University of Calgary
Fall semester 2008

PHYS 673: Quantum and Nonlinear Optics

Homework assignment 5

Due November 25, 2008. Computers are allowed.

Problem 5.1. We discussed in class that propagation through an absorber (transmissivity η) will modify a quantum state's Wigner function. Express the transmitted state's Wigner function through the initial Wigner function. **Note:** the solution is in Leonhardt, but it uses some concepts we did not go over in class. Do not use these concepts in your solution.

Problem 5.2. Read the first two pages of the paper "A scheme for efficient quantum computation with linear optics" by E. Knill, R. Laflamme, and G. J. Milburn, Nature **409**, 46 (2001). Verify that the circuits shown in Figs. 1 and 2 function as they are claimed to. Do the photon detectors need to be number discriminating and of unit efficiency? Justify your answer.

Problem 5.3. Read the paper "Experimental quantum teleportation" by D. Bouwmeester *et al.*, Nature **390**, 575 (1997).

a) Verify the functionality of the Bell state analyzer shown in Fig. 1b. To this end, analyze the transformation of each of the four Bell states $|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|HH\rangle \pm |VV\rangle)$; $|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}(|HV\rangle \pm |VH\rangle)$ incident on a symmetric beam splitter. Show that only one of these states can lead to a coincidence event in detectors $f1$ and $f2$.

b) The scheme in the paper can distinguish only one out of four possible Bell states. Propose a modification of the detector scheme that would allow one to distinguish two Bell states.

Problem 5.4. Read the paper "Experimental test of quantum nonlocality in three-photon Greenberger-Horne-Zeilinger entanglement" by J.-W. Pan *et al.*, Nature **403**, 515 (2000).

a) Understand the operation of the circuit in Fig. 1. To check your understanding, determine the state of light in the channel between the BS and PBS (the upper-right side of the square) under the condition that two photon pairs have been generated, and detectors T and D_3 have measured exactly one photon.

b) Write explicitly the quantum operators that x and y measurements correspond to.