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Report on my stay at the Yukawa Institute for Theoretical Physics for the 2018-19 school year

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Abstract. In this report I will describe my scientific activities at the Yukawa Institute for Theoretical Physics as an Advanced Future Studies Researcher since my arrival in June 2018.

Keywords: Quantum error correction, tensor networks, superconductivity, Monte Carlo.

1. Scientific Activity

I started my position at the Yukawa Institute for Theoretical Physics in June 2018. This report will outline my research activities from my arrival until the end of March 2019.

I have given several talks since my arrival YITP. including a talk at the Asia Quantum Information Sciences sattelite workshop at YITP and visiting talks at The University of Sherbrooke. The title of both talks was “Linear time decoding algorithm for the surface code”. In November 2018 I presented some of the techniques I’ve developed for studying error correction to start-up companies in California.

1.1. Superconductivity vs. stripe order in the Hubbard model

When I first started my position at the Yukawa Institute of Physics, I was working on a problem in condensed matter physics. One of the big open challenges in physics currently, is to understand high-temperature supercondutivity in copper-oxide superconductors. The remarkably high critical temperature in doped cuprates discovered around 30 years ago, however its physical mechanism still remains under debate. A detailed understanding of the mechanism of high-temperature superconductivity could pave the way to breakthroughs in the design and application of superconductors.

A simple model, believed to capture the essential physics of cuprates, is the square lattice Hubbard model. Despite the simple form of the model, the properties of the ground state remain largely under debate. The model is particularly challenging due to the fact that a large number of low-lying excited states compete strongly in the doped region. Resolving the differences requires accurate numerical techniques.

We applied a variational Monte Carlo method to study the ground state of the Hubbard model. The method combines a variety of variational wavefunctions, in order to capture the different types of order that may be present. After intensive calculation using K-computer, Japan's largest supercomputer, we found an extremely complex low-energy space, with strong competition between charge ordered states and superconducting states. In a large region of the phase diagram, the ground state was found to be stripe ordered, with electron density varying periodically in one direction.

We found some remarkable similarity with experimental results. For instance, superconductivity was found to be strongest in the ground state at a very similar doping point to the where the critical temperature has been experimentally observed to highest. This suggests that the Hubbard model may be able to describe the essential physics of high-temperature superconductors. We have published a paper containing this result in Physical Review B (Darmawan 2019).

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1.2 Decoding of topological error correcting codes

Noise is one of the biggest obstacles to overcome in the construction of full scale quantum computation. Topological error correction represents a simple way to protect the information stored in a quantum computer from noise. There is a classical processing component of error correction, called decoding, which involves choosing the best correction given limited information from measurements performed during the error correcting process. The performance of the decoder can drastically affect the logical error rate, and overall cost of quantum computing. I am currently pursuing a number of research directions in improving decoding of topological error correcting codes. These approaches are based on tensor-network methods.

One question the importance of information about the underlying noise process to the decoding algorithm. There are certain cases where information in the noise can greatly enhance the power of error correcting codes. However, in practice, noise can only be known approximately, and it is unclear how much information is needed to perform near optimally. We are currently investigating this question using tensor-network numerical simulations.

I am also looking more generally at how decoders and numerical techniques for error correction can be improved. This involves enhancements to existing methods to reduce cost and increase performance. I am also looking at how state-of the art numerical methods in condensed-matter physics, based on tensor networks, may be applied directly to error correction.

2. Conclusion

This year I have been working on several problems in quantum information theory and quantum condensed-matter physics using techniques for studying quantum many-body systems that have broad application. This research has been done in close collaboration with Japanese and international research groups.