Macroscopic realism versus quantum mechanics: Macroscopic Bell-inequality violations and Wheeler's delayed choice using cat states

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Much importance is given to study quantum systems at the mesoscopic scale. Here we introduce a framework to test the postulates of local realism and related concepts and paradoxes on a mesoscopic scale. We describe theoretical studies and experimental proposals of an approach using superpositions of coherent states ("cat states"), that go beyond the experiments carried out to date. Our work is motivated by studies and experiments devoted to testing macroscopic realism versus quantum mechanics. Macroscopic realism is the assumption that a system with two macroscopically distinct states available to it will actually be in one of those states at any given time. (Here, "states" has the most general meaning). To date, the most powerful tests are those given for Leggett and Garg's macrorealism. Those tests show a discrepancy between the macrorealistic and quantum predictions but involve an additional assumption beyond macroscopic realism associated with the noninvasiveness of a quantum measurement on a macroscopic system. This assumption can be challenged.

We therefore propose to test macroscopic realism in a set-up where macroscopically distinct states are identified by a coarse-grained measurement, and where the noninvasiveness assumption is replaced by that of locality, for dichotomic measurement outcomes that indicate macroscopically distinct states [1]. We demonstrate violations of Bell inequalities where the qubits become the coherent states $|\alpha\rangle$ and $|-\alpha\rangle$, for α arbitrarily large. The unitary dynamics U_θ giving the choice of measurement setting θ is realized by a nonlinear Kerr-like interaction [1]. A final measurement is made of the quadrature phase amplitude of each mode, which is then binned according to sign to distinguish the states $|\alpha\rangle$ and $|-\alpha\rangle$. We also show how the Wheeler-Chaves-Lemos-Pienaar (CLP) delayed-choice experiment [2] can be performed macroscopically using the cat-state qubits. We demonstrate violations of the dimension witness inequality applied to the Wheeler-CLP experiment, where measurements need only distinguish the macroscopic qubit states [1]. This motivates an interpretation where retrocausality can be avoided, thereby implying the need for a higher dimensional model to interpret the results. Similarly, we examine conclusions for a Wigner friend's paradox.

Our results demonstrate incompatibility between quantum mechanics and a (convincingly defined) version of macroscopic realism. However, we expect macroscopic realism to hold in some sense, and other definitions are possible. Indeed, we show that macroscopic realism as applied to the system after the dynamics U_θ is fully consistent with the quantum predictions. This motivates a closer study of realism in quantum mechanics.

[1] Manushan Thenabadu and M. D. Reid, *Phys. Rev. A* **105**, 052207, (2022); ibid, **105**, 062209 (2022).

[2] R. Chaves, G. B. Lemos, and J. Pienaar, *Phys. Rev. Lett.* **120**, 190401 (2018).