Quantum entanglement in polarization and space

Lee, Peter Sing Kin

CHAPTER 1

Introduction

1.1 Quantum entanglement

Since quantum mechanics was born in the early 20th century, its controversial character has intrigued many physicists in their perception of nature. Undoubtedly, quantum mechanics offers a precise and elegant description of physical phenomena in various disciplines, ranging from subatomic physics to molecular physics and condensed-matter physics. In the shadow of this success, however, counterintuitive concepts of quantum mechanics have always been looming and have triggered several discussions on the foundations of quantum mechanics.

One of these concepts is quantum entanglement which originates from the well-known Gedankenexperiment proposed by Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) in 1935 [1]. In this experiment, two physical systems are considered to interact with respect to a certain observable. Due to the interaction the two systems will exhibit a strong mutual relation with respect to this observable. This so-called quantum entanglement means that the *individual* outcomes of the observables cannot be predicted with certainty for each of the two EPR systems, but the outcomes of the observables for the two systems are always strictly correlated. Quantum entanglement offends physical reality in the sense that the individual measurement results are fundamentally undetermined before the measurement. According to quantum mechanics, a measurement of a certain value of the observable in one EPR system instantaneously determines the state of the other system, irrespective of the distance between the systems. This latter condition implies that quantum entanglement also contradicts the concept of locality. The EPR paper thus concluded that quantum mechanics is apparently incompatible with a local and realistic description of nature, and therefore cannot be considered as a “complete theory”.

It was not until 1964 that John Bell translated the somewhat philosophical EPR discussion into a concrete test of the conflict between local realism and quantum mechanics [2]. This test consists of a set of inequalities which must be satisfied by any local and realistic theory. Quantum mechanics, however, predicts violation of these so-called Bell's inequalities for measurements on specific quantum-entangled systems. Some years later, Clauser, Horne, Shimony and Holt (CHSH) introduced a generalized version of Bell's inequalities which applies to real laboratory experiments with, for example, quantum-entangled photons [3]. By now, many of such experiments on EPR particles have shown strong violation of Bell's inequalities and thus confirmed the non-local nature of entanglement [4–13]. Especially in the last 15 years, investigations on the fundamental concept of quantum entanglement have also led to perspective applications in information science, such as quantum cryptography [14,15], quantum teleportation [16, 17] and quantum computation [18].

1.2 Quantum-entangled photons

The first experimental proof of quantum entanglement via violation of Bell's inequalities was reported by Clauser and Shimony in 1978 [4]. A few years later, Aspect and co-workers [5] performed similar experiments in a more efficient way which yielded even more convincing results. For this pioneering work, photon pairs were used as the EPR particle systems. Ever since this major breakthrough, these photon pairs have remained the most popular tool for testing quantum correlations.

Despite the success of these early-generation EPR experiments [19], the employed atomic cascade source of photon pairs has only incidentally been employed in follow-up experiments [9] because of the poor pair-production rate and collection efficiency. Instead, the production of quantum-entangled photons via the non-linear process of spontaneous parametric down-conversion (SPDC) in a birefringent crystal [20] became more favourable. In fact, the first SPDC source of photon pairs was already presented by Burnham and Weinberg in 1970 [21]. They successfully observed photon coincidences by matching the detection to the energy- and momentum-conservation conditions of the SPDC process. The new generation of EPR experiments [19], where a SPDC source is used to test the quantum correlations between photons, was simultaneously introduced by two groups in the late 80's [6, 7], and quickly adopted by others [10, 11]. The popularity of EPR photon pairs is also reflected by the ongoing development of high-quality and high-intensity SPDC sources [8, 22–24].

As mentioned before, the entanglement of two-particle systems is always with respect to a certain observable. For quantum-entangled photons three of such observables can be distinguished, being polarization, energy or time (longitudinal space), and transverse momentum or transverse space. The corresponding types of entanglement are called polarization, time and spatial entanglement of photons, respectively. The entanglement of photons is in principle simultaneous in the three mentioned observables. In this respect, one can also speak about multiparameter or hyperentanglement [25, 26].

In the first entanglement experiments [4, 5] only polarization correlations of EPR photons were measured. Since then, EPR experiments with polarization-entangled photons have always been most popular due to their practical simplicity [6–8, 23, 24]. Time entanglement of photons has been widely investigated in several interferometric schemes [9–11, 27–29]. Somewhat less explored are the spatial correlations of entangled photons. The most notable experiments on spatial entanglement study these correlations by conditional imaging of the transverse positions of the pair-photons [30, 31].

1.3 Thesis

The contents of this thesis covers research that has been performed to gain deeper insight into both polarization entanglement and spatial entanglement of photons. The general theme of this work is to investigate the quality of entanglement under different experimental settings. The explored conditions are associated with the manipulation of both the production and detection of entangled photons. Apart from the entanglement quality, the general interest was also focused on the yield of photon pairs under these conditions. As a kind of sidetrip, particular attention is paid to the degradation of polarization correlations caused by time- and space-related decoherence processes in a metal hole array (Chapter 5). Below, the structure of the thesis is presented in some more detail.

- Chapter 2 provides a brief description of the non-linear process of spontaneous parametric down-conversion (SPDC) as a source of quantum-entangled photons. Starting from the two-photon entangled state, polarization entanglement and spatial entanglement of photons are introduced in an analogous way.
- Chapter 3 presents a novel method for simultaneous determination of the thickness and cutting angle of a birefringent non-linear crystal that can e.g. be used as a SPDC source. Although this simple method is based only on polarization interferometry, it allows a highly accurate measurement of both the crystal thickness and cutting angle.
- Chapter 4 demonstrates how the thickness of the SPDC source determines its brightness, i.e., the generated number of polarization-entangled photons pairs. This result follows from simple scaling laws and is supported by experimental data.
- Chapter 5 addresses the question whether time- and space-related polarization- decoherence channels commute. These channels are created by sending entangled photons in succession through a birefringent delay and focusing them on a metal hole array, thereby using the thin crystal discussed in Chapter 4 to create sufficient time resolution. The experimental results are interpreted in terms of the propagation of surface plasmons that are excited on the hole array.
- Chapter 6 shows the consequences of focused pumping on the spatial distribution of the generated SPDC light and the obtained quality of polarization entanglement.
- Chapter 7 focuses on the polarization-entanglement attained behind single-mode optical fibers. The concept of transverse mode matching, which is needed for optimal photon-pair collection, is revised by explicit count rate measurements. The limitations to the entanglement quality are investigated for detection behind both apertures and fibers.
- Chapter 8 specifically treats the *spatial* entanglement of photons that are generated via SPDC. The theoretical and experimental work in this chapter study the spatial coherence of the two-photon wavepacket under different geometries of the employed two-photon interferometer.

- Chapter 9 demonstrates how the same interferometer, but now with an additional image rotator in one the two interferometer arms, allows for determination of the number of entangled orbital-angular-momentum (OAM) modes. This mode number follows from the OAM entanglement measured as a function of the spatial-profile rotation of the entangled light.