First publ. in: Physica / B [Condensed Matter], Vol. 267-268 (1999), pp. 149-153

Magnetic flux distribution inside an $YBa_2Cu_3O_7$ superconducting thin film in the mixed state

V. Lauter-Pasyuk[a,b,*], H.J. Lauter[c], M. Lorenz[d], V.L. Aksenov[b], P. Leiderer[a]

[a]*Universität Konstanz, Fakultät für Physik, Postfach 5560, D-78434 Konstanz, Germany*
[b]*Joint Institute for Nuclear Research, 141980 Dubna, Moscow Region, Russia*
[c]*Institut Laue–langevin, BP 156, F-38042, Grenoble Cedex 9, France*
[d]*Universität Leipzig, Institut für Experimentelle Physik II, D-04103 Leipzig, Germany*

Abstract

The study with polarized neutron reflection showed the spatially resolved nuclear and magnetic structure in a high-temperature superconducting (HT_c) film of $YBa_2Cu_3O_7$ in the mixed state in an external field parallel to its surface. The obtained magnetic flux profile is composed of the penetrating Meissner field and the flux-line rows. The flux-line rows show good linear arrangements. A local critical magnetization inside the HT_c film was determined. The total magnetization exhibits flux-line row transitions and increases in average with increasing external field due to the surface barrier and the flux-line interaction.

PACS: 61.12.Ha; 74.76.Bz; 74.60.Ec

Keywords: Neutron reflectometry; HT_c-superconducting films; Mixed state

1. Introduction

Polarized neutron reflectometry (PNR) was already used to investigate the magnetic penetration depth λ at the surface of superconductors or in thin superconducting films. For these studies the magnetic field is applied parallel to the surface of the film. The success of these studies, but also the problems encountered, were reported in Ref. [1]. Since then the magnetic penetration depth of Nb films [2] was carefully studied. For $YBa_2Cu_3O_7$ films the magnetic penetration depth λ_{ab} was determined in Ref. [3]. The penetration of flux-line rows into multilayer superconducting films (e.g. Cu/Nb multilayers) was studied by various techniques summarized in Ref. [4].

New events in thin HT_c (YBCO) films in the mixed state studied by PNR will be presented here. The structure of the penetrating magnetic flux perpendicular to the sample surface was determined through the magnetic scattering length density (SLD_m) profile for different external fields (H_{ext}). In general, the profile of the SLD_m reflects the

*Corresponding author: Institut Laue Langevin, BP 156 F-38042, Grenoble Cedex 9, France Tel.: + 33-4-76-20-75-56; fax: + 33-4-76-20-71-20.

E-mail address: vlauter@ill.fr (V. Lauter-Pasyuk)

contributions from several factors: the magnetic penetration depth λ, the limiting value of the magnetization and the distribution of the penetrating flux (flux lines) inside the film. Furthermore, the magnetization profile obtained from the SLD_m profile as a function of the external field above H_{c1} shows the penetration of flux-line rows. The magnetization increases with increasing H_{ext} within the measured range due to the surface barrier [5] and the flux-line row configuration in agreement with theoretical predictions [4] which was not fully supported up to now by experimental data (e.g. Ref. [6,7]). In the PNR experiment setup the fluxlines in the film are in the equilibrium state, so the results concur with the theory.

2. Experimental details

This study has been carried out on the reflectometer ADAM at ILL. The magnetic behavior of a thin superconducting HT_c film in the mixed state was investigated as a function of increasing external magnetic field $H > H_{c1}$. The sample, a 2000 Å thick $YBa_2Cu_3O_7$ film with the c-axis perpendicular to the film surface (so, $\lambda = \lambda_{ab}$), was cooled to a temperature of 4 K in zero field (ZFC). Then H_{ext} applied parallel to the film surface was successively increased for the measurements from 1.5 to 12 kG. The neutrons were scattered from the film through the substrate of $SrTiO_3$ with an area of 20×20 mm^2 and a thickness of 1 mm (a sketch is shown as inset in Fig. 1). The advantage of using this geometry is described in Refs. [2] and [3]. The main effect is that the oscillations in the reflectivity curve shown in Figs. 1 and 2 are enhanced due to a better contrast in the nuclear SLD combination. Similar experiments on a thicker HT_c film of 3000 Å have been carried on SPN, the reflectometer with polarized neutrons, at the IBR-2 reactor at Dubna [8].

3. Results and discussion

The structure of the film without the magnetic contributions was deduced from the measurement at a temperature of 96 K, thus in the normal-conducting state of the film without external magnetic field. The experimental reflectivity curve is shown in Fig. 1 together with the fit to the data. For the data analysis a fitting program using the multilayer matrix method was applied [9]. The film is not homogeneous as can be seen from the

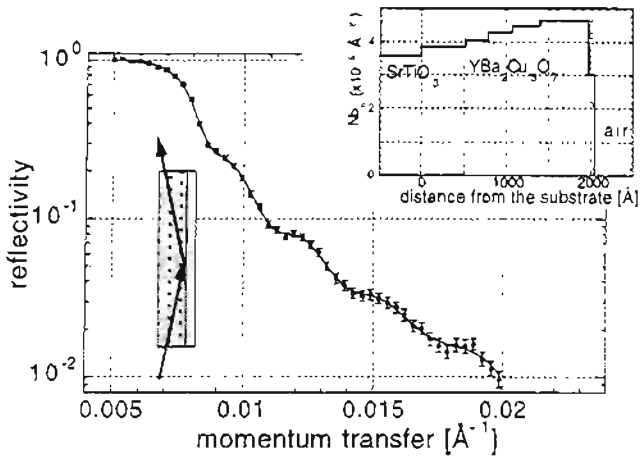

Fig. 1. Reflectivity curve from a 2000 Å thick $YBa_2Cu_3O_7$ film at 96 K. The full line is the fit to the data from which the nuclear scattering length density (SLD) profile was obtained. The SLD profile is seen in the inset. The other inset shows the scattering geometry of the experiment.

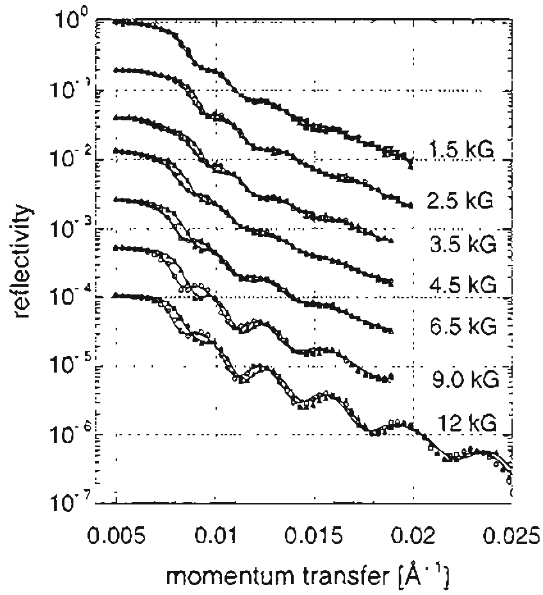

Fig. 2. A set of reflectivity curves for different external magnetic field at 4 K. For R^+ (o) the neutron magnetic moment and the magnetic field are parallel and for R^- (♠) antiparallel.

inset representing the nuclear SLD. The SLD decreases from the surface towards the substrate–film interface. This means that during the laser ablation the full density of the film was not obtained near the substrate interface and it was built up only at the vacuum–film interface. This effect will also influence the magnetic field distribution inside the film.

The reflectivity curves measured at a low temperature of 4 K and applied external field (parallel to the sample surface) are shown in Fig. 2 together with the fit to the data. A small splitting between the two reflectivity curves R^+ and R^- obtained for the two spin states of the polarized neutrons appears near the critical momentum transfer Q_c for an applied field of 1.5 kG. This splitting increases and starts to extend to higher Q with increasing external magnetic field. The corresponding magnetic profiles through the HT_c film were obtained by a model-fit to the reflectivity curves. For this purpose the nuclear SLD deduced from the curve in Fig. 1 was fixed and the profile of the SLD_m was obtained by a simultaneous fit to each pair of R^+ and R^-.

The SLD_m profiles are shown in Fig. 3 for some values of the external magnetic field between 1.5 and 12 kG. It is evident that these magnetic profiles do not show the simple penetration depth behavior, the $\cosh((x-d/2)/\lambda)$-proportionality (x is the distance from the substrate) over the full film thickness d as in the previous publications [3] for the Meissner state at lower fields. The step function character of the SLD_m profiles arises from the model-fit with a fixed number of slices, between 10 and 13 slices, across the film thickness. The profiles for the two spin states are symmetric around the pure nuclear potential, which is here straightened to the flat zero line. In addition, the normalized magnetization profiles are shown by dashed lines. The normalization was made to a field of 1 kG. One should note that the SLD_m is proportional to the magnetization through the equation $SLD_m = cB(z)$, where $c = 2\pi\mu_n m_n/h^2 = 2.31\times10^{-10}$ $\text{Å}^{-2}\,G^{-1}$.

The general description of the SLD_m profile is the following. A clear increasing separation of the two SLD_m (corresponding to R^+ and R^-) starting at both interfaces of the HT_c film represents a

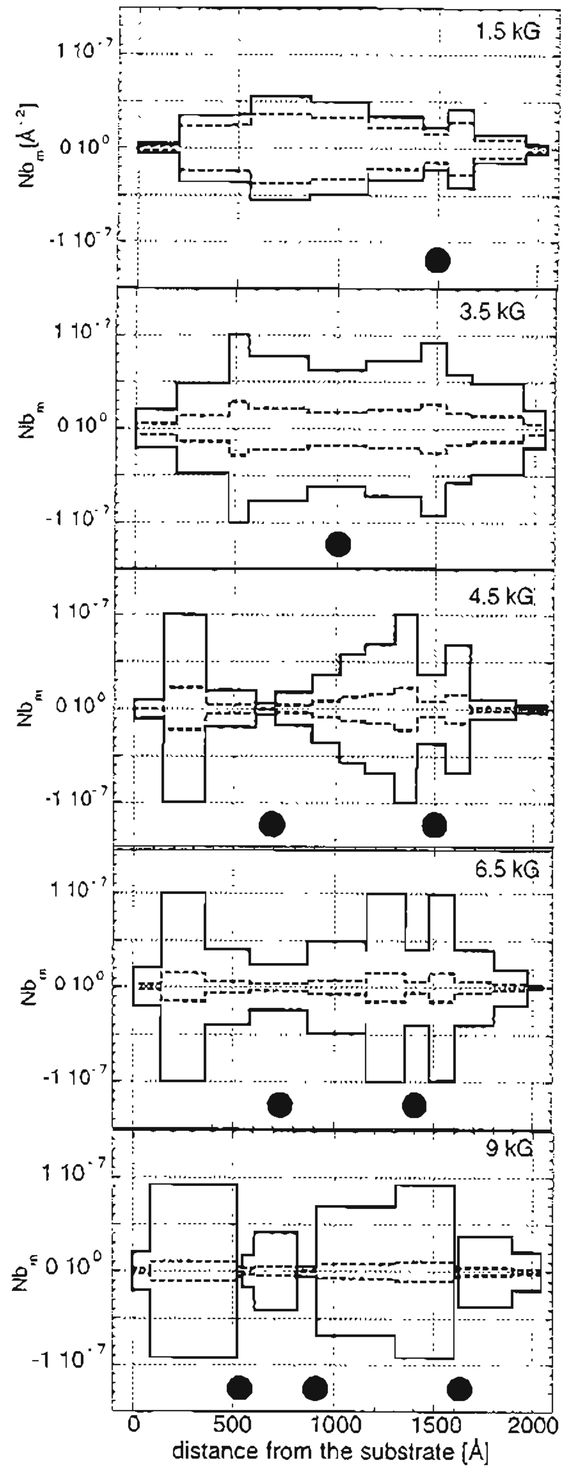

Fig. 3. SLD-profiles obtained from the fit to the data in Fig. 2 for various magnetic fields (full line). The dashed lines give the SLD normalized to 1 kG. The filled circles indicate the positions of flux-line rows.

penetrating field into the film originating from the applied external field. The following drop of the magnetization seen through the SLD_m shows that

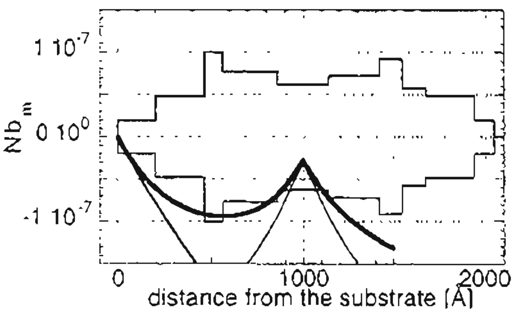

Fig. 4. The SLD-diagram of the measurement with 3.5 kG at 4 K. The thin full line through zero at $x = 0$ shows the penetrating flux from outside the film. The thin full line with the peak at $x = 1000$ Å represents a flux line row. The thick full line is the combination of the two beforehand described effects.

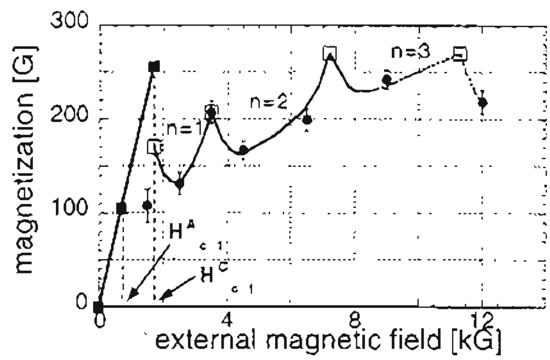

Fig. 5. The total magnetization of the HT_c film as a function of H_{ext}. The full line through the points (●) is based on a calculation [4], n gives the number of flux-line rows in the film. Open squares mark the values of H_{ext} at which flux-line row transitions take place [4]. The straight line characterizes the Meissner state, H_{c1}^{A} and H_{c1}^{C} are explained in the text.

flux (flux-line row) penetrated also into the film. The depicted distribution is the average of the magnetic flux along the film. Between the flux-line rows and the field penetrating from the outside the SLD_{m_0} shows a limiting value of about 1×10^{-7} Å^{-2} independent on the external field. This value corresponds to a magnetization of 430 G [3] and represents an intrinsic H_{c1} for a certain flux-line configuration and density for which a transition to $n + 1$ (n is number of flux-line rows) happens. For all measured magnetic fields in Fig. 3 this critical magnetization is the same. This effect extends also to other HT_c samples (YBCO) measured separately [8].

In Fig. 4 a partial fit to the data explains the connection between the penetrating field from the outside of the film and the flux-line rows. The SLD_m diagram with a field of 3.5 kG was chosen as an example. The left thin line starting at $x = 0$ represents the field penetrating from the substrate side. The peak of the SLD_m of a flux-line row is centered at $x = 1000$ Å. The combination of both curves gives the thick line which touches the limiting value of -1×10^{-7} Å^{-2}. The influence of the penetrating field from the free surface side of the film was neglected.

In Fig. 3 the positions of flux-line rows are marked by filled circles corresponding to the reduced splitting in the SLD_m profiles. The number of flux lines for a given external magnetic field agrees with the theoretical values obtained in Ref. [4].

The SLD_m-values normalized to 1 kG are shown as dashed lines in Fig. 3. If these normalized values averaged over the film thickness remain constant with increasing field, then the magnetization is proportional to the external field and shows, e.g. a Meissner state. The feature is, however, that these normalized values decrease with increasing field, which shows that the magnetization deviates from an extrapolated Meissner state.

The total magnetization M of the film is given by the average of the magnetization profile in Fig. 3 for each value of H_{ext}. The dependence of M as a function of the H_{ext} is shown in Fig. 5 with filled circles. The straight solid line represents the calculated Meissner state in a thin film. H_{c1} in the ab plane for a bulk YBCO is 180 G [10]. When the thickness of the film d reduces to the value of the penetration depth λ, then H_{c1} increases [11], in addition the surface barrier leads to another enhancement of H_{c1} [5]. For a thin film of thickness of 2000 Å and $\lambda_{ab} = 1400$ Å [3] H_{c1} is $H_{c1}^{A} = 700$ G due to the restricted geometry [11]. Taking into account the surface barrier it shifts up on the straight line to $H_{c1}^{C} = 1.7$ kG [4]. However, it is seen in Fig. 3, that already at a field of 1.5 kG a flux-line row entered the film and also in Fig. 5 that the measured magnetization for 1.5 kG is lower than the theoretical one for 1.7 kG. This difference can be explained by the fact that the theoretical formula for H_{c1} was obtained for the case when $d \leqslant \lambda$ and in our case the thickness of the film was slightly bigger than the penetration length. With increasing external field beyond 1.5 kG a curve (solid line in Fig. 5) was adapted to the experimental points. This line derived from a calculation in Ref. [4] shows transition $n \to n+1$ through the peaks in the magnetization. The values of H_{ext} for these transitions calculated under the condition of $d = \lambda$ [4] are marked as open squares. The amplitude in the magnetization was adapted to the experimental points around the transition $n = 1 \to n = 2$. The dashed line around the transition $n = 3 \to n = 4$ calculated to be at 11.3 kG describes an assumed behavior.

So, the magnetization reveals the distinct penetration of flux-line rows into a thin YBCO film through the appearance of peaks. It is essential that the proof of the corresponding increasing number of flux lines is given independently in the SLD_m profile in Fig. 3. It is remarkable that beyond H_{c1} the magnetization in average is increasing over the measured range of H_{ext} in contrast to the behavior of bulk type-2 superconductors. In the case of bulk superconductors a big amount of flux lines can penetrate at H_{c1} without an appreciable flux-line interaction and the magnetization decreases abruptly with increasing H_{ext}. In contrast, only a limited volume is available in the case of a thin film and after a sharp drop of the magnetization at H_{c1}^{C} a local minimum is reached showing the flux-line interaction, i.e. a compression of the flux lines along the flux-line row. This compression with its resistance to further flux-line penetration leads to an increase of the magnetization with increasing H_{ext}. At the second maximum at $H_{ext} = 3.5$ kG a situation is reached where it is energetically more favorable to switch to the configuration with two flux-line rows. Thus, with this rearrangement a big portion of flux lines enters the film and the magnetization drops. But again, with increasing H_{ext} the flux-line interaction enhances which gives a second minimum and which leads to a next maximum and so on.

4. Conclusions

The appearance of the flux-line rows in a thin YBCO film parallel to the film surface was measured in a range of external magnetic fields from 1.5 to 12 kG. The PNR measurement revealed the internal magnetic structures of the film. The magnetization profile perpendicular to the film surface shows the part arising from the screening current and the part from flux-line rows. A local critical magnetization inside the HT_c film along the *ab* plane was determined. The total magnetization exhibits a behavior determined by the surface barrier and the number of flux-line rows. The magnetization increases with increasing external field and is characterized by the flux-line row transitions.

Acknowledgements

We thank J. Schiessling and R. Siebrecht for help during the experiment. This work was supported by the BMBF and INTAS.

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