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Investigation on the quantum-to-classical transition by optical parametric amplification: Generation and detection of multiphoton quantum superposition

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A B S T R A C T

We review an extended research carried out on the theoretical and experimental realization of a macroscopic quantum superposition (MQS) made up with photons. The described scheme is based on a nonlinear process, the quantum injected optical parametric amplification, that transforms the quantum coherence of a single particle state, i.e. a Micro-qubit, into a Macro-qubit, consisting in a large number M of photons in quantum superposition. Since the adopted scheme was found resilient to decoherence, the MQS demonstration was carried out experimentally at room temperature with $M \geq 10^4$. This result elicited an extended study on quantum cloning, quantum amplification and quantum decoherence. The MQS interference patterns for large M were revealed in the experiment and the bipartite Micro–Macro entanglement was also demonstrated for a limited number of generated particles. At last, the perspectives opened by this new method are considered in the view of further studies on quantum foundations and quantum measurement.

Contents

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1. Introduction

The observation of the quantum features of physical systems at the macroscopic level has been the object of extensive theoretical studies and recognized as a major conceptual paradigm of physics since 1935 [1]. However, in general severe problems stand up to spoil the observation of these features. The most important one is the unavoidable interaction with the surrounding environment that determines the loss of any quantum coherence effect by the corruption of the phase implied by any correlation of the quantum states [2]. Such effects are commonly believed to become increasingly severe with the growing of the size of the system being studied [3].

In the last several years many experimental attempts have been undertaken to create superposition of multiparticle quantum states. Different experimental approaches have been pursued based on atom-photon interacting in a cavity [3], superconducting quantum circuits [4], ions [5], micromechanical systems [6], and optical systems [7]. In particular in the last few years a significant advance toward generating superposition states of large objects using opto-mechanical systems has been achieved [8,9]. When dealing with the superposition of multiparticle quantum states, two are the fundamental issues to be considered: what is the effective size of the superpositions and how the state behaves under decoherence phenomena [4]. Several criteria have been developed to establish the effective size of macroscopic superpositions in interacting or imperfect scenario, as well as their applications to real systems [4,11]. A large effective size of the state usually conflicts with the robustness of the quantum superposition under interaction with environment. Moreover the observation of macroscopic interference phenomena requires to tailor proper measurement strategies. In particular one faces the problem of achieving a measurement-precision that enables the observation of quantum effects at such macro-scales [10].

In this paper we discuss how the amplification of quantum states can be adopted to generate multiphoton superpositions and to investigate the quantum-to-classical transition. By the present method a quantum superposition state is first generated in the microscopic (Micro) world of a single photon particle. Then, such system is mapped into the macroscopic (Macro) realm by generating a quantum superpositions via the stimulated emission process in the regime of high gain parametric amplification [12,13]. Such approach is a natural platform for the investigation of the quantum-to-classical transition, linking quantum and classical matter description. We will review the properties of the generated states. The experimental methods will be outlined and the corresponding results reported and briefly described. The open question to devise a method apt to demonstrate experimentally the Micro–Macro entanglement will be finally addressed.

We shall show that while a clear experimental evidence of a MQS interference, in the absence of bipartite Micro–Macro entanglement, has been attained with a fairly large associated number M of particles, the Micro–Macro entanglement could be consistently demonstrated, by an attenuation technique only for a small number of particles: $M \leq 12$. Indeed, as suggested by [14,15] a novel "*detection loophole*" for larger M a very high measurement resolution impose severe limitations to the detection of quantum entanglement in the Micro–Macro regime.

2. Optical parametric amplification of quantum states

Let us now start from the non-degenerate optical parametric amplifier which lies at the core of the present analysis. Consider Fig. 1a). Three different modes of the electromagnetic radiation field – say the signal $\hat{a}_1$, the idler $\hat{a}_2$ and the pump $\hat{a}_P$ – are coupled by a non-linear (NL) medium, generally a crystal, characterized by a high third-order tensor expressing the non-linear "second-order susceptibility" $\chi^{(2)}$ [16–18]. A typical NL medium, adopted in the experiments dealt with in this paper, consists of a suitably cut slab of crystalline *beta barium borate*, commonly dubbed (BBO). Two "phase matching" conditions must be fulfilled during the coherent three-wave interaction, viz. a scalar one, the energy conservation, and a vectorial one, the momentum conservation:

$$\nu_P = \nu_1 + \nu_2 \quad (1)$$

$$\vec{k}_P = \vec{k}_1 + \vec{k}_2 \quad (2)$$

where the labels $\{P, 1, 2\}$ refer to the "pump", signal and idler field modes, respectively. The Hamiltonian of the amplifier under the phase-matched condition (2) can be written in the rotating wave approximation as follows:

$$\hat{\mathcal{H}} = ik\hbar(\hat{a}_1^\dagger \hat{a}_2^\dagger \hat{a}_P + \hat{a}_1 \hat{a}_2 \hat{a}_P^\dagger) \quad (3)$$

The first term of the Hamiltonian (3) describes the physical process in which a photon is annihilated at frequency ν_P and the twin photons are generated at frequencies ν_1 and ν_2. The second term corresponds to the inverse process. In exact phase-matching condition the parameter k is proportional to the crystal $\chi^{(2)}$ and to the effective crystal length l_{crist} [17,18].

The Hamiltonian in Eq. (3) describes also the frequency degenerate case, case in which the frequencies associated with the modes $\hat{a}_1$ and $\hat{a}_2$ are equal but the respective wave-vectors

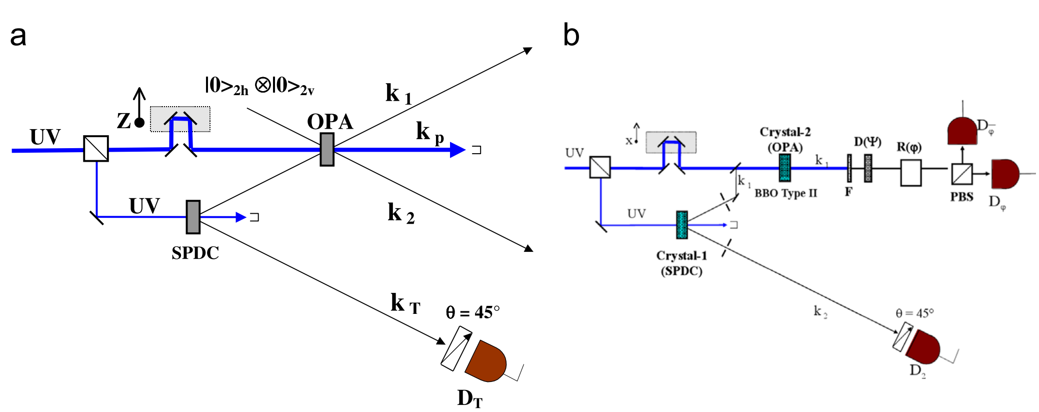

Fig. 1. Two different configurations for the amplification of quantum states. (a) Schematic diagram of the non-collinear quantum injected optical parametric amplifier. The injection is provided by an external spontaneous parametric down conversion source of polarization entangled photon states [12]. (b) Collinear quantum injected optical parametric amplifier [13].