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中文摘要

量子纠缠是量子信息学中最重要也是最为奇特的一个课题。在量子信息学中，量子信息的处理离不开量子态及其操纵，而量子纠缠态毫无疑问是各种各样的量子态中最重要的一种。量子纠缠在量子信息学的两大领域---量子通信和量子计算中都有着广泛的应用。要实现量子计算首先就要实现两比特逻辑门，通常是受控非门（CNOT），这种逻辑门事实上就是将两个量子比特纠缠起来的过程。除此之外，量子纠错码方案通常也要使用量子纠缠态；在量子通信中，使得纠缠态具有重要意义的主要是量子隐形传态技术。甚至有人认为在某种意义上可以将量子通信等价于异地纠缠态的建立，操纵和测量。另一方面，对于量子纠缠态的性质研究也会使得我们能够更深刻地理解量子力学。以上所说也正是本人将量子纠缠的研究作为博士论文主要内容的原因。本论文在实验上取得了以下主要成果：

I、连续光纠缠源的制备

迄今为止，实现量子纠缠态的制备、操纵的最重要、最常用也是最方便的方法就是利用在非线性光学晶体中的自发参量下转换过程产生光子纠缠态。这种方法制备的纠缠态具有高纠缠度、高保真度和易操纵的特点。

我们利用连续波激光束泵浦非线性晶体的自发参量下转换过程制备出了双光子偏振纠缠态（第二章），其纠缠源亮度和纠缠度都接近于国际上同类研究的领先水平。此外，我们的纠缠源还具有参数可调谐的特点，即它不仅能产生常用的最大纠缠态，还能很方便的产生各种纠缠度的非最大纠缠态，其纠缠度是便于控制的，这为研究纠缠态的各种性质变化提供了有力、方便的工具。利用这种纠缠源，我们还制备了量子信息学中另一种重要的混合态纠缠态---Werner 态，采用的方案使得 Werner 态中纠缠的成分是可控制的。Werner 态可直接用于纠缠纯化的实验研究，这对于量子通信从理论研究到实验研究甚至实用化研究都有重要的作用。在我们的实验之前尚未有 Werner 态制备成功的实验报导。

II、普适量子克隆的光学实现

关于量子态信息的可能进行的操作方面，在量子信息学中有一条很重要的定理，叫做量子态不可克隆定理，它根据量子力学的线性性禁止了对于任意未知量子态的精确克隆。这一点是和经典信息学中完全不同的，它体现了量子信息和经典信息的根本差别。这一定理使得人们对于量子信息处理的能力很受限制，但是信息处理的需求总是很强烈的，这就导致了很多科学家转向考虑如何绕过这条定理，进行概率克隆或者不精确克隆，因为这两种方式的量子态操作并未被禁止。在各种量子态克隆方案当中，最重要的一种是普适量子克隆机方案，该方案能以相同的保真度克隆输入的任意未知量子态，其中，Buzek-Hillery 普适克隆机是一种达到了最佳保真度的量子比特的普适克隆机。

我们利用线性光学元件以及路径比特概念的引入在实验上用单光子实现了 Buzek-Hillery 普适克隆机，得到了和理论值一致的保真度（第三章）。值得注意的是，虽然在这个实验中我们并未使用 SPDC 系统来得到量子纠缠态，但是纠缠态及其操纵在此实验中还是起着基本的作用，因为我们是用单光子的偏振自由度和路径自由度的纠缠来构成纠缠态的。

III、非最大纠缠态的 CHSH 不等式检验

除了应用于量子通信和量子计算方面之外，量子纠缠态还在讨论量子力学基础方面起着重要的作用，这一点主要表现在关于 EPR 佯谬以及隐变量理论的争论上。1935 年，Einstein、Poldolsky 和 Rosen 三人质疑量子力学的概率幅解释，提出了著名的 EPR 佯谬，从此引发了隐变量理论与量子力学之间长达几十年的争论。按照 Einstein 的观点所构造的隐变量理论叫做局域隐变量理论，这种理论假设由隐变量事先确定的力学量测量值不依赖于其他和这个力学量类空分隔的被同时测量的力学量。正是由于“类空分隔”的要求反映了“局域性”的观点，所以被称为局域隐变量理论。1964 年，Bell 提出了一个不等式，给出了一个可以进行实验检验的判据：隐变量理论不会违背这一不等式，而量子力学在某些情况下会违背。从此以后，人们进行了大量的 Bell 不等式检验的实验，几乎所有结果都支持量子力学。

从 Bell 不等式出发，容易想到这样一个问题：“纠缠”是否等价于“Bell 不等式的违背”？关于这个问题，Gisin 在 1991 年指出：任何两比特系统纠缠纯态必定违反某一 Bell 不等式。

我们在实验上利用自发参量下转换系统制备的双光子偏振最大纠缠态及非最大纠缠态进行了 CHSH 不等式的检验（第四章），验证了对于两比特纠缠纯态，“纠缠”等价于“Bell 不等式违背”这一结论，这将使我们对于纠缠的含义以及它和 Bell 不等式的关系有进一步的理解。

IV、Kochen-Specker 理论的实验检验

除了局域隐变量理论之外，还有一种主要的隐变量理论---环境无关的隐变量理论（NCHV），关于这种隐变量，类似于 Bell 不等式，有一个 Kochen-Specker 理论，其主要内容是证明 NCHV 和量子力学的矛盾。近年来人们提出了不少用于检验 Kochen-Specker 理论的实验方案。但是还没有人在实验上实现基于 Kochen-Specker 理论框架的 NCHV 检验。

我们最近完成了一个用单光子实现的检验 Kochen-Spcker 理论的实验（第五章），该项结果已经发表在 Phys. Rev. Lett 上（**90**, 250401, 2003）。这个实验基于 C. Simon 在 2000 年提出的一个方案，实验结果证明了 NCHV 是不存在的。需要说明的是，在这个实验中虽然我们是用单光子的两比特纠缠态来代替双光子纠缠态的，我们还是使用了 SPDC 技术。而且，纠缠态及其操纵在此实验中仍然扮演着重要的角色。

关键词：光子纠缠、操纵、自发参量下转换

Title: Experimental Preparation and Manipulation of Quantum Entangled States

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ABSTRACT

Quantum entanglement is one of the most important subject, and also, the strangest part of quantum information. In quantum information, the processing of information depends on quantum state and its evolution, while quantum entangled states certainly is the most important kind among all kinds of quantum states. Quantum entanglement has many applications in both the fields of quantum communication and quantum computation. To realize quantum computation, we have to perform two-qubit logic gate, usually said, two-qubit controlled-not gate(CNOT). The realization of CNOT gate is in fact a procession of entangling two qubits. Besides that, quantum error correcting schemes usually use quantum entangled states. In quantum communication, the scheme of quantum teleportation makes entangled states very important. Some people even think that quantum communication can be viewed as the construction, control and measurement of distant entangled states. On the other hand, the research on the property of quantum entangled states gives us deeper understanding on the opinion of quantum mechanics.

Up to now, the most important, most often used and most convenient method to produce and control entangled states is to produce photons entangled states according to the spontaneous parametric down-conversion (SPDC) process in nonlinear optical crystals. The entangled states produced in this way has high entanglement degree and high fidelity, and it is easy to control. We use continuous wave(CW) laser beam to pump nonlinear crystals and successfully prepared two-photon polarization entangled states(Chapter II) with high brightness and entanglement degree. Besides, our entangled photons source is tunable in entanglement degree, so it is easy to produce any non-maximally entangled states we required. We also use this source to produce another kind of important entangled states---Werner states with tunable

entanglement fraction in it. Werner states can be directly used in the experiment research in entanglement purification, this will be important to quantum communication.

About the possible action which we can do to quantum state information, there is an important theorem---the quantum state no-cloning theorem. This theorem forbids anyone to clone an arbitrary unknown states according to the linearity of quantum mechanics. This is completely different from classic information. No-cloning theorem greatly limits people's ability to process quantum information. But people are always willing to do more research. So, many scientists set out to consider how we can probabilistically or approximately clone quantum states, because these are not forbidden. In all these trials, one of the most important scheme is the universal cloning machine, it can clone any input unknown states equally well, with fidelity . Buzek-Hillery universal cloning machine, which attains the optimal fidelity of universal cloning machines, clones one qubit to two qubits. We realized the Buzek-Hillery machine using location qubit and linear optics with single photons, and get the optimal fidelity .

Besides the applications in quantum computation and communication, entangled states is also important for the discussion of fundalmental quantum mechanics. It acts mainly on the arguments about the EPR paradox and hidden variables theory. In 1935, Einstein, Poldolsky and Rosen gave out their famous argument for entangled states against quantum mechanics probabilistic version---the EPR paradox. Since then, the arguments on this topic have last for several decades. EPR paradox gives birth to the local hidden variables theory(LHV). LHV supposes that the predetermined value of an observable does not depend on what other observables are simultaneously measured in a space-like separated region. It is the requirement of "space-like separation" that gives it the name of LHV. In 1964, John Bell gave out an inequality---Bell inequality, which proves that LHV is uncompatible with QM during a certain kind of experiment measurement. After that, scientists have performed many experiments to test Bell inequality and almost all experiment results violated the Bell inequality, that means QM is right.

Maybe some people will quickly think about such question after learning the Bell inequality: Is "entanglement" equals to "the violation of Bell inequality"? About this question, Gisin has pointed out in 1991 that any two-qubit entangled pure states will violates certain Bell inequality. So, we use our two-photon polarization non-maxmally entangled states to perform the Bell inequality test and our experiment results proves Gisin's conclusion.

There is another kind of hidden variables theory---the noncontextual hidden variables theory (NCHV). To NCHV, there is a theorem like Bell inequality---the Kochen-Specker theorem. The Kochen-Specker theorem proves that NCHV is uncompatible with QM. In recent years, several experiment schemes have been proposed to test Kochen-Specker theorem, but no experiment has been performed. We recently have finished an experiment which test Kochen-Specker theorem with single photon's polarization and location two-qubit entangled states. Our experiment is based on C. Simon's scheme proposed in 2000 and gets a result which disproves NCHV.

Key borad： entangled photons, manipulation, spontaneous parametric down-conversion(SPDC).