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Constraints on macroscopic realism without assuming non-invasive measurability

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ABSTRACT

Macroscopic realism is the thesis that macroscopically observable properties must always have definite values. The idea was introduced by Leggett and Garg (1985), who wished to show a conflict with the predictions of quantum theory, by using it to derive an inequality that quantum theory violates. However, Leggett and Garg's analysis required not just the assumption of macroscopic realism *per se*, but also that the observable properties could be measured non-invasively. In recent years there has been increasing interest in experimental tests of the violation of the Leggett-Garg inequality, but it has remained a matter of controversy whether this second assumption is a reasonable requirement for a macroscopic realist view of quantum theory. In a recent critical assessment Maroney and Timpson (2014) identified three different categories of macroscopic realism, and argued that only the simplest category could be ruled out by Leggett-Garg inequality violations. Allen, Maroney, and Gogioso (2016) then showed that the second of these approaches was also incompatible with quantum theory in Hilbert spaces of dimension 4 or higher. However, we show that the distinction introduced by Maroney and Timpson between the second and third approaches is not noise tolerant, so unfortunately Allen's result, as given, is not directly empirically testable. In this paper we replace Maroney and Timpson's three categories with a parameterization of macroscopic realist models, which can be related to experimental observations in a noise tolerant way, and recover the original definitions in the noise-free limit. We show how this parameterization can be used to experimentally rule out classes of macroscopic realism in Hilbert spaces of dimension 3 or higher, without any use of the non-invasive measurability assumption. Even for relatively low precision experiments, this will rule out the original category of macroscopic realism, that is tested by the Leggett-Garg inequality, while as the precision of the experiments increases, all cases of the second category and many cases of the third category, will become experimentally ruled out.

1. Introduction

The concept of macroscopic realism was introduced by Leggett and Garg (1985) to focus attention upon an apparent inconsistency between quantum mechanics and our experience of the real world. Roughly speaking, macroscopic realism maintains that a macroscopically observable property must always have a definite value. Therefore the only possible states are ones for which macroscopic observables take definite values. Leggett and Garg further argued that this view could be shown to be inconsistent with observable predictions of quantum theory, by deriving an inequality for the correlations between a sequence of measurements of the macro-observable, that quantum theory could, in principle, violate.

However, Leggett and Garg's derivation required, in addition to macroscopic realism, the use of another assumption: that it was possible, in special cases, to measure the macro-observable non-invasively. This left open the possibility that a macroscopically realist interpretation of quantum theory is possible that still violates the inequality by denying the possibility of non-invasive measurements.

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In recent years there have been increasingly sophisticated experiments seeking to test the Leggett-Garg inequality violations in quantum theory.[1] These experiments have used a variety of materials, including superconducting devices, photons, and nuclear and electron spins in silicon and in diamond, and techniques, including weak and strong projective measurements, all confirming the violation. It should be noted that none of these experiments have actually tested a macroscopically observable property: rather, they have shown violations of the Leggett-Garg inequality for microscopic quantum observables, and represent a proof of principle that tests of the inequality are possible. Alongside these tests has been a revival of discussion of the significance of the choice of macroscopic realism vs non-invasive measurability.[2]

In this paper we follow the analysis of Maroney and Timpson, who identified three types of macroscopic realism, and argued that experiments violating the Leggett-Garg inequality only ruled out one, albeit rather natural, type. Allen, Maroney, and Gogioso (2016), building on earlier work by Allen (2016), then showed problems for a second type. However, the distinction between this type, and the third remaining type as introduced by Maroney and Timpson, is not noise tolerant, and so Allen's result can not be directly subjected to experimental testing.

Our main concern in this paper is to show how experimental tests of macroscopic realism are possible without making use of the non-invasive measurability assumption, and in doing so show that it is possible to rule out a wider class of models than is possible using Leggett-Garg inequality violations. We start in Section 2 by using the ontic models formalism (a general framework used for classifying realist interpretations of operational theories) to characterize macroscopically realist models for quantum theory. By looking at the relationship between macroscopic realism and the eigenvalue-eigenstate link, we will identify the types of macroscopic realism discussed by Maroney and Timpson: here called eigenpreparation mixing models (which are in conflict with Leggett-Garg inequality violations), eigenpreparation supported models, and eigenpreparation undermining models. Broadly speaking, eigenpreparation mixing is equivalent to macroscopic realism with a strict interpretation of the eigenvalue-eigenstate link, eigenpreparation support keeps a more generalized form of the eigenvalue-eigenstate link, and eigenpreparation undermining models maintain macroscopic realism without a connection to the link.

In Section 3 we review how eigenpreparation mixing and eigenpreparation supported models are incompatible with quantum theory for Hilbert spaces with dimension two or more and three or more respectively, extending the earlier result in (Allen et al., 2016). However, in Section 4 we show that the distinction between eigenpreparation supported and eigenpreparation undermining macroscopic realism needed for this result, is subject to finite precision loopholes, which means that no experimental test can directly distinguish them. To address this problem, we introduce two parameters for characterizing macroscopically realist models for quantum theory, which qualitatively distinguish eigenpreparation supported from eigenpreparation undermining models, and which can be tested against experimental data. With this parameterization, eigenpreparation mixing models can be experimentally ruled out, without using assumptions of non-invasive measurability. Qualitatively eigenpreparation supported models can also be ruled out, with a larger range of such models being ruled out as experimental precision increases. For very high precision measurements only some eigenpreparation undermining models remain viable, thus providing a generalization of the noise-free results of Section 3.2 in the limit. Overall, we will show that a much larger class of macroscopically realist models can be experimentally ruled out than is allowed by Leggett-Garg inequality violations, and without making any use of the assumption of non-invasive measurability.

2. Macroscopic realism and the eigenvalue-eigenstate link

Leggett and Garg originally defined macroscopic realism in terms of the existence of macroscopically distinct states:

> A macroscopic system with two or more macroscopically distinct states available to it will at all times *be* in one or other of those states (Leggett & Garg, 1985, p. 857).

Intuitively, however, their idea is that it is certain observable *properties*, such as the positions of tables and chairs, that have definite values at all times. This shifts the focus from macroscopic states to macroscopic observables. That this shift does not alter the meaning should be clear: two states will be macroscopically distinct if, and only if, they assign different values to some macroscopic observable. But it is non-trivial to make precise why some observables are macroscopic and others are not.[3] What we are interested in here is a proof of principle about what kinds of realism about observable properties can be shown to be incompatible with quantum mechanics. We therefore follow the standard in the literature and set aside the question of what notion of macroscopicity is supposed to be captured by the “macro”-part. Although neither the observables we consider here, nor the ones that have been experimentally investigated, fit our intuitive notion of macroscopicity, the results we obtain here do rule out a particular form of realism about these observables. Whether the results can then be scaled to more *macroscopic* observables is for later concern. That this is theoretically a possibility is almost trivially so, but whether it is also experimentally possible ultimately relies on what we can technologically achieve and on the ultimate validity of quantum mechanics on the macroscopic scale.

A useful way to approach macroscopic realism is via another idea one often finds in orthodox expositions of quantum mechanics: the eigenvalue-eigenstate link. This is the axiom that *an observable for a system has a definite value if and only if the system is in an eigenstate for that observable*. The conjunction of this axiom with the idea that the macro-observables are always value definite yields the requirement that a system is always in one of the eigenstates of a macro-observable. In other words, the observable imposes a superselection rule: every possible state is a mixture of eigenstates (i.e., a density operator as opposed to a proper superposition). This is the type of macroscopic realism that Maroney and Timpson (2014, §3) attribute to Leggett and Garg (1985), and can be shown to be ruled out by experimental violations of the Leggett-Garg inequality.

It is important to note that macroscopic realism *per se* is not in conflict with quantum mechanics and so there are principled limitations on what can be shown. A useful example is the de Broglie-Bohm theory in which all particles have a definite position at all time.[4] If we assume that macroscopic properties supervene on

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[1] (Dressel, Broadbent, Howell, & Jordan, 2011; George et al., 2013; Goggin et al., 2011; Knee et al., 2012, 2016; Palacios-Laloy et al., 2010; Xu, Li, Zou, & Guo, 2011).

[2] (Foster & Elby, 1991; Elby & Foster, 1992; Bacciagaluppi, 2015; Clemente & Koer, 2016; Hess, De Raedt, and Michielsen, 2016; Maroney & Timpson, 2014).

[3] Although there have been several noteworthy attempts to make the notion of macroscopicity precise. See for example (Yadin & Vedral, 2016) and references therein.

[4] See also (Bacciagaluppi, 2015; Kofler & Brukner, 2013).

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