

Chapter 2

Measurement-Induced Entanglement Recovery

Abstract Using photon pairs created in parametric down-conversion, we report on an experiment, which demonstrates that measurement can recover the quantum entanglement of a two-qubit system in a pure dephasing environment. The concurrence of the final state with and without measurement is compared and analyzed. Furthermore, we verify that recovered states can still violate the Bell inequality, that is, to say, such recovered states exhibit nonlocality. In the context of quantum entanglement, sudden death and rebirth provide clear evidence, which verifies that entanglement dynamics of the system is sensitive not only to its environment, but also to its initial state.

2.1 Introduction

As a unique feature without a classical counterpart of a many-body system, quantum entanglement is a powerful tool in studying fundamental aspects of quantum physics, which also plays a central role in quantum computation and quantum communication (Zeilinger 2000). Though entangled state can be produced in different physical systems (Nielsen and Chuang 2000; Preskill 1998), even multiphoton and multidimensional entanglement can be achieved (Pan et al. 2012), it will inevitably interact with the environment, as a result, entanglement becomes very weak and easily degenerated (Dodd and Halliwell 2004; Mintert et al. 2005; Życzkowski et al. 2001). If quantum computation and quantum communication of actual value are to be realized, long-range nonlocal entanglement, including its storage and recovery have become the research focus of the quantum information science (Gisin and Thew 2007; Simon et al. 2010). The key to solve this problem is to determine the dynamics property of entanglement in the environment (Konrad et al. 2008). The environment is a very general concept, it can be divided into the Markovian environment and non-Markovian environment on whether information flow is reversible or not in the system evolution process (Liu et al. 2011). The Markovian environment corresponds to infinite heat reservoir and lost information will not back flow to the system, it is a very ideal noise environment. However, in the overwhelming majority of tests, the environment dimension is limited and a intrinsic environment spectrum exists. For the non-Markovian environment with a certain intrinsic spectrum, research on

entanglement evolution seems to be more fundamental (Strunz et al. 1999). In this environment with a certain memory effects, entanglement dynamics exhibits many strange characteristics, such as sudden death and revival of entanglement (Almeida et al. 2007). Researches on entanglement dynamics in the non-Markovian environment will help us understand quantum entanglement phenomenon profoundly; more importantly, the entanglement state life can be extended by adding operation to recover entanglement during the evolution process, therefore, it is of significant actual application value (Xu et al. 2010a, b).

Quantum measurement, another important concept in quantum physics, was written into standard textbooks in the form of postulates from the birth of quantum mechanics (Landau and Lifshitz 1958; Von Neumann 1955). In the early development of quantum mechanics, it was generally interpreted by Von Neumann's orthogonal projection model (Landau and Lifshitz 1958; Von Neumann 1955). As quantum measurement is directly related to the transition of the system from quantum to classical, it remains to be the hotspot and difficulty of basic theory research of quantum mechanics (Zurek 1991). In the 1980s of past century, Zurek et al., proposed a complete set of quantum decoherence theory to re-explain the quantum measurement process (Zurek 1981, 1982). In this theory frame, a complete quantum measurement is usually divided into two steps: the first step corresponds to entanglement of information carrier of the quantum system and the pointer state of the measurement device, forming a new complex; the second step is decoherence of complex state in a noncontrollable macro environment. The latter will degenerate the diagonal term describing the density matrix of the state of the combination, physically, it means that quantum information contained in combination will be dissipated into the whole subsequent uncontrollable environment, thus making a quantum measurement converted into an ordinary classical measurement. This interpretation, to some extent, explains the irreversibility of the quantum measurement process, which plays a very important role in quantum mechanics, because basic equations of quantum mechanics are of time-reversal symmetry whereas the second stage of quantum measurement is of time-reversal asymmetric, enabling us to sense the past and the future (Landau and Lifshitz 1958). Though we seem to be powerless when quantum measurement is fully completed, fortunately, the measurement process may be done by step or even be done partially, making people begin to focus on how to use quantum measurement, for instance, apply it to quantum information processing and propose measurement-based quantum computation (Raussendorf and Briegel 2001). Some information extracted in quantum measurement may even be erased with a quantum eraser, thus recovering the quantum state after the partial measurement (Katz et al. 2008). Recently, Xu Jin-shi et al., have successfully recovered single qubit coherence lost in a dephasing environment (Xu et al. 2009).

In this chapter, we adopt a method similar to the one Xu Jin-shi et al., used and experimentally demonstrate the entanglement dissipation recovery under dephasing environment through quantum measurement for the first time. Through two measurements, entanglement dissipation can be recovered to some extent. Entanglement dissipation and recovery process can be given intuitively by comparing the degree

of entanglement of different evolution stages. It is pointed out that entanglement can be revived through measurement even after sudden death of entanglement.

2.2 Theory Description

2.2.1 Experimental Realization of Dephasing Environment

In linear optics, the polarization is generally used as information carrier for its easy operation and high operation fidelity. Other freedoms of photons such as frequency and route etc., can be used to simulate the environment. Here, we adopt the freedom of frequency to simulate the environment and introduce the experimental realization method of dephasing environment (Kwiat et al. 2000). When ignoring other freedom of photons but only considering photon polarization and frequency, the two dimensions are usually independent for the initial state, which can be described as (Berglund 2000)

$$|\Psi\rangle = \sum_{i=1}^2 k_i |\kappa_i\rangle \otimes \int d\omega f(\omega) |\omega\rangle, \quad (2.1)$$

where $|\kappa_i\rangle, i \in \{1, 2\}$ represents the basic vector of polarization dimension, k_i is the corresponding complex amplitude, satisfying $\sum_{i=1}^2 |k_i|^2 = 1$. $|\omega\rangle$ represents the basic vector of frequency dimension and its corresponding complex amplitude is $f(\omega)$, its square modulus is the characteristic spectrum of the environment and satisfies $\int d\omega |f(\omega)|^2 = 1$. The corresponding density matrix is

$$\hat{\rho}(0) = \sum_{i,j=1}^2 k_i k_j^* |\kappa_i\rangle \langle \kappa_j| \otimes \iint d\omega_1 d\omega_2 f(\omega_1) f^*(\omega_2) |\omega_1\rangle \langle \omega_2|. \quad (2.2)$$

Mutual coupling of the system and the environment mean that with the proceeding of evolution, a phase error depending on environment spectrum and interaction time will be added to polarization bit, i.e.,

$$U_i(\omega, t) |\kappa_i\rangle = e^{i\delta_i(\omega, t)} |\kappa_i\rangle, \quad (2.3)$$

where $\delta_i(\omega, t)$ is the real function of ω and t . The system state after the system has evolved in the environment for a certain time is the partial trace of the density matrix of the combination concerning at that moment over the frequency dimension, that is, mathematically written as

$$\begin{aligned}
\hat{\rho}_P(t) &= \int d\omega \langle \omega | \hat{U}(\omega, t) \hat{\rho}(0) \hat{U}^\dagger(\omega, t) | \omega \rangle \\
&= \sum_{i,j=1}^2 k_i k_j^* |\kappa_i\rangle \langle \kappa_j| \times \int d\omega |f(\omega)|^2 e^{i[\delta_i(\omega, t) - \delta_j(\omega, t)]}.
\end{aligned} \tag{2.4}$$

Pure dephasing environment means that the diagonal term of the density matrix will not change during system evolution process, but non-diagonal terms will decay, that is to say, the integration results to frequency in Eq. 2.4 are time-related t attenuation function. The phase error depending on environmental spectrum and interaction time may easily be realized through a birefringent crystal in an experiment. In the case of not considering dispersion, the l -thick birefringent crystal will introduce the phase error of

$$\delta(\omega, t) = \omega t. \tag{2.5}$$

Where virtual time $t = \frac{\Delta n l}{c}$, c is the velocity of light in vacuo and $\Delta n = n_o - n_e$ represents the difference between refractive indices of ordinary (n_o) and extraordinary (n_e) light. In this way, Eq. 2.4 can be simplified as

$$\hat{\rho}_P(t) = \begin{pmatrix} \hat{\rho}_{1,1}(0) & \hat{\rho}_{1,2}(0)F^*(t) \\ \hat{\rho}_{2,1}(0)F(t) & \hat{\rho}_{2,2}(0) \end{pmatrix}, \tag{2.6}$$

where $F(t)$ is the Fourier transform of the environment wave function.

It can be seen that the dephasing process is only related to photon frequency wave function (Berglund 2000) when using photon frequency dimension to simulate the environment and using birefringent crystal to introduce phase error. A variety of environments can be obtained by changing the form of photon frequency wave function, i.e., changing the environmental characteristic spectrum. The advantage of our method is that photons are always collinear evolving during the whole process, which can ensure high operation fidelity and stability.

2.2.2 Recover Entanglement Through Measurement in Dephasing Environment

Xu Jin-shi et al., recovered single qubit coherence (Xu et al. 2009) in a dephasing environment by measurement, we expanded this result to a two-qubit case and find that measurement can recover the entanglement of two qubits. The experimental setup is shown in Fig. 2.1. For convenience, we define the horizontal polarization state $|H\rangle$ and the vertical polarization state $|V\rangle$ of photons as the computing base of the system, considering the maximum entanglement state

$$|\phi\rangle = \frac{1}{\sqrt{2}}(|HH\rangle_{a,b} + |VV\rangle_{a,b}), \tag{2.7}$$

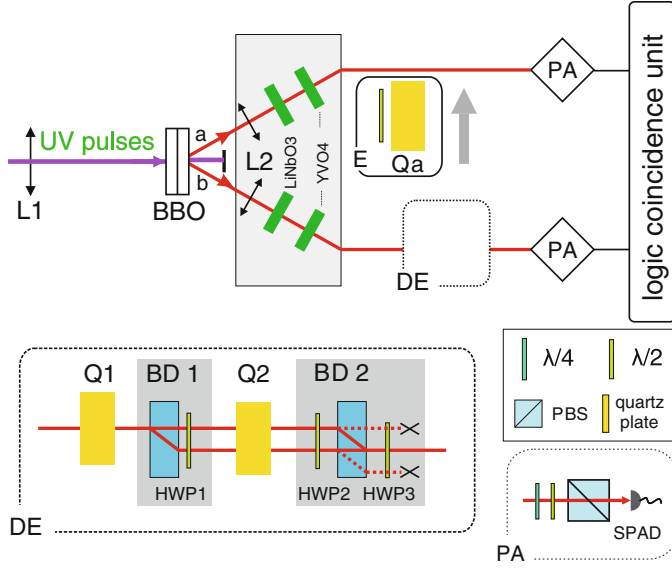


Fig. 2.1 Scheme of the experimental setup. DE, decoherence evolution denoted by a *dashed pane*; Measurement apparatus (M) is denoted by two *gray boxes*. PBS, polarizing beam splitter; L1 and L2, lens; PA, polarization analyzer; SPAD, single-photon detector; BD1 and BD2, beam displacing prism; The *solid pane* E is inserted in path *a* to prepare the partially entangled state. The parameters of these elements are provided in the text. Reprinted with permission from Ref. Xu et al. (2010c). Copyright 1998 by American Physical Society

where a and b are photon labels, for convenience, we will omit these labels and default a as the first photon and b as the second. Add birefringent crystal in the path b -photon passes to simulate dephasing channel, the two-photon polarization state after evolving for a time interval t can be expressed by the following reduced density matrix:

$$\hat{\rho}_1 = \frac{1}{2}(|HH\rangle\langle HH| + |VV\rangle\langle VV| + k_b^*|HH\rangle\langle VV| + k_b|VV\rangle\langle HH|), \quad (2.8)$$

where b photon's frequency complex amplitude $f(\omega_b)$ satisfies the normalization conditions $\int d\omega_b |f(\omega_b)|^2$. k_b is defined as the decoherence parameter, according to the analysis above, $k_b = \int d\omega_b f(\omega_b) e^{i\omega_b t}$ can be easily obtained, i.e., Fourier transform of photon frequency wave function.

In experiment, photon frequency is generally determined by interference filter placed in front of a detector, its frequency wave function can be written as

$$f(\omega_b) = \frac{2}{\sqrt{\pi}\sigma} \exp\left[-\frac{4(\omega_b - \omega_0)^2}{\sigma^2}\right] \quad (2.9)$$

where ω_0 and σ are the central frequency and bandwidth of the interference filter. The following formula can be obtained through calculating the above integration.

$$k_b = \exp(-\sigma^2 t^2 / 16 + i\omega_0 t). \quad (2.10)$$

For a quantitative analysis of the entanglement evolution in the experiment, a parameter, which represents the degree of entanglement, should be introduced. The concurrence (Wootters 1998), which is widely used in studying two-qubit states, is defined as

$$C(\hat{\rho}) = \max\{0, \sqrt{\lambda_1} - \sqrt{\lambda_2} - \sqrt{\lambda_3} - \sqrt{\lambda_4}\}, \quad (2.11)$$

where $\hat{\rho}$ is density matrix of two-qubit state in the canonical basis ($|HH\rangle, |HV\rangle, |VH\rangle, |VV\rangle$), $\lambda_i (i = 1, \dots, 4)$ are the eigenvalues in decreasing order of the Hermitian matrix $\hat{\rho}(\hat{\sigma}_y \otimes \hat{\sigma}_y)\hat{\rho}^*(\hat{\sigma}_y \otimes \hat{\sigma}_y)$ with $\hat{\rho}^*$, which corresponds to the complex conjugate of $\hat{\rho}$, $\hat{\sigma}_y$ is the second Paoli operator.

Substitute Eq. 2.8 into 2.11, it is easy to obtain

$$C(\hat{\rho}_1) = |k_b| = \exp -\sigma^2 t^2 / 8. \quad (2.12)$$

As shown by solid line in Fig. 2.2a, with the increase of evolution time t , concurrence of the system will gradually attenuate and disappear finally. Just as described above, the environmental characteristic spectrum will directly affect entanglement dynamical evolution, more peculiar phenomenon can be obtained through changing the environmental spectrum (Yan-Xiao et al. 2008).

Here, we consider to change entanglement dynamical evolution by adding measurement, as shown in Fig. 2.1. Add a measurement device (M) consisting of two parallel polarization beam splitters (BD1 and BD2) and three half-wave plates (HWP1, HWP2 and HWP3) after the evolution of the system for a time interval t_1 . Optical axes of BD1 and BD2 are oriented horizontally to realize the coupling of polarization and route, thus realizing measurement of polarization; the optical axis of HWP1 is set to 22.5° to realize Hadamard operation, the optical axis of HWP2 is set to 22.5° to realize the conversion $|H\rangle \rightarrow |+\rangle|V\rangle \rightarrow |-\rangle$, where $|+\rangle = (|H\rangle + |V\rangle)/\sqrt{2}$, $|-\rangle = (|H\rangle - |V\rangle)/\sqrt{2}$; the optical axis of HWP3 is set to 45° to realize bit-flip operation. BD1 measures the photons polarization in the H/V basis and introduces the path information as a probe bit. Before this measurement is completed, the second decoherence environment is inserted, with the evolution time of t_2 . Then the two-photon state can be written as

$$\left(\frac{1}{2} |H\rangle (|H\rangle + e^{i\omega_b t_2} |V\rangle) \right)_I + \left(\frac{1}{2} e^{i\omega_b t_1} |V\rangle (|H\rangle - e^{i\omega_b t_2} |V\rangle) \right)_{II}. \quad (2.13)$$

Where $t_1 = \Delta n l_1$, $t_2 = \Delta n l_2$. Subscripts I and II represent the upper path and the lower path between the two BDs, respectively. The path information is erased by BD2 at last, which realizes a postselection of the recovered state. Then the system state at this moment can be represented by the following density matrix

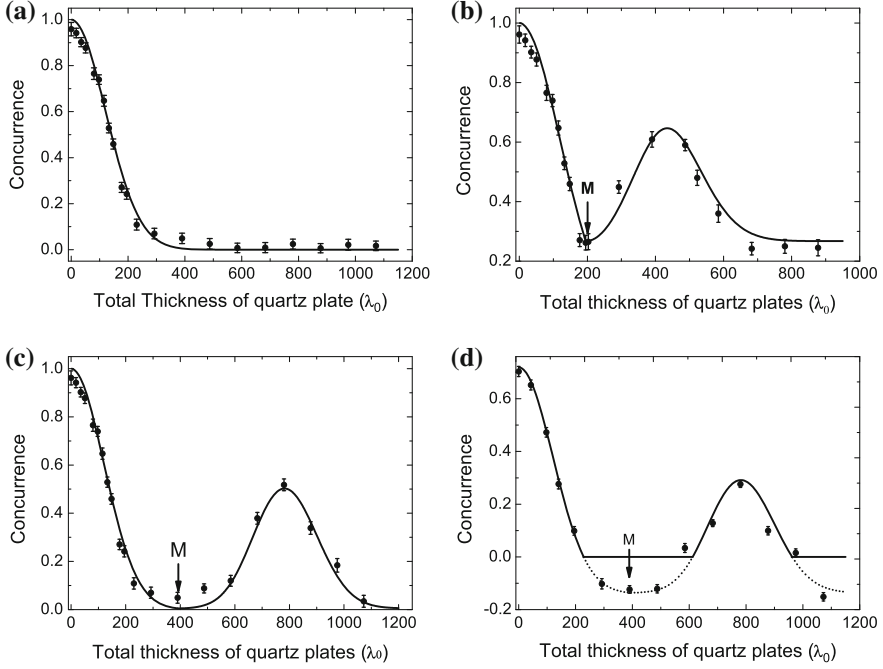


Fig. 2.2 Major results (*dots*) for entanglement dynamics in the experiment. The *solid lines* are theoretical predictions of concurrence. Two error types are considered: the shot-noise error in the measured coincidence counts and the uncertainty in the settings of the angles of the wave plates used to perform the tomography (James et al. 2001). **a** Represents the entanglement evolution of a maximal entangled state in a pure dephasing environment without M; **b**, **c** Represent the entanglement evolution with M inserted at $L_1 = 195$ and $L_1 = 390$, respectively; **d** represents the entanglement evolution of the partially entangled state in a dephasing environment with M inserted at $L_1 = 390$. $\lambda_0 = 800$ nm. Reprinted with permission from Ref. Xu et al. 2010c. Copyright 1998 by American Physical Society

$$\hat{\rho}_2 = \frac{1}{2}(|HH\rangle\langle HH| + |VV\rangle\langle VV| + k_b'^*|HH\rangle\langle VV| + k_b'|VV\rangle\langle HH|). \quad (2.14)$$

Where decoherence parameter

$$k_b' = \frac{\exp(i\omega_0 t_1)}{2[1 + \cos(\omega_0 t_2) \exp(-t_2^2 \sigma^2 / 16)]} \{ \exp[-(t_1 + t_2)^2 \sigma^2 + i\omega_0 t_2] + \exp[-(t_1 - t_2)^2 \sigma^2 - i\omega_0 t_2] + 2 \exp[-t_1^2 \sigma^2 / 16] \}. \quad (2.15)$$

According to Eq. 2.11, its concurrence is $C(\hat{\rho}_2) = |k_b'|$ under this evolution. The above decoherence coefficient is complex, the whole entanglement evolution is not as simple as before. Mathematical simulation results show that under the condition that the length of the first crystal l_1 is fixed, increase of the length of the second

crystal l_2 will recover the entanglement dissipated in the environment. When l_2 is relatively small, concurrence will oscillate with the phase, when l_2 is big enough, the oscillation amplitude will tend to 0. What we consider here is maximum recovery of entanglement, therefore, we only care about entanglement only when the phase is at the zero, that is, oscillation envelope corresponds to crystal thickness of integer order, as shown by solid line in Fig. 2.2b, c.

As a matter of fact, entanglement dynamics not only depends on the environment but is also sensitive at the initial state (Roszak and Machnikowski 2006; Yu and Eberly 2006). For some special quantum entanglement, the sudden death of entanglement will appear in a dephasing environment, this is very different from the above-said exponential decay case (Almeida et al. 2007; Xu et al. 2010a). In this thesis, we point out that entanglement can be revived in the environment with Gaussian characteristic spectrum through quantum measurement after sudden death of entanglement. First, we add the Hadamard operation to the first photon and let it pass through a dephasing channel with the evolution time of t_a . Then, the density matrix of two-photon state can be written as

$$\hat{\rho}_0 = \frac{1}{4} \begin{pmatrix} 1 & 1 & k_a^* & -k_a^* \\ 1 & 1 & k_a^* & -k_a^* \\ k_a & k_a & 1 & -1 \\ -k_a & -k_a & -1 & 1 \end{pmatrix}, \quad (2.16)$$

where $k_a^* = \int d\omega_a g(\omega_a) \exp(i\omega_a t_a)$ is the corresponding decoherence coefficient, while $g(\omega_a)$ reflects the environmental characteristics of the first photon. In this way, we prepared a Werner-type mixed state (Werner 1989). In literature (Xu et al. 2010a), the author observed the sudden death and revival of entanglement by changing the characteristic spectrum of the environment, whereas revival of entanglement will not appear in an environment with Gaussian characteristic spectrum. If we allow the state described in Eq. 2.16 to pass through the above-mentioned measurement device M, we can still realize entanglement revival in an environment with Gaussian characteristic spectrum.

The system state, described in Eq. 2.16, after passing through M can be expressed by the following density matrix,

$$\hat{\rho}_3 = \frac{1}{4} \begin{pmatrix} 1 & k_b'^* & k_a^* & -k_a^* k_b'^* \\ k_b' & 1 & k_a^* k_b' & -k_a^* \\ k_a & k_a k_b'^* & 1 & -k_b'^* \\ -k_a k_b' & -k_a & -k_b' & 1 \end{pmatrix}. \quad (2.17)$$

Substitute it into Eq. 2.11, $C(\hat{\rho}_3) = \max\{0, (k_a + k_b' + k_a k_b' - 1)/2\}$ can be easily obtained. When $(k_a + k_b' + k_a k_b' - 1)/2$ becomes negative, then $C = 0$, it means the death of entanglement. However, we can observe revived entanglement by changing the value of k_b' , which will reach its maximum when $l_1 = l_2$, as shown in solid line in Fig. 2.2d.

2.3 Experimental Results

2.3.1 Description of the Experimental Setup

The experimental setup is shown schematically in Fig. 2.1. Two 0.5-mm-thick barium borate (BBO) crystals, cut at 29.18° for type-II phase matching and aligned so their optical axes are perpendicular to each other, are pumped using focused ultraviolet pulses polarized at 45° , which are frequency doubled from a Ti:sapphire laser with the center wavelength mode locked at 800 nm (with a 130-fs pulse width and a 76-MHz repetition rate). Degenerate polarization-entangled photon pairs at 800 nm are generated by spontaneous parametric down-conversion (SPDC) at a 3° angle with the pump beam (Kwiat et al. 1999). By compensating the time difference between H- and V-polarized components with birefringent elements (LiNbO_3 and YVO_4), one of the maximal polarization-entangled states, namely, the well-known Bell state (Bell 1964), showed in Eq. 2.7 can be produced with high fidelity.

2.3.2 Entanglement Dynamics

All experiment results are shown in Fig. 2.2. The central wavelength and the bandwidth of the interference filter used in the experiment are 800 and 3 nm respectively. Within the considered wavelength, the birefringence of birefringent crystal used can be seen as constant, take $\Delta n = 0.01$, as the frequency range considered is narrow, dispersion effect can be ignored. The maximum entanglement produced in the experiment is 0.962 ± 0.029 . In Fig. 2.2a, entanglement decays exponentially until it disappears completely when interacting with the environment, its dynamics process follows the half-life law. As phase instability problem does not exist, all data points conform to the theoretical prediction well. In Fig. 2.2b, the measurement device M is inserted when $l_1 = 195\lambda_0$, the system entanglement at that point is 0.262 ± 0.024 . In the experiment, when $l_2 = l_1 = 195\lambda_0$, dissipated entanglement is recovered maximally, and the recovered system entanglement is 0.609 ± 0.026 . When $l_2 > 683\lambda_0$, the system entanglement will no longer change, which always remains at the level when the measurement device is inserted. In Fig. 2.2c, the point at which M is inserted is $l_2 = 390\lambda_0$ where the concurrence tends to zero, that is, to say, there are few entanglements at this point. Incidentally, the maximally recovered entanglement measured in the experiment is 0.518 ± 0.025 at about $l_2 = 780\lambda_0$, which agrees well with theoretical predictions. In Fig. 2.2d, the partially entangled input state with concurrence 0.704 ± 0.019 is prepared by inserting an HWP with optical axes set at 22.5° and quartz plates of thickness $98\lambda_0$ with horizontally set optical axes in mode a . We insert M at $l_1 = 390\lambda_0$ at which entanglement sudden death has occurred, and there is no entanglement; entanglement rebirth occurs at about $l_2 = 585\lambda_0$, and then the entanglement collapses at about $l_2 = 975\lambda_0$ again. The concurrence is corrected to zero according to Eq. 2.11 when its measured value

is negative. Entanglement can be reborn at a maximal value of 0.276 ± 0.013 in the experiment.

2.3.3 Recovery of Nonlocality

As one of the important characteristics of quantum mechanics, nonlocality has changed the viewpoint and methods in understanding nature at its fundamental level. Since it can be studied by the well-known Bell inequality (Bell 1964, 1966), a quantum state with nonlocal correlations could be a very useful feature to exploit in future quantum technologies (Gisin 2009). In our experiments, if recovered entanglements have nonlocality correlation, it will greatly improve its application prospects. We use a more convenient Clauser–Horne–Shimony–Holt (CHSH) (Clauser et al. 1969) inequality to prove that entanglement at the maximum recovery in Fig. 2.2b, c have nonlocality. For two-qubit case, CHSH inequality is expressed as

$$S \leq 2 \quad (2.18)$$

satisfies for any local realistic theory, where

$$S = E(\theta_1, \theta_2) + E(\theta_1, \theta'_2) + E(\theta'_1, \theta_2) - E(\theta'_1, \theta'_2) \quad (2.19)$$

with

$$E(\theta_1, \theta_2) = \frac{C(\theta_1, \theta_2) + C(\theta_1^\perp, \theta_2^\perp) - C(\theta_1, \theta_2^\perp) - C(\theta_1^\perp, \theta_2)}{C(\theta_1, \theta_2) + C(\theta_1^\perp, \theta_2^\perp) + C(\theta_1, \theta_2^\perp) + C(\theta_1^\perp, \theta_2)}. \quad (2.20)$$

In the formula, $\theta_i(\theta'_i)$, $i = 1, 2$ represent the linear polarization settings in path a and b separately, and $\theta_i^\perp = \theta_i + 90^\circ$, $i = 1, 2$. $C(\theta_1, \theta_2)$ represents the coincidence counting at corresponding measurement setting. According to the measured density matrix of the maximal recovered entangled state showed in Fig. 2.2b, c, θ_1 and θ_2 can be obtained at maximal violation by numerical computation method, which is $(\theta_1 = -15^\circ, \theta'_1 = 21^\circ, \theta_2 = 86^\circ, \theta'_2 = -52^\circ)$ and $(\theta_1 = -82^\circ, \theta'_1 = 66^\circ, \theta_2 = -4^\circ, \theta'_2 = 28^\circ)$, respectively. When measuring at this angle in the experiment, S value obtained is 2.336 ± 0.003 and 2.210 ± 0.003 , respectively, which exceeds by 104 and 64 standard deviations respectively, far beyond the limit predicted in local realism. It proves that the entangled states recovered through measurement have nonlocality.

2.4 Discussion

Single qubit coherence recovery caused by measurement was explained intuitively in the literature (Xu et al. 2009) with time domain wave packet. As a matter of fact, entanglement recovery caused by measurement can be understood under the theoretical framework of partial-collapse measurement and recovery. BD1 has realized the measurement of photon polarization on H/V base, while BD2 has accomplished the work of two aspects simultaneously, first achieved partial collapse measurement on the upper path of the H/V base and then erased information obtained in partial collapse measurement with the same coupling strength. After BD2, photons of two dark channels are discarded, it can be deemed that no photon is detected in the case of coincidence counting. Partial collapse measurement and recovery process of the same coupling strength can maintain the entanglement in the initial state, the probability of success will be changed with the increase of l_2 , therefore, we believe when l_2 is big enough, entanglement remains unchanged, as shown in Fig. 2.2b, c. This result has important significance in actual quantum communication, based on the experimental results, we have completed an experiment on the decoherence channel capacity of activated quantum.¹

2.5 Summary

We have utilized quartz plates to realize a non-Markovian environment in linear optics, which has shown that entanglement can be recovered through measurement and quantum erasure. We have also justified the nonlocality of recovered entangled state with high standard deviation, thus ensuring the application prospects of the scheme. Our experimental results can be used to resist phase decoherence. Even in such an environment, the system entanglement has been dead, we can still recover part of entanglement through measurement no matter how long the entanglement has been dead. This indicates that we can achieve controllable entanglement recovery. In the subsequent work, we can explore entanglement dynamics characteristics under other different operation modes.

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¹Robust bidirectional links for photonic quantum Networks, Jin-Shi Xu et al., accepted for publication in *Science Advances*.

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2016, XXIII, 126 p. 48 illus., 17 illus. in color., Hardcover

ISBN: 978-3-662-49802-6