Defining the Quantum Mechanical Time Observable

K. Bordon[a], F. Tanjia[b] and J. A. Vaccaro[b]

[a]Centre for Quantum Dynamics, Griffith University, Gold Coast, QLD 4215, Australia.
[b]Centre for Quantum Dynamics, Griffith University, Nathan, QLD 4111, Australia.

Time is perhaps the most enigmatic concept in physics [1]. The lack of a universally accepted treatment of time has produced deficiencies such as the lack of an acceptable explanation of the observed direction of time and the definition of an operator to represent the time observable [2 - 4].

Vaccaro's recently introduced Quantum Theory of Time (QTT) [5 - 8] describes the evolution of a quantum state over time as a variable, undergoing virtual fluctuations, alike D'Alembert's Principle of virtual displacement [9]. The theory attributes the differences between the spatial and temporal dimensions to the violation of the time reversal symmetry, known as T-violation. If there is no T-violation present, the spatially-averaged time is fixed at one value and so there is no time evolution however, with T-violation in the system, time is represented as fluctuating at every point in space about a spatially-averaged time that corresponds to the usual time evolution. Despite basing the theory as a heuristic model of time, it is currently, without reference to an operator that represents the time observable. The aim of this work is to rectify this shortcoming and investigate how the time observable can be represented.

Any time observable needs to have a canonically conjugate relationship with the Hamiltonian, due to the fact that the Hamiltonian is the generator of translations in time. We apply the complement of the Hamiltonian, Pegg's Age operator [3], as a basis for defining the time observable in QTT. Whereas Pegg defined the Age to represent time associated with a single system, it has merit as the time associated with a point in space as well. We further explore if the Age observable has potential of being applied to the spatially-averaged time. We compare the statistics of the time observable to values previously obtained utilising heuristic models. The uncertainty relation for energy (i.e. Hamiltonian) and time will be defined and investigated for its simple and most elegant forms. We further examine the relationship of the observable to conventional studies of time in quantum mechanics such as the time associated with flight measurement [10].

[1] C. Rovelli. *The Order of Time*, Penguin Books Limited (2017).

[2] A. S. Eddingotn. *The Nature of the Physical World*, 276-81, *Nature* **137,** 255 (1927).

[3] D.T. Pegg. *Complement of the Hamiltonian*, Phys. Rev. A. **58**. 10.1103/PhysRevA.58.4307 (1998).

[4] W. Pauli. *Die allgemeinen prinzipien der wellenmechanik*. Springer, Berlin, p.84, 190 (1990).

[5] J. A. Vaccaro. *Quantum asymmetry between time and space*, Proc. R. Soc. A. **472**, 2185 (2016).

[6] F.Tanjia, A. Sadeghi and J.A. Vaccaro, *Quantum asymmetry between space and time: Phenomenological emergence of Lorentz invariance*, submitted to AIP Congress (2022).

[7] A. Howarth, F.Tanjia and J.A. Vaccaro, *Interpretation of Dirac Fermions as a Four-Dimensional Gaussian*, submitted to AIP Congress (2022).

[8] J.A. Vaccaro. *Quantum asymmetry between time and space: emergence of time and the laws of motion from 4D space*, submitted to AIP Congress (2021).

[9] J. D'Alembert. *Traite de Dynamique*, David l'Aine, Paris (1743).

[10] D.J. Lum. *Ultrafast time-of-flight 3D LiDAR*. *Nat. Photonics* **14,** 2–4 (2020).