Unruh-DeWitt Detectors with Relativistic Centre of Mass

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Models of quantum particles interacting with an external field, which may for example describe the physics of atom-light interactions, are frequently referred to as particle detector models. One of the most widely used is a model where a quantum particle is linearly coupled to a relativistic quantum field, which is known as the Unruh-DeWitt (UDW) model. In this model, it is traditionally assumed that the detector (i.e. the atom or particle) follows a classical worldline, and only its internal degrees of freedom are quantised. However, a fully quantum treatment should also include a quantised description of the detector's external centre-of-mass degrees of freedom. This was previously proposed in Ref. [1], and studied for uniformly accelerating detectors in Ref. [2]. However, these past analyses have so far only considered detectors in the non-relativistic regime, which is insufficient to fully model the dynamics and is known to lead to spurious effects and unphysical friction forces acting on the detector [3, 4].

To resolve these conflicts, we extend the non-relativistic model to include the full relativistic dispersion relation of the detector's quantised centre of mass, and consequently consider the UDW detector in the regime of a "first-quantised" relativistic quantum mechanics. Our extension, beyond simply a demonstration of self-consistency across various regimes, explores more deeply the transition of relativistic quantum field theory to non-relativistic quantum mechanics, and in particular studies the nature of mass-energy and localisation of particle states in these two theories.

Our model has several possible applications, such as a phenomenological description of neutrinos or low-energy composite particles coupled to quantum fields. Free quantum composite particles (not interacting with fields) provide an idealisation of quantum clocks and can be described by a class of minimum uncertainty states, which are localised and are able to maintain spatial coherence [5]. These states minimise the Schrödinger-Robertson uncertainty between position and velocity, and transform covariantly under boosts, thus providing a suitable description for the relativistic regime. This work can thus also be seen as an extension of the treatment of ideal clocks to idealised detectors by describing the coupling of relativistic composite particles to quantum fields, providing the thus far missing model of a UDW detector with dynamical, relativistic centre of mass.

[1] N. Stritzelberger and A. Kempf, Phys. Rev. D **101**, 036007 (2020).
[2] V. Sudhir, N. Stritzelberger, and A. Kempf, Phys. Rev. D **103**, 105023 (2021).
[3] M. Wilkens, Phys. Rev. A **47**, 671 (1993); M. Wilkens, Phys. Rev. A **49**, 570 (1994).
[4] M. Sonnleitner, N. Trautmann, and S. M. Barnett, Phys. Rev. Lett. **118**, 053601 (2017); M. Sonnleitner and S. M. Barnett, Phys. Rev. A **98**, 042106 (2018).
[5] C. E. Wood and M. Zych, Phys. Rev. Res. **3**, 013049 (2021).