

Preface

Quantum mechanics, born nearly one century before and originating from some fragmentary pieces of ideas, has finished the establishment of a relatively complete theoretical framework, that is, a mathematical framework based on the wave function description of a quantum object and the superposition principle, for describing the law of motion in the microscopic world. It can be used not only to answer the ancient and fundamental philosophical question of whether matter is infinitely divisible, but also to interpret the macroscopic physical phenomena within the scale extended to the universe. In the aspect of technology application, many high and new technologies have been produced primarily due to quantum mechanics, such as semiconductor technology, laser, new energy, new material, etc. For the fundamentality and universality of its theoretical framework, its theoretical perspectives and research techniques have been applied in some other subjects, such as the informatics, cryptology, chemistry, biology, etc, then, as a result, many new interdisciplinary sciences have emerged and quickly have become the hotspots and cutting-edge in the relevant subjects.

One of such interdisciplinary sciences is the quantum information, which emerges from the application of the fundamental principles and methods of quantum mechanics in the informatics and computer science. Quantum information originated in the early 1980s, and researchers at that time sought the solution for the power consumption in the classical computer and pinned their hopes on the quantum reversible computing. By the 1990s, Peter Shor devised the famous quantum algorithm for integer factorization, an epoch-making achievement that made people putting their attention to the new subject quantum information for the fear of the possibility of cracking the cryptosystem for public-key encryption, known as RSA and widely used at present. Since then quantum information ushered in the golden age of development. The basic tasks of quantum information are using the quantum state as the fundamental carrier of information, and realizing the preparation, operation, transmission, storage and read of this carrier, in summary, contain two aspects: quantum computation and quantum communication.

The information carriers in quantum information inherit one fundamental property of the quantum object, that is, the coherent superposition. Some other peculiarities originating from the coherent superposition, such as the quantum entanglement and the quantum nonlocality, let researchers have the ability to experimentally exhibit many phenomena which have just been in science fictions, for example, the quantum teleportation. It, of course as an engineering discipline, particularly unfolds the information processing and communicating skills which are superior to the classical ones, for instance, the quantum dense coding, the quantum key distribution, and numerous quantum algorithms. With the development for nearly 30 years, some technologies in quantum information have reached the commercial level, and the most successful one is the quantum key distribution system. The industrialization of quantum information technologies brings in more and more talents and resources to the field. One of the results is the development in quantum information is accelerated, and the other is that the increased control capabilities for the quantum information carriers greatly promote the development of quantum mechanics.

At present, the physical systems for experimentally researching quantum information mainly contain linear optics, cold atoms, ion traps, quantum dots, superconducting Josephson junctions, optical cavity quantum electrodynamics, nuclear magnetic resonance, etc. For the specialties of super-long coherent time and the relatively mature experimental technologies, linear optical systems have been widely used in experimentally testing the fundamentals in quantum mechanics since 1980s. In linear optics, there exist three hotspots, or difficulties, in general. The first one is about the preparation of multi-photon entangled states. The biggest limitation for entangling multiple photons is the nonlinear coefficient in the nonlinear process for producing entangled photon pairs. By optimizing the nonlinear crystals, increasing the collection efficiency, and changing the generation types, researchers had only prepared an eight-photon entangled state all around the world till 2013. Second, the interaction between photons is too weak to realizing genuine two-qubit quantum gate with a practical value in linear optics. Usually, the alternative is the two-photon interferometer with postselection, which is inefficient and non-scalable. The third one is about building an interferometer with a certain degree of complexity and scale, which is essential for practical quantum computation. The reason is the difficulty in matching the mode of light field and controlling the phase stability when environment disturbances exist. Solutions mainly focus on two aspects: One is using the technology of light wave guide, which can manufacture optical chips in small scale and solve the above two difficulties at once; the other is optimizing the construction in bulk optics, such as using the beam displacer and introducing the Sagnac-type interferometer.

This thesis experimentally researches on mainly two aspects based on the linear optics:

The first one is about the problem of quantum measurement, which has been acting as one of the postulates in quantum mechanics since it was born. Although in 1980s Zurek has given a whole set of quantum decoherence theory to interpret the quantum measurement process, even now the mechanism in the collapse of wave

packet in that process is still a research hotspot for the physicists both in theory and experiment. In the very beginning of quantum mechanics, the quantum measurement was interpreted by von Neumann theory, known as the orthogonal projection model. Until the Zurek's decoherence theory, the collapse of wave packet in quantum measurement has been considered to accomplish in an action and recognized as a postulate in standard textbooks. In the decoherence theory, quantum measurement is one case of the decoherence processes induced by the environment, it can also monitor the transition from quantum to classical, in addition, the measurement process can be partial, weak, and even reversible. We have finished the experimental verification of the local and nonlocal reversibility of the partial-collapse measurement. Based on the weak measurement theory, we have given the proposal of ultrasensitive phase estimation with white light and experimentally realized it by using a commercial LED with wide spectrum. We have also predicted in theory and verified in experiment that the quantum measurement process can recover the quantum entanglement.

The second aspect is about the topic of quantum simulation in linear optics and, in detail we have built a multistage interferometer to simulate the Landau–Zener dynamics and given the support to Kibble–Zurek mechanism in experiment. During the study of cosmology, Kibble has given a series of theory, known as the cosmological phase transition, to interpret the process, that is, the formation of the galactic structure we can see today from the very beginning, known as the Big Bang. Kibble's theory is too macroscopic to be verified experimentally. Then in 1980s, Zurek presented that a similar phase transition can be observed in condensed matter systems in the laboratory. Particularly, based on the superfluid system which was popular at that time, Zurek gave an equation to predict the density of the topological defects formed in the phase transition. Though there has already been significant effort to date, the central prediction of Kibble–Zurek mechanism still has not been clearly observed (particularly in quantum phase transitions) in the laboratory due to the difficulty in controlling a sufficient range of quench time scales and in controlling counting defects. In 2005, Damski presented a simple quantum dynamical model, the Landau–Zener model, which exhibits the key features of Kibble–Zurek mechanism. Following Damski's proposal, we first construct a nine-stage optical interferometer with high overall visibility and stability, and then we develop a quantum simulation of the evolution of Landau–Zener model, giving the experimental support to the Kibble–Zurek mechanism in a quantum system.

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