Experimental verification of the commutation relation for Pauli spin operators using single-photon quantum interference

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A B S T R A C T
We report experimental verification of the commutation relation for Pauli spin operators using the single-photon polarization state. The experimental quantum operation corresponding to the commutator, \([\sigma_x, \sigma_y] = k \sigma_z\), showed process fidelity of 0.94 compared to the ideal \(\sigma_z\) operation and \(|k|\) is determined to be 2.12 ± 0.18.

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One of the most fundamental differences between classical and quantum physics is that, in quantum physics, a physical quantity always corresponds to a specific Hermitian operator or an observable and certain pairs of observables are non-commuting. In quantum physics, as a result, physical quantities that correspond to non-commuting observables ‘cannot have simultaneous reality’ [1]. As precise knowledge of one physical quantity precludes precise knowledge of the other physical quantity for a pair of non-commuting observables, the commutation relation is also at the very heart of the Heisenberg uncertainty relation [2,3]. For example, it is known that the position, \(\hat{X}\), and the momentum, \(\hat{P}\), operators of a quantum mechanical particle do not commute, \([\hat{X}, \hat{P}] = \hat{X}\hat{P} - \hat{P}\hat{X} = i\hbar\), and this leads to the position-momentum uncertainty relation, \(\Delta x \Delta p \geq \hbar/2\), which manifests itself in a single-slit diffraction experiment [4]. It is interesting to note that the position-momentum uncertainty has long been thought to enforce Bohr’s complementarity in a two-slit experiment before the quantum erasure [5,6]. Although the commutation relation has been very well understood theoretically, direct experimental verification of the commutation relation for a pair of conjugate observables has been very limited. For fermions, Pauli anti-commutation has been demonstrated in neutron polarimetry and interferometry [7,8]. For bosons, the commutator, \([\hat{a}, \hat{a}^\dagger]\), and the anti-commutator, \([\hat{a}, \hat{a}^\dagger]\), have been demonstrated for the photon creation, \(\hat{a}^\dagger\), and annihilation, \(\hat{a}\), operators, implemented with post-selective single-photon addition and subtraction operations, respectively [9,10]. In this Letter, we report an experimental verification of the commutation relation for Pauli spin operators using quantum interference of the single-photon polarization state. Although Pauli spin operators have fundamental importance in quantum physics and quantum information (e.g., describing single-qubit operations), the experimental test of the commutation relation for Pauli spin operators, however, have not been reported to date. By combining the bosonic interference property of a single-photon and Pauli spin operators for the single-photon polarization state, we have observed the relative phase factor of \(\pi\) between \(\sigma_x\sigma_y\) and \(\sigma_x\sigma_z\) operations (i.e., Pauli anti-commutation) and have experimentally verified the quantum operations corresponding to the commutator, \([\sigma_x, \sigma_z]\), and the anti-commutator, \([\sigma_x, \sigma_y]\), by means of quantum process tomography.

We begin by introducing the basic idea behind the experiment. The Pauli spin operators are defined as

\[
\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix},
\]

and they are essential in describing the unitary evolution (i.e., rotation) and the projection measurement of a two-level quantum system (i.e., a qubit), such as, the spin state of a spin-1/2 fermions (which requires the factor of \(\hbar/2\)), the polarization state of a single-photon, etc.

We can observe non-commutativity of the Pauli spin operators by applying them on an arbitrary qubit \(|\psi_0\rangle = \alpha|0\rangle + \beta|1\rangle = (\alpha |\beta\rangle)

For example, the Pauli spin operators \(\sigma_x\) and \(\sigma_z\) acting on the qubit \(|\psi_0\rangle\) cause the state to evolve as

\[
\sigma_z\sigma_x|\psi_0\rangle = i\sigma_y|\psi_0\rangle = \left(\begin{array}{c} \beta \\ -\alpha \end{array}\right),
\]

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where the subscripts represent the Cartesian coordinates \( x, y, \) and \( z, \) \( \epsilon_{jk} \) is the Levi-Civita symbol, and \( \delta_{jk} \) is the Kronecker delta.

In this Letter, we experimentally implement the quantum operations corresponding to the commutator, \([\sigma_2, \sigma_4]\), and the anti-commutator, \([\sigma_2, \sigma_3]\), by superposing \( \sigma_3 \sigma_4 \) and \( \sigma_2 \sigma_3 \) operations.

Our choice of the physical system for experimentally verifying the commutation relation for Pauli spin operators is the polarization state of a single-photon or the single-photon polarization qubit. This is a particularly convenient choice as all single-qubit quantum operations on the polarization qubit can be implemented with half-wave and quarter-wave plates and superpositions of quantum states (or operations) can be implemented with an interferometer. In particular, if we define \(|0\rangle\) as the horizontal and \(|1\rangle\) as the vertical polarizations, \( \sigma_3 \) and \( \sigma_2 \) operations on a polarization qubit can be realized by using a half-wave plate with its fast axis oriented at 45° and at 0°, respectively, with respect to the vertical polarization.

The experimental schematic is shown in Fig. 1. A type-II PPKTP crystal pumped by a multi-mode diode laser operating at 405 nm generates a pair of orthogonally polarized photons via the spontaneous parametric down-conversion process. The signal-idler photon pair is then split by the polarizing beam splitter PBS. Detection of the horizontally polarized idler photon at the trigger detector signals that the vertically polarized signal photon is prepared in the localized single-photon state [11–13]. A set of pump blocking dichroic mirrors and a 10 nm bandpass filter (not shown in the figure) are used to suppress the pump noise. The signal photon is then prepared in the arbitrary polarization state \(|\psi_0\rangle\) with a set of zero-order half-wave and quarter-wave plates (WP).

If the signal photon gets transmitted at the beam splitter BS, see Fig. 1, the polarization qubit \(|\psi_0\rangle\) undergoes the state transformation, \(\sigma_2 \sigma_1 |\psi_0\rangle / \sqrt{2}\). If the signal photon gets reflected at BS, the polarization qubit undergoes a different state transformation, \(i\sigma_3 \sigma_2 |\psi_0\rangle / \sqrt{2}\). Note that the Pauli spin operators \( \sigma_1, \sigma_2, \sigma_3, \) and \( \sigma_4 \) are all implemented with zero-order half-wave plates. The two amplitudes \( \sigma_2 \sigma_1 |\psi_0\rangle / \sqrt{2} \) and \( i\sigma_3 \sigma_2 |\psi_0\rangle / \sqrt{2} \) can be coherently added (or superposed) if the reflected and transmitted modes are combined at the second beam splitter with the path length difference much smaller than the coherence length of the input signal photon. Thus, at the D1 output port of the interferometer, the input qubit \(|\psi_0\rangle\) will be found to have undergone the quantum operation

\[
\frac{i}{2}(\sigma_2 \sigma_1 e^{i\phi} + \sigma_2 \sigma_3),
\]

and, at the D2 output, the input qubit \(|\psi_0\rangle\) will be found to have undergone a different quantum operation

\[
\frac{1}{2}(\sigma_2 \sigma_1 e^{i\phi} - \sigma_2 \sigma_3).
\]
mirror and the wave plate controls to make sure that the wave plate rotation only affects the polarization state of the photon. In this setting, the detection events at D1 now corresponds to $\frac{1}{2}\langle \psi_0| (\sigma_x,\sigma_z) |\psi_0\rangle$ measurement and the detection events at D2 corresponds to $\frac{1}{2}\langle \psi_0| (\sigma_z,\sigma_x) |\psi_0\rangle$ measurement. Due to the phase difference of $\pi$ shown in Eqs. (2) and (3) between $\sigma_x\sigma_z$ and $\sigma_z\sigma_x$ operations, we now expect that D1 will register no photons but D2 will register the maximum photon count rate.

Therefore, experimental observation of the shift of the photocount distributions from case I (D1 at maximum rate; D2 at zero) to case II (D1 at zero; D2 at maximum rate) verifies the relation $\sigma_x\sigma_z = -\sigma_z\sigma_x$ (i.e., $[\sigma_x,\sigma_z] = 0$) and allows us to experimentally construct quantum operations corresponding to the commutator and the anti-commutator for $\sigma_z$ and $\sigma_x$. Note that the commutator and the anti-commutator operations correspond to different output ports of the interferometer. The experimental data are shown in Fig. 2(b). The changes in the normalized coincidence rates from case I to case II indeed show the expected behavior: D1 at maximum rate and D2 at zero for case I and D1 at zero and D2 at maximum rate for case II. The data, therefore, experimentally confirms the phase shift of $\pi$ in Eqs. (2) and (3). It is interesting to point out that the $\pi$ phase shift of this kind cannot be observed by performing quantum state tomography.

Although the data shown in Fig. 2(b) confirms the $\pi$ phase shift between the operations $\sigma_x\sigma_z$ and $\sigma_z\sigma_x$, we have yet to confirm the commutator relation $[\sigma_x,\sigma_z] = i\sigma_y$, where $k = 2i$ theoretically. This requires quantum process tomography (QPT) which allows us to experimentally characterize the set of quantum processes operated on the input qubit $|\psi_0\rangle$. We therefore inserted a set of quarter-wave and half-wave plates (WP) and a polarizer $P$ in front of D2 and performed quantum state tomography for four input qubits $|H\rangle, |V\rangle, |\psi_0\rangle$ and $|\psi_0\rangle$. The results are then used to reconstruct the QPT matrix $\chi_{\text{exp}}$.

The reconstructed QPT matrix for the experimentally implemented $\frac{1}{2}[\sigma_x,\sigma_z]$ operation is shown in Fig. 3. It is evident from the experimental data that the quantum operation we have implemented experimentally is mainly of the $\sigma_z$ operation. The process fidelity, defined as $F = \text{Tr}[\chi_{\text{exp}}\chi_{\text{ideal}}]$, quantifies the quality of the overlap between the experimentally realized operation $\chi_{\text{exp}}$ and the desired ideal operation $\chi_{\text{ideal}}$. In experiment, the process fidelity of $F = 0.94$ has been observed with $\chi_{\text{ideal}}$ corresponding to the ideal $\sigma_y$ operation.

So far, we have determined that the commutator $[\sigma_x,\sigma_z]$ is proportional to $\sigma_y$ and the proportionality constant $k$ is yet to be determined. Let us now discuss how to determine $|k|$. For the input qubit $|\psi_0\rangle$, the single-photon transmitted at the first beam splitter (just before the second beam splitter) has the quantum state $\sigma_x\sigma_z|\psi_0\rangle/\sqrt{2} = i\sigma_y|\psi_0\rangle/\sqrt{2}$. Similarly, the single-photon reflected at the first beam splitter (just before the second beam splitter) has the state $i\sigma_x\sigma_z|\psi_0\rangle/\sqrt{2} = \sigma_y|\psi_0\rangle/\sqrt{2}$. To determine $|k|$, we first record the rate of events at D2, $N_u$, for the commutator operation to the input state, $\frac{1}{2}[\sigma_x,\sigma_z]|\psi_0\rangle$. We then block the lower path of the interferometer to record the rate of events at D2, $N_b$, and, for the commutator operation to the input state, $\frac{1}{2}[\sigma_x,\sigma_z]|\psi_0\rangle$. The experimental obtained value is $|k| = 2.12 \pm 0.18$.

Determining the phase factor of $\pi/2$ in $k$ requires additional phase sensitive measurement and, therefore, is more difficult than measuring $|k|$. For this measurement, it is necessary to first interfere the single-photon state at D2 output port,
\[ [\sigma_z, \sigma_x] | \psi_0 \rangle = k \sigma_y | \psi_0 \rangle \], with a single-photon field of known polarization, \( \sigma_y | \psi_0 \rangle \). If we then replace the quantum operation \( [\sigma_z, \sigma_x] \) with a single \( \sigma_y \) operation, the phase difference between the two operations (coming from \( \pi/2 \) phase factor in \( k \)) will cause the interferometric signal to change and we can use this result to determine the phase factor in \( k \). In our setup, this scheme could in principle be implemented by introducing an additional beam splitter to split the single-photon beam just before the first beam splitter and interfering it with the output of the commutator output port of the original Mach–Zehnder interferometer. In this experiment, however, because of the difficulties in assuring the interferometric stability for a larger interferometer and experimentally implementing replacement of the quantum operation \( [\sigma_z, \sigma_x] \) with a single \( \sigma_y \) operation, we have not been able to directly demonstrate the \( \pi/2 \) phase factor in \( k \).

In summary, we have experimentally verified the commutation relation for Pauli spin operators using quantum interference of the single-photon polarization qubit. We have demonstrated that, via single-photon quantum interference, there exists the relative phase factor of \( \pi \) between the quantum operations \( \sigma_z \sigma_x \) and \( \sigma_x \sigma_z \). Also, by superposing these operations, we have implemented the commutator, \( [\sigma_z, \sigma_x] \), and the anti-commutator, \( [\sigma_z, \sigma_x] \), operations on the single-photon polarization qubit. Furthermore, we have demonstrated experimentally that the quantum operation \( [\sigma_z, \sigma_x] \) is predominantly a \( \sigma_y \) operation with the process fidelity of 0.94. Finally, we interferometrically determined that \( |k| = 2.12 \pm 0.18 \), in good agreement with the theoretical value of 2, for the commutation relation \( [\sigma_z, \sigma_x] = k \sigma_y \). Although we have not been able to determine the phase factor in \( k \) in this experiment, we have proposed a scheme for such measurement.

Note added

After completing this manuscript, we have become aware of a related work [16].

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