d = 1000 Å in the region of values $k_\perp \gtrsim k_0$. Two cases are given: 1) when Λ = 200 Å (curve 1) and when Λ = 1000 Å (curve 2) if an external field is equal to 420 gausses. $S(k_\perp)$ is of oscillating character (also see fig.2). It is seen that as Λ decreases the effect increases.

Fifure 2 demonstrates the differences of $S(k_\perp)$ for films with a thickness of 1000 Å and 1500 Å, respectively. A film thickness increase has led to an increase in a number of oscillations in a picked interval $k_\perp$.

The comparison of curve 1 in Figs. 1 and 2 allows one to evaluate the dependence $S(k_\perp)$ on an external field value: as a field decreases the effect also decreases being available for measurement when fields are $\gtrsim$ 50 gausses.

Figure 3 presents a specific case, i.e. when a film with a substrate δ thick does not transfer to a superconducting state. The deficiency

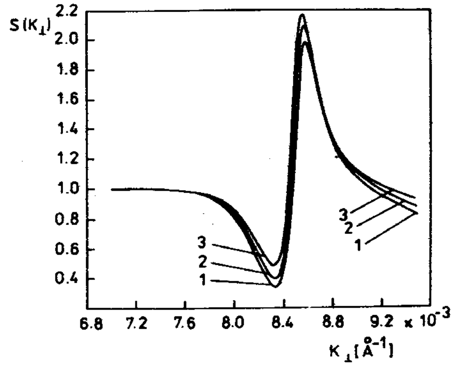

Fig.3. $S(k_\perp)$ *shows the existence of a film layer with the deficiency of oxygen. In a layer* δ *thick on the surface of a film* $B(z) = H = const.$ *Cases: 1* $- \delta = 0$ *Å; 2* $- \delta = 100$ *Å; 3* $- \delta = 200$ *Å. A film 1000 Å thick in the field* H = *420 gausses,* $\Lambda = 200$ *Å.*

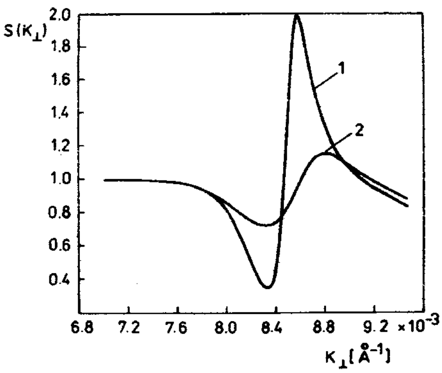

Fig.4. $S(k_\perp)$ *for an ideal reflectometer (curve 1) and considering finite resolution (curve 2). A film with a thickness of 1000 Å, if a field* H=*420 gausses and* Λ=*200 Å.*

of oxygen near a film surface may cause the existence of such a layer. Figure 3 demonstrates the manner in which $S(k_\perp)$ depending on δ is changing.

The finite reflectometer resolution transforms $S(k_\perp)$ into $S_\theta(k)$; the latter function is equal to $S_\theta(k_\perp)$ at a fixed value of parameter θ when $k = k_\perp/\theta$.

Curve 2 in Fig.4 shows $S_\theta(k_\perp)$ at $\theta = 5 \cdot 10^{-3}$; $(\Delta\theta/\theta) = 4 \cdot 10^{-2}$ and $P(k) = 1 - c/k^4$ ($c = 6.28 \cdot 10^{-3}$ Å^{-4}). The dependence P(k) has been taken from /7/ . Curve 1 in Fig.4 is an ideal case. One may see that taking into account the reflectometer real parameters we observe a significant decrease in the effect.

It should be noted that at first sight it seems advantageous to increase the parameter θ because at $(\Delta\theta/\theta)$ it tends to zero. But θ will be confined by $k = (k_0/\theta) \gtrsim k^*$, i.e. $\theta \lesssim (k_0/k^*)$ which comes from the ordinary requirement: the k values must get to the region of k* values where the spectral density of thermal neutron flux is rather high, in order to provide the statistic precision in measuring $S(k_\perp)$. Thus, for example, the typical value of k* for thermal beam of the pulsed reactor IBR-2 of JINR is $k^* = (2\pi/\lambda^*) = 1.7$ Å^{-1} ($\lambda^* \simeq 4 \div 5$ Å). That corresponds to $\theta \lesssim k_0/k^* \simeq 5 \cdot 10^{-3}$.

Conclusions:

1. The experiment on the determination of Λ in film high-temperature superconductors by polarized neutrons will allow one to get the Λ using more precise conditions compared to those used for investigations on thick samples. The estimation of Λ becomes more reliable.

2. The calculation method has been created for handling experimental spectra of neutrons reflected from a thin superconducting film, applied on a mass base and placed in the magnetic field H, to determine the Λ and the thickness of the substrate having no superconducting properties.

3. Neutron-optical parameters for the $YBa_2Cu_3O_7$ film and $SrTiO_3$ base are such that the effect might be statistically observable in the region of values of $k \gtrsim k_0 = 7.7 \cdot 10^{-3}$ Å^{-1} at a grazing angle of $\theta \lesssim 5 \cdot 10^{-3}$. In this case the value of the very effect grows with an increase of the field H and with a decrease of the Λ. The region of $0 \lesssim \Lambda \lesssim 2000$ Å for fields $\simeq 400$ gausses is considered to be available for measurements of the Λ. When a field reduces, this region gets narrower. In real conditions of the experiment the values of $H \lesssim 50$ gausses, apparently, might not provide one with a reliable determination of a Λ at different values. If the first critical fields is $H_1 < 50$ gausses, the latter condition limits the correctness of the experiment interpretation in the frame of a one-dimensional neutron reflection model.

4. Film thickness at which advantages of the thin-film sample $YBa_2Cu_3O_7$, connected with a characteristic non-monotone behaviour of $S(k_\perp)$, are apparent lie in the interval of $1000 \div 1500$ Å.

5. The uncertainty in the reflectometer parameter $(\Delta\theta/\theta) \sim 5\%$ and consideration of incomplete neutron beam polarisation preserve all characteristic peculiarities of the $S(k_\perp)$, reducing the effect by approximately two times.

6. The experiments with monocrystal films allow one to determine the value of Λ along definite crystallographic direction determined by the behaviour of a film growth in the process of its preparation. The experiments with polycrystal films give information on the Λ averaged over crystallographic directions considering the degree of a reciprocal crystal disorder. The comparison of experiments on films with a different degree of a mosaic structure will permit one to estimate crystallographic anisotropy of Λ.

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