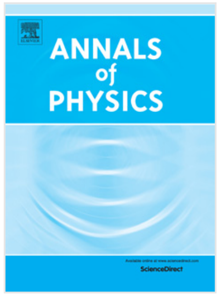

Geometric phase, entanglement, and quantum Fisher information near the saturation point

H. Rangani Jahromi, M. Amniat-Talab

PII: S0003-4916(15)00053-6
DOI: http://dx.doi.org/10.1016/j.aop.2015.02.018
Reference: YAPHY 66749

To appear in: *Annals of Physics*

Received date: 21 November 2014
Accepted date: 11 February 2015

Geometric phase, entanglement, and quantum Fisher information near the saturation point

H. Rangani Jahromi* and M. Amniat-Talab†
Physics Department, Faculty of Sciences,
Urmia University, P.B. 165, Urmia, Iran.

(Dated: January 11, 2015)

Considering a collection of two-level atoms in the presence of a saturating monochromatic, steady-state field, we investigate the geometric phase (GP) of an arbitrary medium's atom. We find that it is possible to detect the saturation of the atomic response by the GP computation. This is an interesting result, because we can predict the collective behaviour of the atomic system-i.e., the saturation of the optical response of the medium-by investigating the GP of a single medium's atom, described as a qubit. Moreover, we find that the plot of the atomic GP in terms of the detuning Δ is very similar to the absorption spectrum of the medium. In addition, it is shown that when the intensity of the driving laser field tends to saturation intensity, the qubit approaches maximum correlation with its environment described by the driving field and other qubits in the atomic system. Furthermore, we find that the behaviour of the entanglement is very analogous to that of the GP and the absorption coefficient. Besides, we adopt the atom to estimate the decoherence parameter by using the quantum Fisher information (QFI), an important measure of the information content of quantum states. Interestingly, we find that when the atomic system approaches its saturation point, the QFI decays with increasing the laser intensity, and therefore the parameter estimation becomes more inaccurate.

PACS numbers: 03.65.Vf, 03.67.-a, 03.67.Lx, 42.65.-k

Keywords: Nonlinear susceptibility, geometric phase, non-unitary evolution, qubit-environment correlation, quantum Fisher information

I. INTRODUCTION

In recent years, there has been a surge of interest in GPs in quantum mechanics and quantum computation. When a quantum system evolves slowly and cyclically in time such that it returns to its initial physical state, its state vector can acquire a GP factor in addition to the familiar dynamic phase, as pointed out by Berry in 1984 [1]. This adiabatic GP is also known as Berry phase, and is, in contrast to the dynamic phase, independent of energy and time. Since Berry's initial discovery, the GP has been found to occur in more general circumstances: nonadiabatic [2, 3] and noncyclic evolutions [4], non-Abelian forms [5], and for the mixed states [6–8]. Recently the study of GPs have been generalized to the case of a pair of spins, which include specific coupling with magnetic fields [9, 10].

One of the important reasons for the interest in the concept of GP is its relevance to geometric quantum computation [3]. Besides, the GP has received renewed interest because of several proposals for its use in the implementation of quantum logical gates. Indeed, the geometric nature of the proposed quantum gates endows them with some degree of inherent robustness against control imprecisions as well as against environment-induced relaxation [11]. In addition to theoretical interest, applications of GPs can be found in various physical fields. Recently, geometric quantum computation, expected as an intrinsical fault-tolerant scheme, has become one of the most important applications [12–16]. It was proposed by using NMR [13], superconducting nanocircuits [17], trapped ions [12] or semiconducting nanostructures [18].

Nearly all realistic quantum systems are open, and thus understanding and controlling of the dynamics rising from the presence of the environment is of central importance in present research. In particular, it is important to investigate the dynamical behavior when the system loses its coherence due to interactions with the external world.

Previous works investigate the behavior of GPs in the presence of decoherence effects such as quantum or classical driving fields, as well as generic reservoirs. For example, Ref. [19] investigated the behavior of the GP of a spin $1/2$ particle interacting with a quantized driving field subjected to decoherence. In Refs. [20, 21] the corrections to the GP for the spin-boson model have been studied. Likewise, it has been shown how to generate a GP through modifications solely on the reservoir that interacts with a small subsystem [22]. Besides, Ref. [23] investigated the qubit GP and its properties in the presence of two sources of decoherence: dephasing coupling (without exchange of energy with environment) and dissipative coupling (with exchange of energy). Moreover, in Ref. [24], by calculating the GP in an auxiliary qubit coupled to a many-body system, the relation between the GP induced in the qubit and the critical points of the many-body system was studied.

A significant kind of open quantum systems is one in which a classical saturating electromagnetic field drives a collection of two-level atoms, where the atoms can interact with each other by means of collisions [25]. However little attention has been paid to analysing the GP of each of the atoms within this medium. On the other hand, the response of many-body electronic open systems, such as complex atoms and molecules, with intense laser fields is one of the most interestingly pursued research topics in light-matter interaction physics. Currently available laser intensities can be made so high as to saturate the atomic response. These saturating lasers have great practical use, for example, when two waves couple with the atomic medium simultaneously, some nonlinear effects such as Raman or multiple-photon processes may

*Electronic address: h.rangani@urmia.ac.ir
†Electronic address: m.amniat-talab@urmia.ac.ir