（別紙様式５）

変革を駆動する先端物理・数学プログラム（FoPM）
国外連携機関長期研修　報告書

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日程	西暦 2023 年 1 月 11 日　～　西暦 2023 年 1 月 24 日

Report of International Research Experience at SPring-8

I have been to SPring-8, a synchrotron radiation facility in Sayo Town, Hyogo, during Jan 11th and 24th. I performed a hard x-ray diffraction measurement of a cuprate superconductor and managed to capture a slight .sign of charge inhomogeneity, which is one of the key features of cuprate superconductors. Here I summarize the experiment and my days in SPring-8.

Purpose of Experiment

It has been 37 years since the first discovery of the cuprate superconductor [1]. While much has been revealed about the mechanism of high-temperature superconductivity, there are still many unresolved aspects. One of the characteristic properties of the cuprate superconductors is their various symmetry-broken phases. For example, in charge-ordered phases, charge carriers align in a form of stripes, breaking translation symmetry. This phase is sometimes called the stripe-ordered phase, and its interplay with superconductivity has long been studied [2].

To investigate the microscopic relationship between charge stripes and superconductivity, I have studied a representative stripe-ordered cuprate $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ by optical pump-terahertz (THz) probe method. The transient reflectivity spectra of the THz range suggest the enhancement of superconductivity by the optical pump. Taking into account that the superconductivity and charge stripe order are competing with each other [2], this phenomenon can be understood to be due to the optical destruction of the competing charge order. However, since charge stripes cannot be directly observed by the THz probe, the optical destruction of the charge stripes has to be confirmed by more direct means.

For this purpose, we employed the hard x-ray diffraction technique, which is capable of observing charge stripes directly, as described in the next section. We measured $La_{1.6-x}Nd_{0.4}Sr_xCuO_4$ with a doping level of $x = 0.12$, which has the highest transition temperature to the charge-stripe phase (69 K). At this time, we focused on the equilibrium measurement without a pump pulse and verified which conditions were appropriate for observing charge stripes.

Hard X-ray Diffraction

Hard X-rays are electromagnetic waves with photon energies above 10 keV. Owing to their higher energy, hard x-rays penetrate much deeper into material than visible or ultraviolet light. While some of the penetrated x-rays are absorbed into the material, the others are diffracted by the crystal lattice of the material and come out from the material along a certain direction, making a diffraction pattern characteristic of the crystal lattice. Conversely, we can obtain information on crystal lattice by measuring the diffraction pattern. This is the principle of the hard x-ray diffraction measurement.

This technique can be applied to the observation of the charge stripes, or charge inhomogeneity, because charge and lattice are connected by Coulomb interaction. Once charge inhomogeneity occurs, atomic nuclei are attracted or repelled by the spatially distributed charges, and the crystal lattice is distorted from what was established in the absence of charge inhomogeneity. This distorted lattice structure is called a superlattice, and it also has a characteristic diffraction pattern. Therefore we can know how charges are distributed by measuring the diffraction pattern by the superlattice.

I have used the BL19LXU beam line in the SPring-8 under the guidance of RIKEN staff members, Yuya Kubota and Yoshikazu Tanaka, and an assistant professor of my lab, Naotaka Yoshikawa. We used a helium refrigerator attached to a 4-cycle diffractometer (Fig. 1). This enables us to precisely sweep the sample orientation with keeping the temperature at 10 K, both of which are necessary to observe charge stripes.

Fig. 1. Inside view of the experimental hatch. Green equipment is the 4-cycle diffractometer and helium refrigerator is mounted on top of it. The sample is in the refrigerator.

Experimental Results

Although we couldn't find the charge-stripe signal when we first tried, by recalculating the origins of the diffractometer's axes of rotation, we successfully observed a superlattice peak of the charge-stripe. The peak intensity was weak but detectable, and at the same order of magnitude as expected from the literature [3]. The FWHM of the peak was also as expected and was sufficiently broader than Bragg peaks (diffraction peaks from the original crystal lattice without charge stripes). This is due to the spatial randomness of the charge stripes.

We next tried to observe other charge-stripe peaks and to compare which one is the most intense. According to the literature [3], x-rays that diffracted with a large angle along the *c*-axis of the sample have higher intensity. However, by setting the sample along those orientations, a large amount of background smeared out the superlattice peak. We speculate that the background is from the graphite window of the refrigerator, which is necessary to perform the measurement below the charge ordering temperature.

Days in SPring-8

Since SPring-8 is designed solely for experiments, it is surrounded by forest and there are few grocery stores or restaurants around the campus. Of course, there are a cafeteria and a convenience store on campus, but they are only open for limited hours. On Saturday, I took a bus to Aioi, the nearest city around SPring-8, and walked around. I found a lot of advertising boards for oysters and they made me hungry, so I tried an oyster Okonomiyaki (Kaki-oko). It was filled with tasty oysters and was great. There were much more shops of restaurants in Aioi city than around SPring-8, but some of them had their shutters closed.

For experiments, SPring-8 is the best facility that I have ever seen. All experimental equipment is systematic and there is everything you need in experiments. The experimental hall is so large that you need a bicycle to go from the main entrance to the experimental hatch. It may be standard for high-energy physicists, but for me, the scale of the experimental hall was impressive.

During the 2 weeks of the research experience, I enjoyed both the experiment and the atmosphere. I sincerely appreciate RIKEN staff members Kubota san, Tanaka san, and Makina Yabashi san, who readily accepted my staying in SPring-8 as a trainee. I also would like to thank FoPM for supporting my traveling to SPring-8.

Fig. 2. Experimental hall of SPring-8. In SPring-8, electrons are accelerated and stored in a ring with a circumference of 1,400 meters. X rays are emitted from the electrons and guided to each beam line and experimental hatch (right side of the figure). Experimental equipment is remotely controlled from the outside.

[1] J.G. Bednorz and K.A. Müller., Zeitschrift für Physik B Condensed Matter, **64**, 189–193 (1986).

[2] J. M. Tranquada *et al.*, J. Phys. Soc. Japan **90**, (2021).

[3] H. Kimura *et al.*, Phys. Rev. B **70**, 134512 (2004).