Emergence of Classical Objectivity on a Quantum Darwinism Simulator

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Quantum-to-classical transition is a fundamental open question in physics frontier. Decoherence theory points out that the inevitable interaction with environment is a sink carrying away quantum coherence, which is responsible for the suppression of quantum superposition in open quantum system. Recently, quantum Darwinism theory further extends the role of environment, serving as communication channel, to explain the classical objectivity emerging in measurement-like process. Here, we used a six-photon quantum simulator to investigate quantum Darwinism process. The environment photons scattered from observed quantum system are used to infer the state of quantum system. We observed redundancy of classical information and suppression of quantum correlation in fragments of environment photons. Our results have experimentally confirmed that multiple observers who independently access environment fragments can establish a consensus view of the classical state of observed quantum system through Darwinism-like mechanism.

Quantum mechanics is a spectacularly successful predictive theory, but there is still an unresolved problem about its interpretation in quantum measurement problem \cite{1}. How the wave function collapses and classical objectivity emerges from quantum substrate? The orthodox Copenhagen interpretation separates the world into quantum domain and classical domain, which is bridged by observation-induced collapse \cite{2}. A detailed mechanism of this quantum-to-classical transition is of fundamentally importance not only for developing an unified view of our physical world but also for developing large-scale quantum machines in quantum information technology.

Quantum decoherence theory identifies that the uncontrolled interactions from the environment can destroy the coherence of quantum system into mixed state and explains the classical behavior in the level of ensemble average \cite{3, 4}. In this theory, however, how the classical objectivity arises in single event of single quantum system is still unresolved. Objectivity is a property that many observers can independently determine the state of the system without perturbing it. In most cases, observers don’t directly touch and interact with the quantum system. They perceive the system by collecting information from its surrounding environment.

Recently, quantum Darwinism explains the emergence of classical objectivity of a single quantum system through information broadcasting and proliferating in its environment. Quantum decoherence theory identifies that the unavoidable interaction with environment is a sink carrying away quantum coherence, which is responsible for the suppression of quantum superposition in open quantum system. Recently, quantum Darwinism theory further extends the role of environment, serving as communication channel, to explain the classical objectivity emerging in measurement-like process. Here, we used a six-photon quantum simulator to investigate quantum Darwinism process. The environment photons scattered from observed quantum system are used to infer the state of quantum system. We observed redundancy of classical information and suppression of quantum correlation in fragments of environment photons. Our results have experimentally confirmed that multiple observers who independently access environment fragments can establish a consensus view of the classical state of observed quantum system through Darwinism-like mechanism.

Quantum Darwinism explains the emergence of classical objectivity of a single quantum system through information broadcasting and proliferating in its environment.
interactions among the environment’s particles, the stored information will be inevitably scrambled out. Hence, only non-interaction environment is good memory for redundant records of system’s state.

We design a quantum Darwinism simulator shown in Fig. 1(b) to simulate non-interaction environment, such as daily photonic environment. In the simulator, a central qubit interacts with the environment qubits through two-qubit controlled-rotation gates $U(\theta) = |0\rangle \langle 0| \otimes I + |1\rangle \langle 1| \otimes R_y(\theta)$ with random angles to mimic the random scattering process, where $R_y(\theta)$ rotates a qubit by angle $\theta$ along the $y$ axis of Bloch sphere. When the system qubit is initialized in superposition state $\alpha|0\rangle_S + \beta|1\rangle_S$, the simulator will produce Darwinism states with branch structure

$$\alpha|0\rangle_S \otimes i=1^N |0\rangle_i + \beta|1\rangle_S \otimes i=1^N (\cos \frac{\theta_i}{2}|0\rangle_i + \sin \frac{\theta_i}{2}|1\rangle_i),$$

where $|\alpha|^2 + |\beta|^2 = 1$ and $N$ is the number of environment qubits.

The interaction with environment selects preferred pointer states of the observed system, which are the states left unchanged under the interactions and thus multiple records of the state can be faithfully copied into environment. For interactions generated from a Hamiltonian form of $H_i = g_ia \otimes B_i$, the eigenstates of monitored observable $A$ are the pointer states, where $A$ and $B_i$ are two observables on system and environment particle $i$, respectively. In our simulator setting, $A = (\sigma_1 - \sigma_2)/2$, $B_i = \sigma_i$ and $g_i\Delta t = \theta_i/2$, therefore, the pointer states from interaction $U(\theta_i) = e^{-iH_i\Delta t}$ are $|0\rangle$ and $|1\rangle$, respectively.

The physical reality of pointer states can be quantified by the disappearance of quantum coherence

$$C(\rho_S) = H_d(\rho_S) - H(\rho_S)$$

where $\rho_S$ is the reduced density matrix of system, $H(\rho_S) = -\text{tr}(\rho_S \log \rho_S)$ is quantum von-Neumann entropy and $H_d(\rho_S) = -\text{tr}(\rho_s \log p_s)$ is classical Shannon entropy, $p_s$ is the diagonal elements of density matrix $\rho_S$ in pointer-state bases [19, 20]. The reality of pointer states will emerge when the quantum system is completely decohered by the environment. In this case, the classical entropy will equal to the quantum entropy. The efficiency of decoherence depends on the initial states of environment [18, 21]. Impure or misaligned (close to the eigenstate of observable $B_i$) environment will reduce the decoherence efficiency. In our simulation, $|0\rangle$ states are used as initial environment states with optimal efficiency.

In quantum Darwinism process, the information about the quantum system is broadcast to the environment. Local observers can only access small fragments of the whole environment. The quantum mutual information

$$I(S; E_i) = H(\rho_S) + H(\rho_{E_i}) - H(\rho_{S|E_i})$$

can be used to quantify how much information an observer $E_i$ (accessing the environment fragment $E_i$) knows about the
quantum system [5]. When \( I(S; E_i) \approx H(\rho_S) \) for all observers \( \{E_i\} \), the system’s state can be determined by all the observers and thus the quantum system becomes objective.

We use a photonic simulator [11, 12] (shown in Fig. 2) to produce quantum Darwinism states consisted of a central system qubit (photon 1) and five environment qubits (photons 2 ∼ 6). The quantum state of system is observed at the superposition state \( (|0\rangle + |1\rangle)/\sqrt{2} \). Two sets of rotation-angle parameter, \( \vec{\theta}_A = (180^\circ, 180^\circ, 180^\circ, 180^\circ) \) and \( \vec{\theta}_B = (180^\circ, 180^\circ, 180^\circ, 72^\circ, 100^\circ) \), are used in the experiments from the following considerations.

A real environment fragment can contain many elementary subsystems. If the fragment is large, its quantum states can be simplified and expressed as orthogonal logical states \( |0_L\rangle = \otimes_{i=1}^n |0_i\rangle \) and \( |1_L\rangle = \otimes_{i=1}^n (\cos \frac{\theta}{2} |0_i\rangle + \sin \frac{\theta}{2} |1_i\rangle) \), due to \( \langle 0_L | 1_L \rangle = \prod_{i=1}^n \cos \frac{\theta}{2} \rightarrow 0 \) for sufficiently large number \( n \) of subsystems in a fragment. Furthermore, if the fragment is small, its quantum states can be expressed as nonorthogonal logical states \( |0_L\rangle \) and \( \cos \frac{\theta}{2} |0_L\rangle + \sin \frac{\theta}{2} |1_L\rangle \).

In our simulation, the photonic qubits represent the quantum state of environment fragments logically and an observer can access one or more fragments to infer the system’s state. The parameter \( \vec{\theta}_A \) is used to simulate 5 large environment fragments and parameter \( \vec{\theta}_B \) is used to simulate 3 large environment fragments and 2 small environment fragments.

The experimental setup is shown in Fig. 2. The qubits are encoded in the horizontal \( (H) \) and vertical \( (V) \) polarization of single photons, which are produced by spontaneous parametric down-conversion (SPDC) process [22, 23]. The Darwinism states in equation (1) are synthesized in three steps.

(1) Preparation of three pairs of polarization-entangled photons in Einstein-Podolsky-Rosen (EPR) state \( (|HH\rangle + |VV\rangle)/\sqrt{2} \) [24] from SPDC process. With a laser pump power of 0.9 W, the generation probability of two twin photons is 0.025 and the fidelity of EPR state is above 99%.

(2) Two EPR pairs are combined on two polarization beam splitters, postselecting the entangled subspace of \( |HH\rangle (|HH\rangle + |VV\rangle) \), to produce a six-photon Greenberger-Horne-Zeilinger (GHZ) state \( (|HHHHHH\rangle + \)
The experiment runs with repetition rate 80 MHz and the single photons are measured with collecting and detecting efficiency of 0.65. Thus, we obtain six-photon coincidence counting rates about 5 counts/second. The quantum states are measured through quantum state tomography. There are 729 measurement settings and about 700 counts in each setting. Fig. 3(a) and (b) show the measured density matrices. For setting $\vec{\theta}_A$, the quantum state fidelity is $0.859 \pm 0.002$ and the purity is $0.777 \pm 0.004$. For setting $\vec{\theta}_B$, the quantum state fidelity is $0.703 \pm 0.004$ and the purity is $0.692 \pm 0.006$. The standard deviation is estimated from Monte Carlo method with 100 trials.

The quantum coherence $C(\rho_S)$ of system qubit in equation (2) are 0.001 and 0.020 in process $\vec{\theta}_A$ and $\vec{\theta}_B$, respectively, which indicates that the environment has fully decohered the system. The quantum mutual information $I(S; E_i)$, the equation (3), between the system and 31 different combinations of environment fragments are shown in the Fig. 3(c) and (d), respectively. The results have two significant features. The mutual information quickly approaches the system’s entropy $H(\rho_S)$ (exceeding 70%, mainly limited by the purity of prepared entangled quantum states) when accessing small environment fragments, and the mutual information is saturated when increasing the size of environment fragments.

The arrows in Fig. 3(d) show that the environment fragments 5 and 6 are two low-fidelity records of the system’s states, which is expected from the corresponding nonorthogonal rotating angles in process $\vec{\theta}_B$. On the other hand, environment fragments 2346 and 2345 have mutual information exceeding the system’s entropy. This indicates that the mutual information contains more information than system’s information alone. We further analyze the information compositions by dividing it into the locally-accessible classical information and the extra information from pure quantum correlations. We show the classical correlation and quantum correlation between system and environment fragments in Fig. 4.

The first one, Hovelo bound $\chi(S; E_i)$, measures the capacity of environment acting as communication channel to deliver system’s classical information. The Hovelo bound

$$\chi(S; E_i) = \max_{\{M_s\}} \{H(\sum_s p_s \rho_{E_i|s}) - \sum_s p_s H(\rho_{E_i|s})\}$$

is maximum mutual information of the classical-quantum state between system and environment fragments with optimal measurement $\{M_s\}$ on the system [15], where $\rho_{E_i|s}$ is quantum state of environment $E_i$ conditioned on a measured result $s$ on the system with probability $p_s$. The second one, quantum discord

$$D(S; E_i) = I(S; E_i) - \chi(S; E_i)$$

measures the loss of information due to the observers can only locally access the environment, which quantifies the pure quantum correlation between environment and system [15].

In Fig. 4, the classical correlations and quantum correlations display very different features. The classical correlations have initial rise and saturate at classical plateau, which indicate the environment has recorded redundant copies of system’s classical information for independent observers. In sharp contrast, the quantum correlations raise when the nearly whole environment is accessed, manifesting quantum correlations cannot be shared between the observers [26]. The Fig. 4 (b) and (c) also demonstrate the effects of low-fidelity environment fragments (photons 5 and 6 in process $\vec{\theta}_B$), which
will lead to early raise of quantum correlation (Fig. 4 (b)) or delay the raise of classical correlation (Fig. 4 (c)).

Our results exhibit that environment not only decoheres quantum system and also selectively delivers the system’s information to observers. The environment channel is high-efficient for classical information and inefficient for quantum information. Only the classical information of quantum system’s decohered pointer states survives the environment-selected broadcasting and proliferates throughout the environment. Consequently, classical objectivity of quantum system originates from Darwinism-like broadcast structure of quantum substrate and quantum objectivity is prohibited by quantum mechanics due to quantum no-broadcast phenomenon [26, 27].

In summary, we have experimentally observed the classical objectivity emerging from classical information redundancy of single quantum system on a six-qubit quantum Darwinism simulator. We have demonstrated that the environment acting as communication channel and selectively broadcasting quantum system’s pointer states are the crucial mechanism of quantum Darwinism. Our work presents a first step to test quantum Darwinism in small-scale controllable quantum environment. We expect further works to investigate the quantum Darwinism in small-scale controllable quantum environment [18, 21] along with the considerable progress of current experimental quantum simulation technology [12, 28–30] and high-efficient quantum state characterization technology [31, 32].

**METHOD**

**Quantum states measurement and post-processing.** The Darwinism states are measured through full quantum state tomography. There are $3^6$ measurement settings of Pauli operators $\{\sigma_X, \sigma_Y, \sigma_Z\}^{\otimes 6}$ and in each setting, we collect about 700 six-photon coincidence counts. Due to statistical fluctuation, the direct synthesis of density matrix will generate some small negative eigenvalues and conflicts with the subsequent calculation of the entropy of information. We use the high-efficient algorithm introduced in [33] to renormalize the eigenvalues. We further resample the measured density matrix and produce 100 new density matrices through Monte Carlo bootstrapping method. The 100 statistical-fluctuation density matrices are used to calculate all the presented error bars.

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