Visualization of Quantum Dynamical Nature Utilized Quantum Measurements

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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.

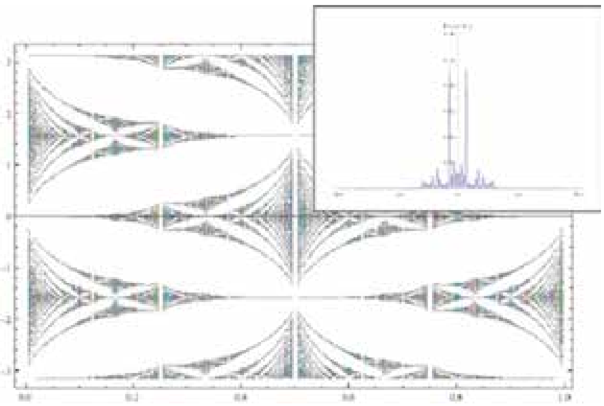

Figure 1. Example of the complex but regular phenomena from the simple law; the discrete-time quantum walk, which is a mathematical toy model to be defined as a quantum-mechanical analogue of the random walk. The probability distribution is depicted in the left top panel. This main distribution is called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

Through the von Neumann interaction followed by post-selection, we can extract not only the eigenvalue of an observable of the measured system but also the weak value. In this post-selected von Neumann measurement, the initial pointer state of the measuring device is assumed to be a fundamental Gaussian wave function. By considering the optical implementation of the post-selected von Neumann measurement, higher-order Gaussian modes can be used. In this paper, we consider the Hermite–Gaussian (HG) and Laguerre–Gaussian (LG) modes as pointer states and calculate the average shift of the pointer states of the post-selected von Neumann measurement by assuming the system observable A with $A^2 = I$ and $A^2 = A$ for an arbitrary interaction strength, where I represents the identity operator. Our results show that the HG and LG pointer states for a given coupling direction have advantages and disadvantages over the fundamental Gaussian mode in improving the signal-to-noise ratio (SNR). We expect that our general treatment of the weak values will be helpful for understanding the connection between weak- and strong-measurement regimes and may be used to propose new experimental setups with higher-order Gaussian beams to investigate further the applications of weak measurement in optical systems such as the optical vortex.

2. Quantum Measurement with Squeezing Technique[2)]

We investigate, within the weak measurement theory, the advantages of non-classical pointer states over semi-classical ones for coherent, squeezed vacuum, and Schroedinger cat states. These states are utilized as pointer state for the system operator A with property $A^2 = I$, where I represents the identity operator. We calculate the ratio between the signal-to-noise ratio (SNR) of non-post-selected and post-selected weak measurements. The latter is used to find the quantum Fisher information for the above pointer states. The average shifts for those pointer states with arbitrary interaction strength are investigated in detail. One key result is that we find the post-selected weak measurement scheme for non-classical pointer states to be superior to semi-classical ones. This can improve the precision of measurement process.

3. Single-Photon Nonlinearity Amplification by Post-Selection[3)]

Phase-squeezed light can enhance the precision of optical phase estimation. The larger the photon numbers are and the stronger the squeezing is, the better the precision is. We propose an experimental scheme for generating phase-squeezed light pulses with large coherent amplitudes. In our scheme, one arm of a single-photon Mach–Zehnder interferometer interacts with coherent light via a nonlinear-optical Kerr medium to generate a coherent superposition state. Post-selecting the single photon by properly tuning a variable beam splitter in the interferometer yields a phase-squeezed output. Our proposed scheme is experimentally feasible under current quantum technology.

4. Discrete-Time Quantum Walk as Quantum Dynamical Simulator[4,5)]

Discrete-time quantum walks can be regarded as quantum dynamical simulators since they can simulate spatially discretized Schroedinger, massive Dirac, and Klein-Gordon equations. Here, two different types of Fibonacci discrete-time quantum walks are studied analytically. The first is the Fibonacci coin sequence with a generalized Hadamard coin and demonstrates six-step periodic dynamics. The other model is assumed to have three- or six-step periodic dynamics with the Fibonacci sequence. We analytically show that these models have ballistic transportation properties and continuous limits identical to those of the massless Dirac equation with coin basis change.

5. NMR Sensitivity Improvement by Composite Pulse[6)]

ConCatenated Composite Pulses (CCCPs) are derived from various composite pulses widely employed in NMR and have been developed as high-precision unitary operations in Quantum Information Processing (QIP). CCCPs are robust against two systematic errors, pulse-length and off-resonance errors, in NMR simultaneously. We show experiments that demonstrate CCCPs are powerful and versatile tools not only in QIP but also in NMR measurements.

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3) F. Matsuoka, A. Tomita and Y. Shikano, arXiv:1410.8046 (2014).
4) G. Di Molfetta, L. Honter, B. B. Luo, T. Wada and Y. Shikano, *Quantum Stud.: Math. Found.* **2**, 253–254 (2015).
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