Ultimate Quantum Measurements for Quantum Dynamics

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Due to great development on experimental technologies, it is possible to capture quantum dynamics in some physical and chemical systems. On the other hand, all experiments are in principle open and dissipative systems. Up to now, the well explained experiments are approximated to the equilibrium situation. However, by recent technological development, some experiments reach to a transition from equilibrium to non-equilibrium situations. While there are the well-known tools on the non-equilibrium situations; the linear response theory and the Keldysh Green function method, this analysis cannot basically catch dynamical situations. Our goal is to construct the time-resolved theoretical models included the non-equilibrium situations. However, the quantum measurement theory is needed on measuring quantum dynamics, especially considering the measurement back action. Our current activities are to resolve how sensitive (quantum) measurement can we carry out in principle, to build up some toy models on quantum dynamic and to explain unique quantum-mechanical phenomena using precise quantum-state engineering technology.

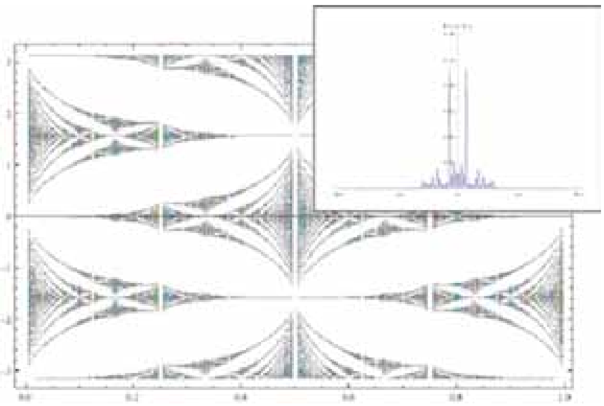

Figure 1. Example of the complex but regular phenomena from the simple law; the discrete-time quantum walk, which is a mathematical toy model to be defined as a quantum-mechanical analogue of the random walk. The probability distribution is depicted in the left top panel. This main distribution is called Hofstadter's butterfly to show the multi-fractal structure.

Selected Publications

- Y. Shikano and A. Hosoya, "Weak Values with Decoherence," *J. Phys. A* **43**, 025304 (15 pages) (2010).
- Y. Shikano and H. Katsura, "Localization and Fractality in Inhomogeneous Quantum Walks with Self-Duality," *Phys. Rev. E* **83**, 031122 (7 pages) (2010).
- A. Noguchi, Y. Shikano, K. Toyoda and S. Urabe, "Aharonov-Bohm Effect with Quantum Tunneling in Linear Paul Trap," *Nat. Commun.* **5**, 3868 (6 pages) (2014).
- H. Kobayashi, K. Nonaka and Y. Shikano, "Stereographical Visualization of a Polarization State Using Weak Measurements with an Optical-Vortex Beam," *Phys. Rev. A* **89**, 053816 (5 pages) (2014).

1. Quantum Measurement with Higher Order Gaussian Modes[1)]

We propose a stereographical-visualization scheme for a polarization state by two-dimensional imaging of a weak value with a single setup. The key idea is to employ Laguerre Gaussian modes or an optical vortex beam for a probe state in weak measurement. Our scheme has the advantage that we can extract information on the polarization state from the single image in which the zero-intensity point of the optical vortex beam corresponds to a stereographic projection point of the Poincaré sphere. We experimentally perform single-setup weak measurement to validate the stereographical relationship between the polarization state on the Poincaré sphere and the location of the zero-intensity point.

2. Quantum Measurement Sensitivity without Squeezing Technique[2)]

The weak measurement was proposed in the context of the time-symmetric quantum measurement without collapsing the quantum state. The weak value as the measurement outcome of the weak measurement can exceed the eigenvalue. By this fact, the signal can be amplified. This is called the weak-value amplification. To study the invisible region under the standard technique, there are several studies on the weak-value amplification. Here, the following question arises. How can the signal maximize? To solve this problem, the probe wave function should be changed from the Gaussian distribution, which is originally used. We show the probe wave function to maximize the shift while this mode is not the propagation mode in light.

3. Discrete Time Quantum Walk as Quantum Dynamical Simulator[3)]

Constructing a discrete model like a cellular automaton is a powerful method for understanding various dynamical systems. However, the relationship between the discrete model and its continuous analogue is, in general, nontrivial. As a quantum mechanical cellular automaton, a discrete-time quantum walk is defined to include various quantum dynamical behavior. Here we generalize a discrete-time quantum walk on a line into the feed-forward quantum coin model, which depends on the coin state of the previous step. We show that our proposed model has an anomalous slow diffusion characterized by the porous-medium equation, while the conventional discrete-time quantum walk model shows ballistic transport.

4. Aharonov-Bohm Effect with Quantum Tunneling[4)]

A quantum tunneling is also one of the unique quantum mechanical phenomena. However, nobody has yet measured a tunneling particle. There are still many quantum mysteries. While we have known that a tunneling particle can be coupled to an electromagnetic field, we have not yet demonstrated a coupling between a tunneling particle and a vector potential of the electromagnetic field. This effect is called the Aharonov-Bohm effect.

Our experimental setup done in Urabe group, Osaka University uses an ion trap system. The ion trap system is one of the great candidates to implement a quantum computer and a quantum simulation. Especially, a linear Paul trap, which is also used in our experiment, has the high scalability under the one-dimensional quantum system due to the great development of quantum information technology. While the two-dimensional structure of ions is very difficult to be cooled down in the linear Paul trap, we found that we can manipulate the almost ground state of the ion rotational motion by the laser cooling technique. This is a new quantum technology to implement a two-dimensional quantum simulation and a quantum computation used in a liner Paul trap. Then, we realized the almost ground state of rotational mode of three calcium ions arranged to a triangular structure. The distance between two ions is 6.8 micro meter. This ground state has the two structures, upward and downward triangles. This can be taken as the quantum rotor, which is often used in molecular science such as a diatomic molecule, with a quantum tunneling region. We confirmed that this transition is led by quantum tunneling even in the large tunneling region. Since we cannot distinguish clockwise and anticlockwise transitions, this system can be taken as the double-slit experiment. Changing the strength of the magnetic field, we showed that the transition probability was oscillated. This oscillation can be predicted by Aharonov-Bohm effect.

References

1) H. Kobayashi, K. Nonaka and Y. Shikano, *Phys. Rev. A* **89**, 053816 (5 pages) (2014).
2) Y. Shikano, "On Signal Amplification from Weak-Value Amplification," in *Kinki University Series on Quantum Computing Volume 9* "Physics, Mathematics, and All that Quantum Jazz," S. Tanaka, M. Bando and U. Gungordu, Eds., World Scientific; Singapore, pp. 91–100 (2014).
3) Y. Shikano, T. Wada and J. Horikawa, *Sci. Rep.* **4**, 4427 (7 pages) (2014).
4) A. Noguchi, Y. Shikano, K. Toyoda and S. Urabe, *Nat. Commun.* **5**, 3868 (6 pages) (2014).

Awards

SHIKANO, Yutaka; FQXi (Foundational Questions Institute) Essay Contest "It from Bit or Bit from It" Fourth Prize. (2013)
SHIKANO, Yutaka; 2013 Quantum Information Processing Top Reviewers.
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