Quantum center of mass, gauges and quantum optics: The light-matter interaction in relativistic quantum information

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Abstract. We analyze in what regimes different degrees of approximation of light-matter interactions in quantum optics and relativistic quantum information are reasonable and in what cases they need to be refined to capture the features of the light-matter interaction. This is particularly important when considering the center of mass (COM) of the atom as a quantum system that can be delocalized over multiple trajectories. For example, we show that the simplest scalar-analogue model with a quantum COM fails to capture crucial Roentgen terms coupling COM and internal atomic degrees of freedom with each other and the field.

Keywords: Quantum optics, Quantum delocalization, Light-matter interaction, Relativity

The multipolar Hamiltonian of a first-quantized atom interacting with the quantized EM field, even in the dipole approximation, contains the so-called Roentgen term (e.g. [1, 2]) which couples the center-of-mass (COM) degrees of freedom of the atom with its internal degrees of freedom and the electromagnetic field, and that is not commonly considered in studies concerned with quantum information protocols in relativistic setups. However, if one wants to model atomic physics, this kind of terms can only be neglected in a few select scenarios.

We analyze effective models, such as the Unruh-DeWitt (UDW) model and the dipole coupling approximation, that can capture realistic dynamics of a first-quantized atom interacting with the quantum EM field. This includes a quantized COM, the quantum nature of the atomic multipole operator, and not assuming either the single-mode or rotating-wave approximation, nor taking a discrete field-momentum spectrum in free space. We will take into account recent results by Stritzelberger and Kempf [3] where they studied precisely the influence on the atomic dynamics of the initial delocalization of the COM. We will extend those studies to show the extra considerations that one needs in order for the predictions of the model to be gauge-independent and to include the effect of Roentgen terms. As a particular example, we will illustrate the effect of the Roentgen term in atomic transition rates in the presence of initial COM delocalization.

In particular, we will show that there is only one scenario where one can neglect the Roentgen term: when one considers the atomic COM degrees of freedom to be classical, the atoms are tightly localized, and there exists a common rest frame for all the moving atoms in which the Roentgen term vanishes. This is for example the case of entanglement harvesting for comoving inertial atoms (see, e.g. [4]), or a single atom when we work in the detector's COM frame for not very relativistic trajectories. If the atomic COM is treated as quantum, or when there is no common rest frame, this additional term cannot be neglected. We will also discuss the higher order terms that appear in the case of more relativistic trajectories of the COM.

We compare these considerations to the usually employed effective light-matter interaction models. Thus, we discuss the limitations of the effective dipolar coupling and scalar-analogue models such as the Unruh-DeWitt model. In the case of scalar-analogue models, we argue here that a coupling of COM and radiation degrees of freedom has to be included in most scenarios if one wants to capture the atomic dynamics.

Finally we will show that considering only the effective dipole term for a classical COM still yields relativistically covariant predictions. We will provide arguments that, even if we are failing to describe precise atomic physics with this simplification, there is utility in using this interaction as a testbed to implement measurements on the EM field whose qualitative behavior captures the features of the light-matter interaction under some assumptions.

References

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