（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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The National High Magnetic Field Lab in Tallahassee, Florida held its tenth annual Theory Winter School virtually from January 10 to 14, 2022. I joined this winter school because the topics are the non-equilibrium quantum matter, the non-equilibrium quantum dynamics in quantum many-body systems, which is related to my research topic, quantum integrable systems. I also aimed to reach out my interest to other fields, such as quantum circuits, quantum computing. This winter school aims to communicate exciting new developments in this area of condensed matter physics to a wide audience. There were many lectures on this subject (eigenstate thermalization, many-body localization, quantum many-body scars, Floquet theory, random circuits, etc.), and the discussion among the speaker and audience was very exciting even though it was held online.

The lecture of Maksym Serbyn - A new form of ergodicity breaking from quantum many-body scars is especially helpful for my future research. I studied some basic ingredients of “Quantum many-body scars” in this lecture, briefly explained in the following. The generic nonintegrable quantum systems are believed to obey the eigenstate thermalization hypothesis (ETH), that is relaxation and equilibration (thermalization) occur within the long-time limit. Quantum many-body scars are the special eigenstate that breaks strong ETH despite the nonintegrability but satisfies weal ETH. In weak ETH cases, “almost all” the eigenstate thermalizes. In the presence of Quantum many-body scars, the system could avoid thermalization and the relaxation does not occur. These phenomena have been observed in an actual experiment using an ultracold atom. Understanding this exceptional strong ETH breaking state is important to gain a deeper understanding of the mechanism of thermal equilibration and macroscopic thermodynamics. However, the origin of Quantum's many-body scars is not well understood. One of the examples of Quantum many-body scars is the PXP model, which has quantum many-body scars state of order of system size (Fig. 1). One of the ways for the construction of quantum many-body scars is using special symmetry or algebra of the system. In the PXP model, there is SU (2)-like symmetry and the quantum many-body scars states are approximately constructed by the algebra. After the basic explanation of quantum many-body scars in this MagLab Theory Winter School, I came across an idea. Quantum integrable systems are exactly solved by Bethe ansatz. The integrability is due to the Yang-Baxter algebra of the model. The many-body problem of diagonalization of hamiltonian can be reduced to non-linear algebraic simultaneous equations of the order of system size. The question is, “Can quantum many-body scars be caused by Yang-Baxter like algebra?” In the Bethe ansatz method, all the spectrum of eigenvalue problems can be obtained, so the model is integrable. In the quantum many-body scars context, we are interested in non-integrable cases. In my knowledge, the case is not yet known that a part of the non-integrable spectrum can be solved analytically by solving non-linear simultaneous equations, like the Bethe equation. This special eigenstate may satisfy weak ETH, but not strong ETH. I wonder this special state can be quantum many-body scars if present. Then we come across one more question about local conserved quantities. Quantum integrable systems have an extensive number of local conserved quantities, this is of course stem from Yang-Baxter algebra. In Yang-Baxter-like scars cases, if present, there should not be extensive local conserved quantities because if so, the steady-state will be the generalized Gibbs ensemble, not the canonical ensemble desired in quantum many-body scars context. So, we can see the big difference between usual integrable systems and Yang-Baxter-like scars is the presence of an extensive number of local conserved quantities. This is a

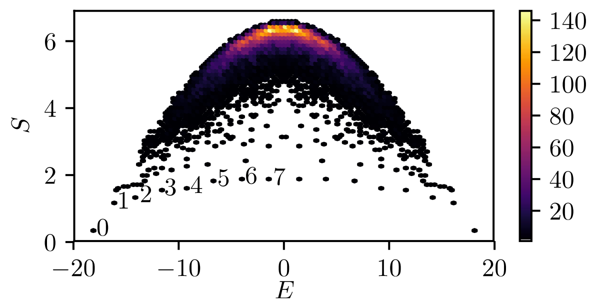

fig. 1 Biparticle entanglement entropy of PXP model. The anomalously low entangle states are scars states [C. J. Turner, et.al, PRB, 2018].

very fatal point for the application of Yang-Baxter algebra to quantum many-body scars, because the integrability is based on the mutual commutation property of transfer matrices of different spectral parameters, and the mutual commutation property leads to the existence of an extensive number of local conserved quantities. Therefore, the direct application of the framework of Yang-Baxter algebra to quantum many-body scars is probably impossible. The previous quantum many-body scars were constructed based not on conserved quantities but on "dynamical symmetry", to put it simply, such as the ladder operator of SU (2) symmetry. We need to find dynamical symmetry with a nontrivial highest weight state. In the previous quantum many-body scars studies, the highest weight state is usually given trivially. In the quantum integrable case, the highest weight state is given by solving the Bethe equation. It is a naïve question whether there is dynamical symmetry with nontrivial highest weight state given by solving a nonlinear algebraic equation, other than the framework of quantum integrable system or not. The above content is not directly concerned with my research now going but considering these problems new to me is a very fresh experience and this winter school was a great learning opportunity for me.

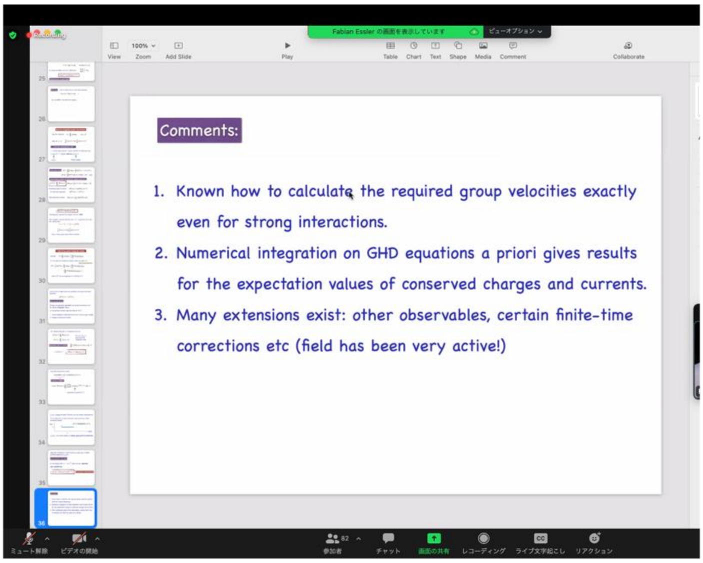

fig. 2 The scene of the lecture of Fabian Essler - BBGKY, Boltzmann equation and GHD