論文の要旨
（Thesis Summary）

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論文題目(Thesis Title)

Experimental investigation into physical aspects of quantum joint-statistics via optical sequential measurements
（光の連続測定による量子結合統計の物理的様相への実験的探求）

A unique characteristic of quantum statistics is non-commutativity. The non-commutativity of two canonical observables is a mathematical foundation of quantum mechanics that the uncertainty principle is derived from and that concerns the interpretation of quantum states, which has resulted in many controversies about the details of their physical meaning. In consideration of finding a clue, we have recognized difficulty in particular to observe the expectation value of a product of non-commuting observables, since their product is no longer an observable. If we wish to find correlations between the measurement outcomes of the two observables, we need to obtain the experimental outcomes in a manner that allows us to identify the actual experimental correlations with the theoretical correlations that correspond to the mathematical formalism of quantum mechanics. Theoretically, correlations between non-commuting observables can be expressed by a quasi-probability distribution that represents a quantum state in analogy with classical phase space distributions of the non-commuting variables. Such quasi-probability distributions are given by non-positive joint probabilities, so that it is difficult to see the connection to actual experiments. However, it is possible to perform a joint measurement with errors in the measurement outcomes for the non-commuting observables.

Here, I investigate experimentally observed correlations between joint outcomes obtained from a sequential measurement of photon polarization and compare the results with a quasi-probability distribution for the initial state. Since the outcomes of two non-commuting observables are obtained in a sequence of measurements, the first measurement causes a disturbance of the state, resulting in an error of the final measurement. By using a measurement with finite measurement strength, the outcomes involve a trade-off between the measurement error due to the finite resolution and the measurement back-action caused by unavoidable influences on other non-commuting observables. The back-action effects are observed in the second measurement, which measures an observable that does not commute with the first measurement. The statistical effects of the measurement resolution and back-action, which are conceptually known as measurement uncertainties, contribute to the experimental statistics of joint outcomes obtained with the sequential measurement. If we can evaluate these errors in the statistics, the original correlations

between the non-commuting observables can be determined at any measurement interaction strength. In a two level system, we can recover the initial statistics from the experimental probabilities of the sequential measurement outcomes using the experimental evidence from the statistical contrast between opposite eigenvalues observed as outcomes in the measurement apparatus.

In this thesis, I experimentally demonstrate that the original quantum statistics can be identified in the data from sequential measurements of photon polarization, so that the same result is obtained at any measurement strength. An experimental outcome of the first measurement is given by two output ports of an interferometer that realizes a diagonal (PM) polarization measurement with variable measurement strength. The following measurement of Horizontal/Vertical (HV) polarization is performed with polarizers inserted after the interferometer. Polarization rotations in paths of the interferometer can control the measurement back-action, so that we can realize PM measurements from the weak regime to the strong regime. The errors of PM resolution and the back-action effect on the outcomes of the HV measurement can be confirmed experimentally from the measurement probabilities for P and H polarized input photons respectively. These experimentally evaluated errors can be modelled as independent flipping probabilities of the eigenvalues. Using this assumption, I reconstruct the initial joint probability distribution from the experimental probability distribution for a photon polarization halfway between P and V polarization, where the joint probabilities before the measurements provide a consistent description of the initial quantum state. The reconstructed joint probabilities correspond to the correlation that Leggett and Garg discussed in the formulation of their inequality. Such Leggett-Garg inequalities (LGIs) indicate that non-classical correlation correspond to negative joint probability in the sequentially measured observables. The results of the reconstructed joint probabilities have the same values for different measurement strengths of the PM measurement and these values are equal to the theoretical values of the Dirac distribution, where the negative values indicate a violations of the LGIs. Therefore, the experimental obtained statistics of the two non-commuting observables reveals the presence of non-classical correlations, which can be reconstructed as non-positive probabilities, where the quantum state statistics and the measurement errors can be separated by changing the strength of the measurement.

In the LGI measurement scenario, the reconstruction neglected the possibility of correlations between errors because the real part of the correlation product between PM and HV is always zero. However, the error correlations must be included for a complete characterization of the errors of the PM and HV measurements, since the four possible outcomes for PM and HV can include correlations in their joint probability. This means that complex valued joint probabilities can be reconstructed if the correlation between errors is imaginary. Indeed the operator formalism suggests that the product of the PM and the HV observables is given by the imaginary value of the circular polarization (RL) observable. To observe this imaginary correlation in the sequential measurement of PM and HV, I modify the interferometric setup by introducing additional polarization rotations in the interferometer. Previously, the rotations were realized toward a direction of common diagonal P polarization and were therefore limited to linear polarization. By contrast, the polarizations in the new setup are twisted towards the RL directions while keeping the same orientation towards P polarization. This rotation effect of the new degree of freedom will appear as a back-action effect in the HV measurement. The back-action effect can be evaluated by converting the imaginary correlation into real correlation between the outcomes obtained from an R state input. As before, the same reconstructed joint probabilities can be obtained at any measurement strength and the statistics of an initial elliptical polarization has both real and imaginary parts that are both independent of measurement strength. This complete measurement of the correlations between non-commuting observables provides new insights into the physics of measurement uncertainties and into the statistics of physical properties in quantum states.