Study on Local Magnetic Flux Distribution in Type II Supercondcutors by Means of Small-Angle Neutron Scattering

Kozo Osamura and Hiroshi Okuda
Department of Materials Science and Engineering, Kyoto University
Sakyo-ku, Kyoto 606-01 Japan

Michihiro Furusaka
Booster Facility, National Laboratory for High Energy Physics
Oho, Tsukuba 305 Japan

Yuji Itoh and Masayuki Imai
The Institute for Solid State Physics, University of Tokyo
Tokai, Tsukuba 319-11 Japan

Teruo Matsushita and Edmund Soji Otabe
Kyushu Institute of Technology, Faculty of Computer Science and Systems Engineering
Iizuka, Fukuoka 820 Japan

Abstract- In order to assess the magnetic flux distribution in type II superconductors, the correlation function was derived from SANS intensities. The distribution in Nb single crystal was consistent with the result of magnetization measurements. An existence of short range ordering in the magnetic flux arrangement in Bi2212 crystal was suggested at 7.7 K under magnetic field of 0.25 T, which is a sufficiently high field larger than the critical field.

I. INTRODUCTION

Several techniques have been applied to investigate the structure of quantized magnetic flux distribution in type II superconductors, since the magnetic flux line lattice (FLL) was predicted by Abrikosov in 1957[1]. The first observation was done by means of the decoration technique in 1968[2] and later by small angle neutron scattering technique in 1971[3]. In 1970s, several experiments were performed for verifying the theory of FLL. To understand the nature of FLL is important in practice to improve the critical current density. In many pinning theories, FLL has been idealized as nearly perfect triangle lattice. In fact, however, FLL is not so perfect. There are some imperfections: lattice defects, transition to disordered state at high magnetic field, deformation due to flux pinning in real superconductors. Recently, several modern techniques to observe FLL have been developed: scanning tunnel microscopy, electron holography, and others. Small angle neutron scattering (SANS) technique is, however, still attractive to investigate the structure of FLL, because almost all materials are transparent to neutrons and therefore three dimensional information is easily obtainable.

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In the present study, the local magnetic flux distrsibutions in several type II superconductors have been investigated by means of SANS measurements. Here the preliminary analytical results are reported.

II. EXPERIMENTAL PROCEDURE

The experiments were carried out using SANS-U facilities installed at JRR-3M, Atomic Reactor of JAERI. The wavelength of incident neutron beam was selected to 0.7 nm with $\Delta\lambda/\lambda \cong 10$ %. The area detector with 64x64 cm^2 was positioned 12 (or 8) m from the sample. At the center of split type electromagnet, the cryostat was installed. The magnetic field was applied parallel to the incident neutron beam.

Two types of single crystals were used. One was a cylinder-shaped Nb single crystal with dimensions of 10 mm dia and 10 mm length. The direction of Nb cylinder axis was [110] and parallel to the incident neutron beam. Second one was plate-like Bi2212 ($Bi_2Sr_2CaCu_2O_y$) oxide single crystals with ~1 mm thick, ~5 mm width and ~20 mm length prepared by the floating zone technique. Both incident beam and magnetic field were parallel to the c-axis of Bi2212 crystal.

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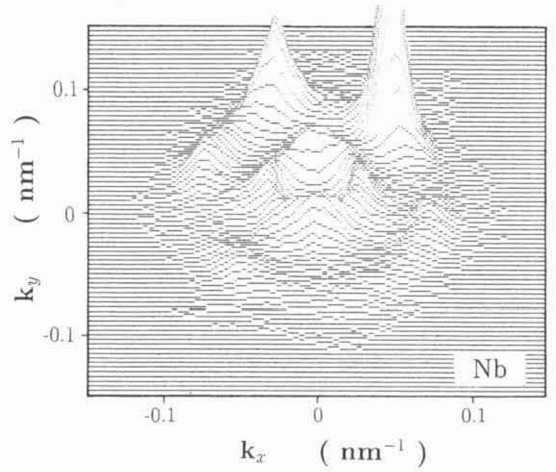

Fig. 1 Two dimensional SANS intensities for Nb under external magnetic field of 0.25 T at 7.2 K.

III. EXPERIMENTAL RESULTS AND DISCUSSION

A. Nb Single Crystal

Nb single crystal was cooled down to 7.2 K under magnetic field of 0.25 T and held there. This condition is called the field cooling (FC) in the text. The 2-dimensional contour map of scattering intensities is shown in Fig. 1. Two types of diffraction were observed: the Bragg peaks with six-fold symmetry and the central small angle scattering hindered partially by the beam stop. The Bragg peaks are assigned as (H,K) with condition of $H^2+HK+K^2 = 1$. The norm of scattering vector $|\mathbf{k}| = 4\,\pi\,\sin\,\theta\,/\,\lambda$ was measured to be 0.074 nm^{-1}, which was identical with the calculated value for external field of 0.25 T. Although they have to have the same scattering intensity, the observed intensities were quite asymmetric, attributing to the mismatch of the incident neutron beam direction to the applied magnetic field.

According to the standard diffraction theory, the correlation function $G(\mathbf{r})$ can be derived from the observed intensities $I(\mathbf{k})$. Assuming the point symmetry for the diffraction pattern, $G(\mathbf{R})$ is expressed as a function of cosine,

$$G(\mathbf{R}) = \int I(\mathbf{k})cos(\mathbf{kR})d\mathbf{k}. \qquad (1)$$

Figure 2(a) is the correlation function transformed from the intensities indicated in Fig. 1. The peak at the center gives the auto correlation $G_o(\mathbf{R})$, which is the direct summation of individual flux lines (FL's). The six nearest neighbour peaks correspond to the correlation among nearest neighbouring FL's, which is named here as $G_1(\mathbf{R})$. Also the higher order correlations were observed.

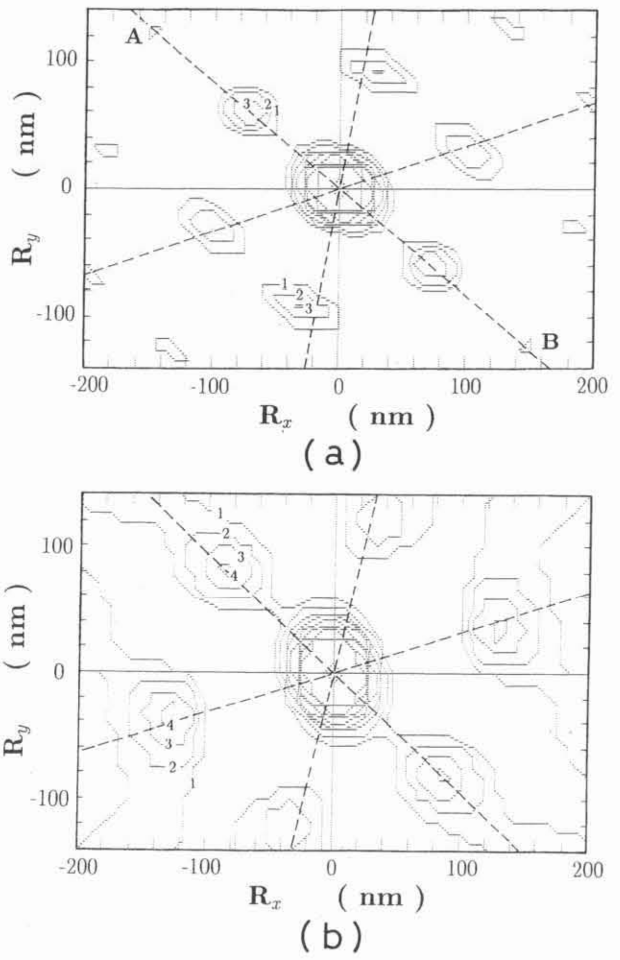

Fig. 2 Two dimensional correlation function for (a) FC/Nb under external field of 0.25 T and (b) ZF/Nb after switching off the field.

After switching off the external field at 7.2 K, the relaxation of magnetic flux distribution in the crystal was investigated by in-situ SANS measurements. This experimental condition is called the zero field (ZF) in the text. During the relaxation process, the data were collected continuously and stored at every 120 sec. The integrated intensity decreased rapidly after the first 120 sec and became constant up to 2.4 ks. Figure 2(b) shows the correlation function obtained from the intensities accumulated during the time interval from 120 to 240 sec. The clear six-fold symmetry for $G_1(\mathbf{r})$ was observed. Comparing two correlation functions of 120-240 and 1800-1920 sec, their patterns and absolute value were found to be almost equal to each other, indicating a steady state of magnetic flux distribution was reached by 120 sec.

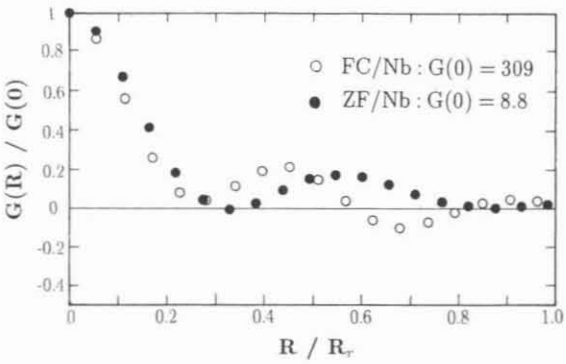

Fig. 3 Normalized correlation as a function of radial distance for two conditions FC/Nb and ZF/Nb. Here the reduced radius, R_r was equal to 216 nm.

When the magnetic field distribution in the superconductor is given by $B(\mathbf{r})$, the correlation function is expressed by the equation,

$$G(\mathbf{R}) = \int B(\mathbf{R}_1 + \mathbf{R})B(\mathbf{R}_1)d\mathbf{R}_1. \qquad (2)$$

Here the translational vector, $\mathbf{R}$ is put as

$$\mathbf{R} = \mathbf{r} + \mathbf{R}_{mn}, \qquad (3)$$

where the vector $\mathbf{r}$ changes within the Wigner-Seitz cell. Then the auto-correlation function is given by $G_o(\mathbf{R}) = G(\mathbf{r})$. The nearest neighbour correlation is given by $G_1(\mathbf{R}) = G(\mathbf{r}+\mathbf{R}_{mn})$, where m and n are integer with the condition of $m^2+mn+n^2=1$.

Figure 3 shows the normalized correlation function as a function of radial distance along the line AB shown in Fig. 2(a). The profile of the auto-correlation means the smeared distribution of quantized magnetic flux as represented by the modified Bessel function. The first peak, R_{peak} locates at 98 nm.

After the relaxation, the first peak shifts to 121 nm and the half width, $\Delta_{1/2}$ became broader. This spreading of half width was caused by the distribution of magnetic flux field in the crystal. Accordingly the average magnetic flux in the crystal after the relaxation was estimated to be 0.16 T. According to Bean's critical state model[4], the critical current density can be derived as the following form,,

$$J_c = \frac{3(B_{max} - B_{av})}{\mu_o D}, \qquad (4)$$

for the cylinder with diameter, D. When the follwoing parameters were used; B_{av} = 0.16 T and B_{max} =

Table 1 Summary of parameters for two conditions, FC:field cooling, ZF: zero external field

condition	G(0)	B [T]	k_{peak} [nm^{-1}]	R_{peak} [nm]	$\Delta_{1/2}$ [nm]
FC/Nb	309	0.25	0.074	98	52
ZF/Nb	8.8	0.16	0.060	121	60

0.25T, J_c was estimated to be 2.1×10^7 A/m^2. From the magnetization measurements, the J_c for the present specimen was assessed to be 1.7×10^7 at zero external field and 1.0×10^5 A/m^2 at 0.25 T. Therefore the magnetic flux distribution estimated from the SANS data is reasonably coincident with the result of magnetization measurements.

B. Bi2212 Single Crystal

For the SANS measurements, 5 plate-like Bi2212 single crystals were stacked in the sample case. The specimens were cooled down under magnetic field of 0.25 T and held at 7.7 K. After the first SANS measurements ($I_1(\mathbf{k})$), the specimens were heated up to about 100 K and the magnetic field was taken off and again cooled down to 7.7 K. The second SANS measurements were carried out ($I_2(\mathbf{k})$). The subtraction of $I_2(\mathbf{k})$ from $I_1(\mathbf{k})$ was performed after the scattering intensities were normalized using the total counts. The result is shown in Fig. 4. The whole scattering intensity is very weak and their angular dependence seems to be rather irregular.

The scattering intensities were Fourier transformed into the correlation function. The result is shown in Fig. 5. A weak four-fold symmetric correlation was observed. This regular correlations are limited only

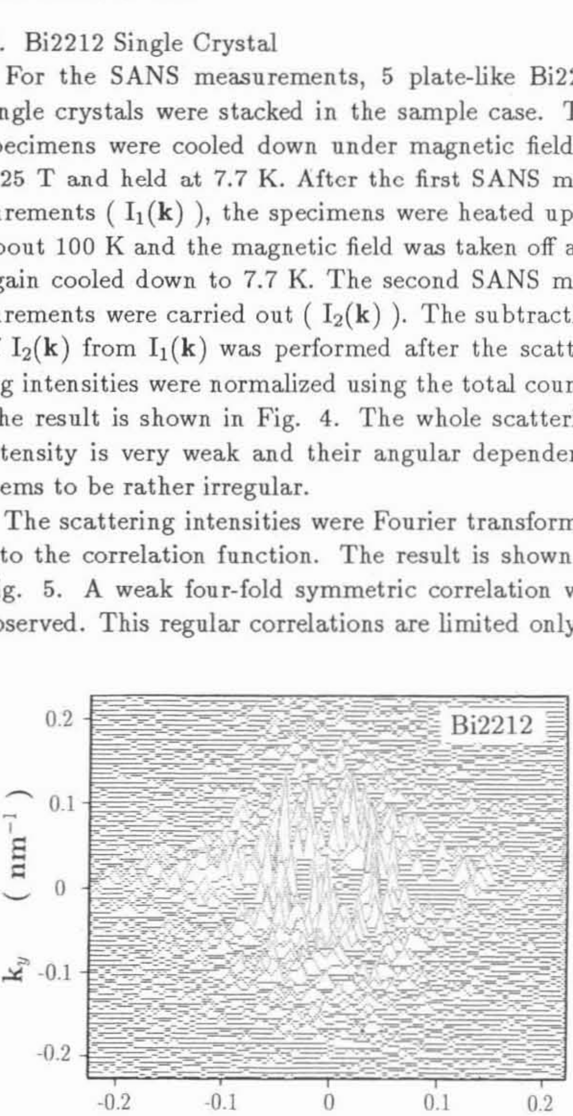

Fig. 4 SANS intensities for Bi2212 under magnetic field of 0.25 T at 7.7 K.

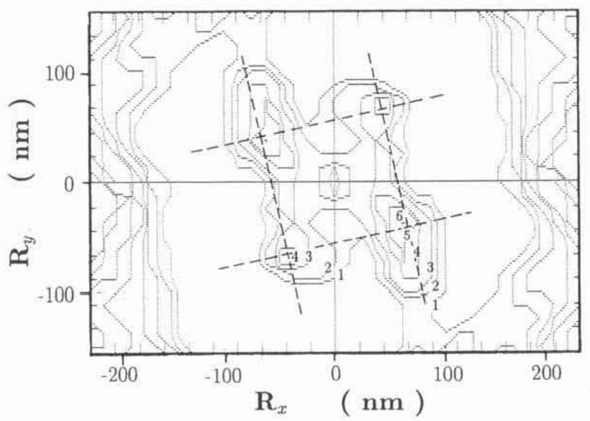

Fig. 5 Correlation function for Bi2212 under external magnetic field of 0.25 T at 7.7 K.

in the central region, but does not continue towards the higher radial distance. This fact suggests an existence of square like short range ordering. The shortest-distance was estimated to be 53 nm.

Recently Cubitt et al[5] investigated the FLL melting and decomposition in Bi2212. They observed the FL signal disappeared at low temperature after applying a sufficiently high field, because of the decomposition of FL into two-dimensional pancake vortices. They suggested that the decomposition takes place at about 0.065 T at temperatures lower than 60 K. The present condition of applied magnetic field, 0.25 T is much higher than this critical field. The long range ordered FLL was not expected in the present experimental condition and therefore the very weak and rather irregular intensity distribution as shown in Fig. 4 was apparently consistent. In the present analysis, however a short range ordering among FL's might be suggested, which is realized within a coherent volume. The dimensionality of these ordered regions, however, has been not deduced from the present data. Perhaps depending on the strength and number density of pinning centers, the behaviour of short range ordering will sensitively change.

IV. SUMMARY

SANS study indicates the following features of magnetic field distribution in crystals. The magnetic field distribution after the relaxation in Nb single crystal was well described in terms of Bean's model. A regular arrangement of FLs in Bi2212 single crystal is suggested to take place in short range under sufficiently high magnetic field larger than the critical field.

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