# Report for the MERIT overseas program

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## Overview

From 26th September to 23rd November 2018, I stayed at the Karlsruhe Institute of Technology (KIT), Germany to carry out collaborative research with Dr. Christoph Meingast, my host, at Institut für Festkörperphysik (IFP). I also visited Laboratory of Irradiated Solids, École polytechnique, France, in late October to perform electron irradiation experiments with Dr. Marcin Konzcykowski, and visited some research group inside the Paris city. Here is the report for my visit of these research institute.

## In Karlsruhe Institute of Technology

During this visit, I tried to measure the young modulus of the iron-based superconductor $RbFe_2As_2$ by three-point-bending technique. Recently, our research group measured the elastoresistance of RbFe2As2, which allow us to evaluate nematic fluctuations from strain-induced change in resistance, and found that this system exhibits a novel nematicity, whose director is 45 degree rotated from usual nematicity in iron-based superconductors. In electronic nematic phase, electronic system spontaneously breaks four-fold symmetry, which also cause in-plane asymmetry in the lattice, and it is expected that lattice shows softening toward the nematic transition temperature. The group in KIT IFP has developed new technique for young modulus measurements of the strong correlated materials. It is based on the three-point-bending technique, commonly used for the mechanical test to study elastic properties of the materials, and they combined with the home-built high-resolution dilatometer. Using this new technique, we examined whether lattice softening can be observed in $RbFe_2As_2$.

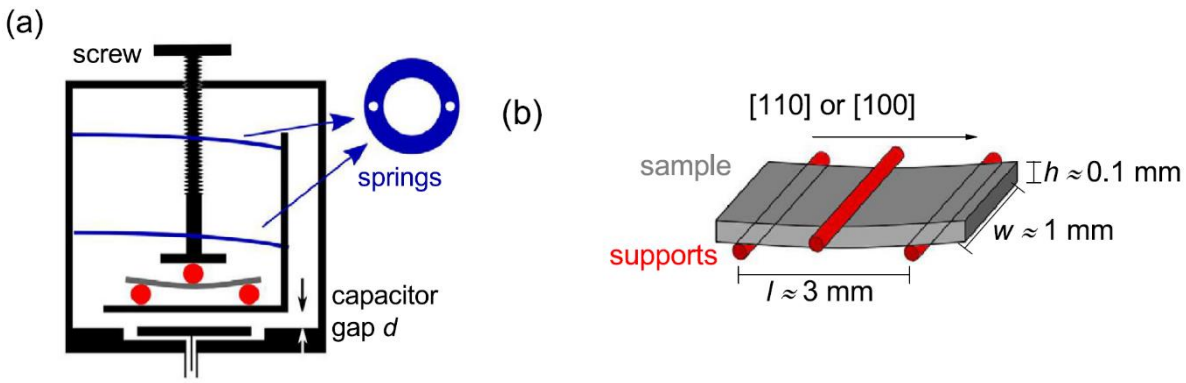


Figure 1.　Experimental setup for the young modulus measurements by three-point-bending technique. ( from Anna E.Böhmer and Christoph Meingast, Comptes Rendus Physique **17** 90 (2016)).

As a result of the measurement, we could not observe distinct lattice softening either [100] or [110] direction. This implies that the anisotropy in the lattice caused by the formation of nematic domains of $RbFe_2As_2$ is much less smaller than that of other iron-based superconductors. Crystals of $RbFe_2As_2$ is relatively soft, so it is easy to cause plastic deformation by three-point bending. Therefore, it is difficult to obtain the intrinsic data during visit, and we did no more than get the preliminary results. However, they kindly accepted to continue the measurements after I came back to Japan as a collaboration work with me.

In addition to New Materials, Transport, Thermodynamics and Mesoscopics group, which I mainly worked with, KIT IFP has several other groups, including Electron Spectroscopy、Inelastic Photon Scattering and Theoretical Solid-State Physics. However, these groups often go to Mensa in the University for lunch no matter which groups they belong to, and their friendly atmosphere was very impressive for me. Although their expert of measurement technique is different, they often collaborated with each other, which I think an ideal research environment.

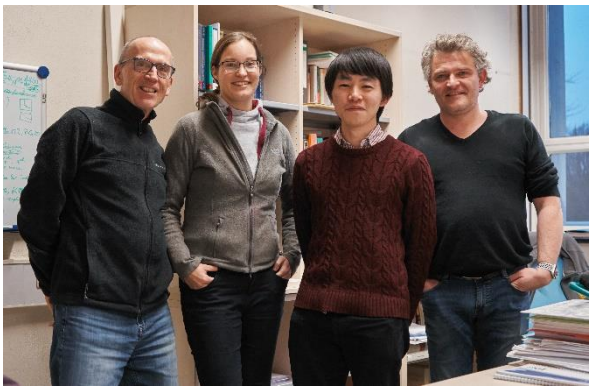

Figure 2. Photo with KIT IFP members. (From left side) Christoph Meingast, Kristin Willa, me, Frederic Hardy.

I also got an opportunity to give an IFP seminar about our recent results. The listeners seemed to find my talk interesting, and they gave me meaningful questions. In particular, Professor Joerg Schmalian, a head of theoretical Solid-State Physics group, discussed the XY-nematic fluctuations, implied by our recent measurements, in a detail, which is very helpful to me. He also provided me an opportunity to discuss more in another day, and gave some comments to our results from theoretical prospective. He gave me a detail explanation of some points that I could not understand in his paper.

Furthermore, I also visited Max Planck Institute for Solid State Research Solid State Spectroscopy group, about one and half an hour away by train from Karlsruhe. I visited this group last year in the MERIT overseas training, but this time I discussed our results on the nematicity in high-$T_c$ cuprate superconductors with their group members, and they gave me a chance to talk in their group seminar. Professor Bernhard Keimer, the leader of the group is famous for the expert in the high-temperature cuprate superconductors, so it was so delightful for me that he listened to my results eagerly and gave me the meaningful information.

## In France

In École polytechnique, our lab had a machine time for the electron irradiation experiments, so I performed electron irradiation to $Sr_xBi_2Se_3$, a candidate material for topological superconductivity, and half-Heusler compounds with Dr. Marcin Konzcykowski. Electron irradiation technique is an original technique, which enables us to induce the homogenous point defects without changing the carrier density. We checked the effect of irradiation from the residual resistivity and hall coefficient.

During my visit in École polytechnique, Dr. Makariy Tanatar, a researcher in Ames Laboratory, also stayed there. He is an expert for the transport measurements, and I discussed our results on the transport properties of iron-based superconductors with him. I also gave some talk in the Laboratory of Irradiated Solids, and I got some comments from them.

Figure 3. Photo in École polytechnique. (From left side) Kohei Matsuura, Makariy Tanatar, me, Marcin Konzcykowski.

Figure 4. Accelerator for the electron irradiation

I also visited research institute inside Paris city. At first, I visited Yann Gallais, who is a professor in Université Paris Diderot and belongs to Laboratoire Matériaux et Phénomènes Quantiques (MPQ) Spectroscopy of quasi-particles (SQUAP) group. They are working on the Raman scattering experiments, and evaluated nematic fluctuations from Raman spectra. This method differs from the elastoresistance and three-point bending in that sample does not need to be under external strain or pressure. We have been collaborating with their group since before, and at this visit, I told them our recent results about the nematicity in unconventional superconductors, and provided our samples. I also discussed with Indranil Paul, a member of theory group.

Next, I visited Quantum Matter group of the Laboratoire de Physique et d'Étude des Matériaux (LPEM) at the Ecole Supérieur de Physique et de Chimie Industrielles (ESPCI). I discussed our results on the electronic nematic state with Kamran Behnia, a director of the group, and after that Post Doc and PhD student in the group explained me what they're working on. Although their research topics are not directly connected to mine: anomalous behavior in the resistivity of $SrTiO_3$, density waves under high magnetic field in graphite, and departure from Wiedemann–Franz law in WP2, all of them sounds interesting to me. I also gave a seminar in this institute, and discussed with theorist Luca de' Medici after my talk.

## Daily life and research environment

Since this is my first time to stay abroad for a long time, I learned a lot about the difference in the daily life and research environment between Japan and foreign countries. Karlsruhe is a relatively new city, centering around the Karlsruhe palace. My accommodation, KIT International Guesthouse, locates near the central street, which is very convenient for me, but at first, I was puzzled when I got to know that all the supermarket is closed every Sunday. As for the transportation, we can buy all the ticket for high-speed rail, tram, and bus by smartphone, which seems

to be more covenant than in Japan.

KIT IFP does not have PhD student like me, but consist of many Post Docs. They were from various countries such as Europe and America, so it was very interesting for me to hear their research life before they got PhD degree. In foreign countries, PhD students are basically paid and tuition of the University is not too high, so they were surprised when I told them the case of Japan. In addition, most of Post Doc changed their working measurement technique and research field, which was very helpful to me.

## Acknowledgement

In this visit, besides Karlsruhe Institute of Technology, I was able to visit several research institute, including École polytechnique, Université Paris Diderot, ESPCI, and Max Planck Institute for Solid State Research. Fortunately, I got chances to present seminars in all the institute, which is a good training for me to have a presentation to foreign researchers.

I would like to thank my supervisor Prof. Shibauchi and Dr. Mizukami for supporting and arranging my visit. My vice supervisor Prof. Hide Takagi, a group leader of the Max Planck Institute for Solid State Research, kindly accepted my plan. I will make use of this experience in future. I wish to appreciate Dr. Christoph Meingast, Dr. Anna Böhmer, Dr. Frederic Hardy, and Prof. Dr. Matthieu Le Tacon , who kindly accepted my visit, and all the members in KIT IFP , including Dr. Amir-Abbas Haghighirad, Paul W. Wiecki, and Dr. Kristin Willa. I also would like to thank Dr. Marcin Konzcykowski, Prof. Dr. Yann Gallais, Dr. Kamran Behnia, and Prof. Dr. Bernhard Keimer, who warmly welcomed me.