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Effects of Time Ordering in Parametric Down-Conversion and Frequency Conversion

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Parametric down-conversion (PDC) and frequency conversion (FC) are two of the most common nonlinear processes used in quantum optics. In the first process a nonlinear crystal is used to down convert photons from a pump laser into pairs of photons correlated by energy and linear momentum conservation constraints. In the second process, the frequency of photons is increased or decreased after interaction with a strong pump field inside a nonlinear crystal. These two processes share the property that the Hamiltonian that governs them does not commute with itself at different times and hence time ordering becomes an important aspect in the description of their dynamics. The two processes also share the attribute that whenever the pump photons are prepared in a coherent state with an amplitude that can be assumed un-depleted during the time evolution, the Hamiltonian is quadratic in the bosonic operators of the down-converted or frequency converted photons. This property implies that the dynamics of the system is "Gaussian preserving" and that the output state of spontaneous PDC is, even when time ordering is considered, a two mode squeezed vacuum. In this work we study the effect of time ordering in PDC and FC using the Magnus expansion. The Magnus expansion approximates the time evolution operator as the exponential of the Magnus series $U_{\text{Magnus}} = \exp(\Omega_1 + \Omega_2 + \Omega_3 + \ldots)$.

We obtain analytic approximations to the evolution operator that are unitary and Gaussian preserving and that allow us to understand order-by-order the effects of time ordering. We contrast our perturbative solution with the more common Dyson series solution $U_{\text{Dyson}} = I + T_1 + T_2 + T_3 + \ldots$ which is not able of preserving the Gaussian form or unitarity at any finite order and thus leads to unphysical results. We also calculate the effects of time ordering in the Joint Spectral Amplitude (JSA) of the photons generated in spontaneous PDC and show that even in the case when the phase matching and pump functions are real the JSA becomes complex because of time ordering. Finally, we show that whenever the phase matching function is broad enough the corrections due to time ordering vanish exactly.

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