Optical Quantum Information Processing using Forced Fermion-like Behavior of Photonic Qubits

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We review a new paradigm for optical quantum logic gates that relies on forced "fermion-like" behavior of photonic qubits, and describe experimental work on demonstrating these gates with entangled photons from a parametric down-conversion source.
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1. Introduction

It has recently been shown that scalable two-qubit logic gates can be realized by forcing non-interacting qubits to behave as fermions in one part of a simple circuit, and bosons in another part of the circuit [1]. This new paradigm has particularly important implications for optical quantum information processing, where the nonlinearities needed for universal logic operations with single-photon qubits have been difficult to achieve [2]

An overview of this general idea is shown in Fig. 1. Here a small circuit implementing a controlled-sign (*CZ*) gate for two path-encoded single-photon qubits is realized by first forcing the photons to display fermionic behavior and swapping their paths, and then allowing them to behave as ordinary bosons while their paths are swapped again. In this scenario, the required π-phase shift originates from the fact that the exchange of fermions multiplies the relevant part of the state vector by a factor of -1, while the bosonic swap simply returns the qubits to their original paths without an additional phase shift [3]. For the case of photonic qubits, the bosonic swap can be realized by simply re-labeling the modes, while the fermion-like swap requires new and interesting physics.

In reference [1] the fermion-like behavior of photons is induced by using strong two-photon absorption to implement a quantum Zeno effect that prevents two photons from occupying the same spatial mode. This is somewhat analogous to the Pauli exclusion principle for fermions, and was adapted to prevent two photons from exiting the same output port of a beamsplitter; ie. to essentially realize the opposite outcome of the usual Hong-Ou-Mandel beamsplitter "dip" [4]. In principle, this effect could be used to overcome the inherent errors in probabilistic Linear Optics Quantum Computing (LOQC) logic devices [5] and realize a new kind of quantum ``Zeno gate" for photons.

More recently, Gorshkov et.al. have shown that the required fermionic behavior can be realized by using photon-storage techniques to temporarily map the photonic qubits into atomic excitations in the form of spin-waves [6]. These fermionic excitations are then exchanged, which provides the desired π-phase shift. In this way, strong atom-atom interactions are used, and the attractive possibility of simultaneously combining photonic storage and logic becomes feasible. Other ideas include the use of Luttinger liquid behavior of photons tightly confined in hollow-core fibers [7].

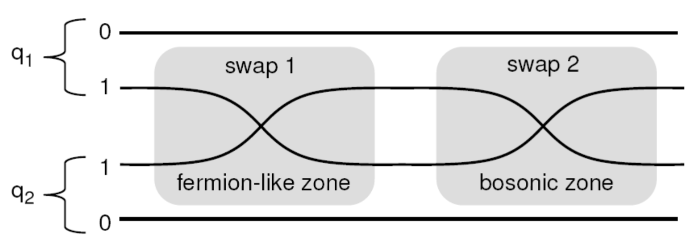

Figure 1: Overview of a dual-rail CZ gate for photonic qubits represented by q_1 and q_2. In the first part of the circuit, the photons are somehow forced to behave as fermions while the logical-value 1 rails are exchanged. This Swap operation imparts the π-phase shift needed for gate operation. The rails are then simply swapped back in a second bosonic zone.

2. Overview

In this work, we review this new paradigm for quantum computing and discuss how combining fermionic-bosonic behaviors gets around the various "no go" theorems for realizing quantum gates with only noninteracting bosons or noninteracting fermions [1]. We also describe our ongoing work aimed at demonstrating a photonic fermion-boson-type *CZ* (analogous to Fig. 1) in a parametric down-conversion (PDC) experiment that relies upon hyper-entanglement, post-selection, and other tools from LOQC [5]. The basic idea of this experiment involves the production of antisymmetric two-photon entangled states.

It is well known that antisymmetric two-photon entangled states can display fermion-like antibunching behavior at a 50/50 beamsplitter [8]. For example, experiments on Bell-state analysis rely on the fact that two photons in the antisymmetric Ψ^- polarization entangled state will always emerge in opposite ports, while photons in the three symmetric polarization entangled states emerge together [9]

The same behavior can also be observed using entanglement in frequency, rather than polarization [8]. We have recently been investigating a new method for producing antisymmetric frequency entanglement that is based on the idea of performing spectral-phase manipulation on two-photon states from a parametric down-conversion source [10,11]. In our experiment, rotary dispersion is used to rotate the linear polarization of one of the PDC photons through an angle that depends on the wavelength (see Figure 2a) . This photon is then passed through a polarizer whose transmission axis is oriented along the polarization corresponding to the center of the photon's spectrum. The projection produces a symmetric reduction in amplitude, but puts a π-phase shift on the lower half of the spectrum (Figure 2b) which converts the naturally symmetric PDC frequency entangled state into an antisymmetric one [12].

The motivation for producing antisymmetric frequency-entanglement is to leave the polarization degree of freedom available for qubit encoding. This opens the possibility of performing a robust proof-of-principle LOQC-type demonstration of the fermion-boson gate of Figure 1 based on polarization, rather than dual-rail encoding. The idea is to use the frequency-entanglement to realize the required π-phase shift in the first swap of Figure 1, while polarization is used for state preparation and measurement. Although such a demonstration requires prior entanglement between the qubits (which prevents scalability), the basic features of the paradigm in Figure 1 could be explored in an experimental setting.

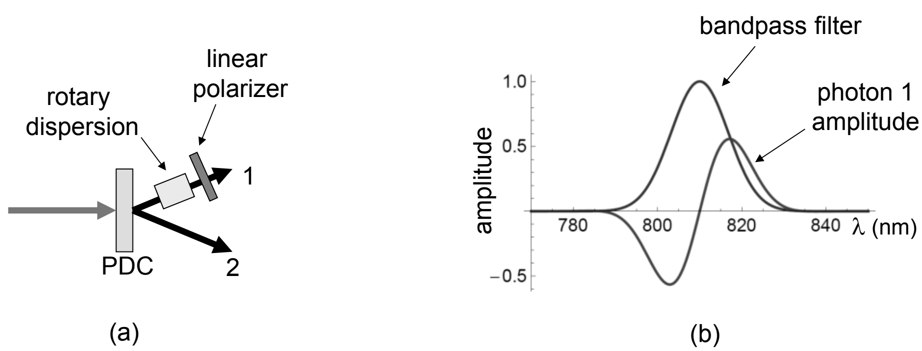

Figure 2: Production of antisymmetric frequency entanglement from a PDC source [12]. In (a), rotary dispersion and projective measurements are used to put a π-phase shift on the lower half of the spectrum of one of the two PDC photons. The resulting amplitude of this photon is shown in (b). The manipulation of the photon 1 amplitude in this way converts the PDC two-photon state into an antisymmetric frequency entangled state. This is somehwhat analogous to using wavelplates and phase shifters to convert a symmetric Ψ^+ polarization entangled two-photon Bell state into an antisymmetric Ψ^- polarization entangled state [9].

3. References

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