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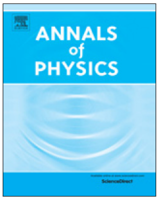

Phase collapse and revival of a 1-mode Bose–Einstein condensate induced by an off-resonant optical probe field and superselection rules

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ABSTRACT

Phase collapse and revival for Bose–Einstein condensates are nonlinear phenomena appearing due to atomic collisions. While it has been observed in a general setting involving many modes, for one-mode condensates its occurrence is forbidden by the particle number superselection rule (SSR), which arises because there is no phase reference available. We consider a single mode atomic Bose–Einstein condensate interacting with an off-resonant optical probe field. We show that the condensate phase revival time is dependent on the atom–light interaction, allowing optical control on the atomic collapse and revival dynamics. Incoherent effects over the condensate phase are included by considering a continuous photo-detection over the probe field. We consider conditioned and unconditioned photo-counting events and verify that no extra control upon the condensate is achieved by the probe photodetection, while further inference of the atomic system statistics is allowed leading to a useful test of the SSR on particle number and its imposition on the kind of physical condensate state.

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1. Introduction

Collapse and revival phenomena in Bose–Einstein condensates (BECs) have been investigated since 1996 [1], shortly after its experimental achievement with ultracold atoms [2,3]. They are a consequence of the quantized structure of the matter field and the coherent interactions between the atoms through atomic collisions (See [4,5], and references therein).

Dynamically originated due the presence of nonlinearities, phase collapse and revival is similar in nature to the collapse and revival appearing in Rabi oscillations when a single two-level atom interacts with a single mode of a quantized optical field in the so called Jaynes–Cummings model [6], or when a coherent light field propagates in a non-linear medium [7]. The Jaynes–Cummings model was one of the first totally quantized and exactly solvable models of interaction between matter and radiation showing non-trivial features. The collapse and revival effects in the population difference between the states of a two-level atom placed in a single mode optical cavity was one of the first predicted and still explored phenomena [8,9], revealing quantum properties of a radiation field. It was observed experimentally for the first time using a microwave mode [10]. Achievement of Bose–Einstein condensation led to a new platform to explore such coherent phenomena considering the interaction of quantized optical fields with ultracold many particle atomic systems [11].

The possibility of coexistence of nonlinear effects due to external influences opens an interesting avenue for investigating and controlling [12] such phenomena in BECs. Particularly, the control of phase collapse in BECs is extremely relevant for atomic interferometry since it might prevent phase diffusion, while allowing a performance below the standard quantum limit [13]. Several attempts on both developing new tools and pushing forward the possible frontiers for collapse control have been investigated for double-well condensates (See [14,15,12] and references therein). A possible approach is to consider the action of an external light probe over the atomic system, although, in general this leads to an even worse situation where the light field itself induces phase collapse in an irreversible manner. It is expected that, unless a time dependent interaction is employed, no further control is achieved.

Nonetheless, the interaction of the atomic system with a quantized light probe field can be engineered with the assistance of an additional pump field (See [11] for an excellent review on this topic). This scheme allows, e.g., the simultaneous amplification of atomic and optical fields, as well as control of the atomic field statistical properties [16–18]. Previously, with a setup relying on the atomic system-probe field interaction mediated through a classical pump [19], we showed that under continuous photo-counting, the moments of the probe light photon number might carry information about the even moments of the atom number. However, neither the possibility of controlling of atomic properties with the proposed setup, or a detailed analysis about the effects of conditioned single photo-counting events over the BEC state, was carried out. Such analysis is important, given the interest in phase collapse time, since in some situations the detection process allows an additional control or better inference of parameters. For example, in [20] an optical probe continuous detection allows one to create relative phase of two spatially separated atomic BEC. Also, as showed in [21], even dissipative environments can be useful to tailor dynamics of states and phase in cold atomic samples [22].

We should remark that the phenomenon of collapse and revival for a single mode condensate overlaps with another significant issue in many-particle physics, which is the particle number Super-Selection Rule (SSR) [23]. The imposition of a global particle number conservation forbids the one-mode (many-particle) state to exist in a superposition of Fock states — only single Fock states or a mixture of those are allowed. However neither a Fock state nor a mixture of Fock states have a well defined phase, and therefore there will be no phase collapse and revival dynamics. A reference frame is needed to confirm that a quantum state which violates superselection rule exists [24], (such as a Glauber coherent state in the context of the particle number SSR). Therefore, although this might be less restrictive when dealing with two or many-modes condensates, see for example the discussion in [5], due to the possibility of creating states with a well-defined relative phase in two mode systems [22] for example, for one-mode condensates this is a severe constraint. Both for systems of identical massive particles (such as bosonic atoms) and for systems of identical massless particles (such as photons) there is however a long standing discussion of whether the SSR on particle number