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# Time in Quantum Mechanics

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## Introduction

Our understanding of how everything should work is built upon a classical, macroscopic world in which we live and observe every day. However, **"macroscopic" phenomenon is a vague notion that has not been well-defined.** To classify whether what we observed is a macroscopic system, the concept of **"Macrorealism"** was therefore proposed [1].

## What is Macrorealisim?

Macrorealism is a concept to **capture our intuition of the macroscopic, classical world**. It is defined from the following three assumptions [2]:

- **The system, even when not observed, is in one of the states at each moment of time**

*A counter-example is Schrodinger's cat, simultaneously in both states of being dead and alive.*

*Image taken from dreamstime.com*

- **Measurements can be done without disturbing the system itself.**
  *Also refered to as Non-invasive measureability*

- **Future measurements cannot affect the present system.**
  *Hold in almost all physical theories, notion of causality*

## Motivation

Contradictorily, one of the obvious places **where macrealism (MR) does not hold is in quantum mechanics, the theory every particle is following.**

However, if **observations are made in a special way**, we can not tell from our measurements that interference or superposition happened, and as far as we are concerned, **the system is as good as a macrorealistic system**. This leads to our objective:

**Aim:**
**We will formulate macrealism into conditions and test them in quantum systems, to see the how our macroscopic world emerge from seemingly contradictory theories.**

## Theory I

There are two main formulations of macrealism that we tested

1. **No-Signaling in Time Condition (NSIT)**

The key difference between a quantum system and an MR system is that it violates the probabilistic sum rule,

$$p_2(n_2) = \sum_{n_1} p_{12}(n_1, n_2).$$

For example, in the double slits experiment, we would expect in a classical system the pattern from two slits is the same as the sum of the patterns from two individual slits. However, this is not the case due to the interference between two slits.

For this formulation of macrorealism to hold, **zero interferences is required**. This is known as the **No-Signaling In Time (NSIT) condition** [3].

## Theory II

2. **Legget-Garg Inequalities (LGIs)**

While classical probabilities do not obey the sum rule in quantum systems, the quasi-probability [2], a quantum counterpart to the classical probability,

$$q(s_1, s_2) = \frac{1}{2} Tr\{(P_{s2}(t_2)P_{s1}(t_1) + P_{s1}(t_1)P_{s2}(t_2))\rho\}$$

does.

Another less-strict interpretation of macrorealism is to require such quasi-probability to be greater or equal to zero. This **does not eliminate interference entirely**, but to constrain it to behave like its classical limit.

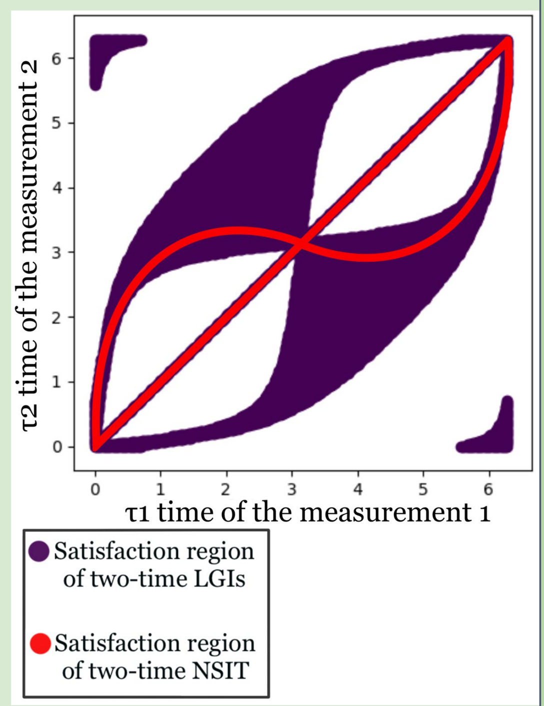
The sets of inequalities ensuring this is refer to as **Legget-Garg Inequalities** [2].

## Results I

We investigated whether spin-half systems (qubit) experiencing magnetic field exhibit MR properties.

1. **Two-time LGIs and NSIT conditions**

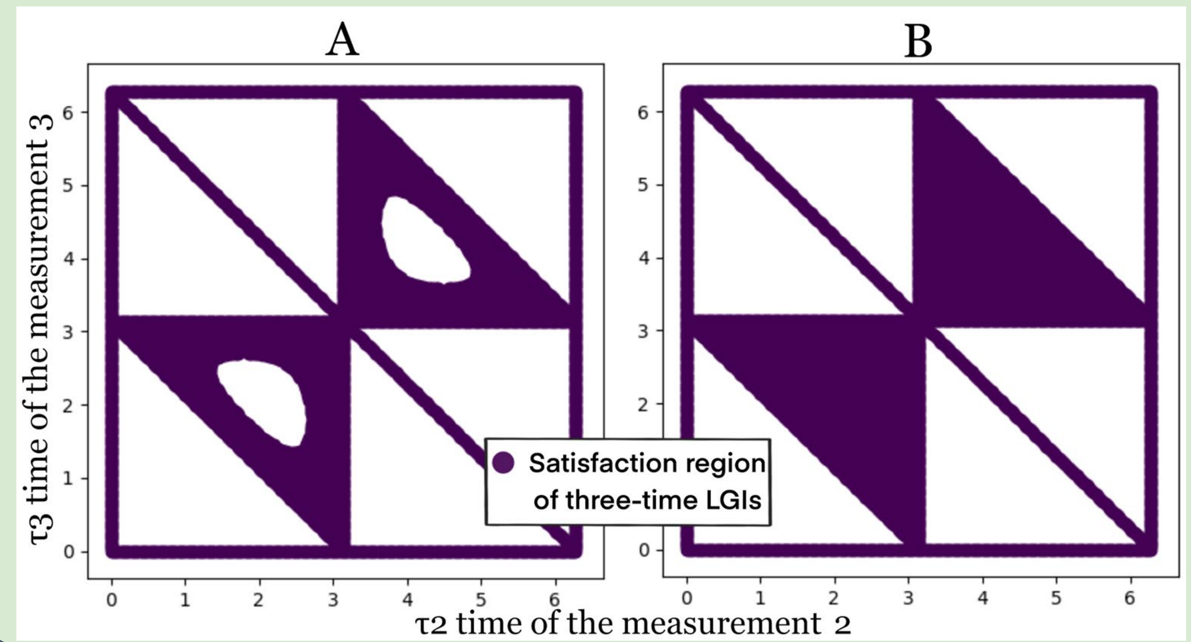
The figure shows the parameter space that satisfies two-time Leggett-Garg inequalities and the NSIT condition. It is clear that there is a significant region satisfying the LGIs but only a few lines satisfying the NSIT condition that lies within the LGIs regions, indicates that **NSIT is indeed a more strict interpretation of MR**. This agrees with our discussions earlier.




## Results II

2. **Three-time LGIs**

The figure shows the satisfaction region of the three-time Leggett-Garg inequalities. Two systems are plotted where the **second system's initial state is prepared to be more certain than the first one**.
The second system indeed has a larger satisfaction region. This shows that a **more classical system is easier to be MR upon observation**, and explains how MR emerges at the classical limit.




## Conclusion

To summarise, we explored two different notion of macro-realistic conditions, NSIT and LGI. The former requires zero interference, and is much more strict than the latter. **Either are equally valid interpretation of macro-realism,** and shows that the exact notion of macrorealism is still an active research topic [2].

We also finds using the spin-half system, a more classical system is easier to satisfy MR conditions, this shines light to **how our macroscopic phenomenon emerges from seemingly contradictory theories.**

## Reference

1. C. Emary, N. lambert, F. Nori, arXiv:1304.5133 (2014)
2. J. Halliwell, C. Mawby, Phy. Rev. A. 102, 012209 (2020)
3. J. Halliwell, Phy. Rev. A. 96, 012121 (2017)