Contribution ID: **21** Type: **talk**

Conditional probabilities, relativistic quantum clocks, and the trinity of relational quantum dynamics

Thursday, October 10, 2019 4:50 PM (20 minutes)

What allowed Einstein to transcend Newton's conception of absolute time was his insistence on an operational definition of time in terms of the measure- ment of a clock. Quantum theory has yet to be liberated from this absolute time as evidenced by the Schr¨odinger equation in which time appears as an external classical parameter.

In this talk I will introduce an operational formulation of quantum theory known as the conditional probability interpretation of time (CPI) in which time is defined in terms of an observable on a quantum system functioning as a clock; in some contexts, the CPI is known as the Page and Wootters mechanism. This clock and the system whose dynamics it is tracking, do not evolve with respect to any external time. Instead, they are entangled and as a consequence a relational dynamics emerges between them.

I will present a generalization of the CPI to the case when the clock and system interact [1], which should be expected at some scale when the gravita- tional interaction between them is taken into account. I will demonstrate how such clock-system interactions result in a time-nonlocal modification to the Schro¨dinger equation. I will then examine relativistic particles with internal degrees of freedom that constitute a clock which tracks their proper time [2]. By examining the conditional probability associated with two such clocks reading different proper times, I will show that these clocks exhibit both classical and quantum time dilation effects. Moreover, in connection with quantum metrol- ogy, it will be seen that the Helstrom-Holevo lower bound requires that these clocks satisfy a time-energy uncertainty relation between the proper time they measure and their rest mass. Finally, I will show how the CPI constitutes one out of a trinity of distinct but equivalent formulations of the same relational quantum dynamics [3].

References:

[1] Quantizing time: Interacting clocks and systems

A. R. H. Smith and M. Ahmadi, Quantum 3 160 (2019)

[2] Relativistic quantum clocks observe classical and quantum time dilation A. R. H. Smith and M. Ahmadi, arXiv:1904.12390 (2019)

[3] The trinity of relational quantum dynamics

A. R. H. Smith, M. P. E. Lock, and P. A. Ho¨hn, Forthcoming (2019)

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Session Classification: Investigating the fundamental properties of physics