Existence of superluminal signaling in collapse theories of quantum mechanics

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May 31, 2022

Abstract

It is usually thought that superluminal signaling is prohibited in collapse theories of quantum mechanics. In this paper, I argue that this is not the case when considering the tails problem and its solution. In collapse theories, the post-measurement state of a measuring device or an observer is a definite result state with tails containing other results. This leads to the well-known tails problem. In order to solve this problem, collapse theories have to assume that a measuring device or an observer being in a post-measurement superposition already obtains a definite result. It is argued that this solution to the tails problem will in principle permit that two ensembles with the same density matrix can be distinguished, which further leads to the existence of superluminal signaling.

In collapse theories of quantum mechanics, the post-measurement state of a measuring device or an observer is a superposition of different result branches, although the modulus squared of the amplitude of one result branch is close to one typically (Ghirardi and Bassi, 2020). This leads to the well-known tails problem (for a recent review see McQueen, 2015). In order to solve this problem, collapse theories have to assume that a measuring device or an observer being in such a superposition already obtains a definite result. This may be via a fuzzy-link principle (Albert and Loewer, 1996), or a principle of inaccessibility (Ghirardi et al, 1995), or a certain psychophysical principle (Monton, 2004; Gao, 2018).[1] In this paper, I will argue that collapse theories with a solution to the tails problem permit superluminal signaling.

Consider two ensembles of identically prepared measuring devices at a given instant. In the first ensemble, the wave function of each device is random, being $|0\rangle$ with probability p_0 or $|1\rangle$ with probability p_1, where $|0\rangle$ and $|1\rangle$ are two different result states of the device, and $p_0 + p_1 = 1$. In the second ensemble, the wave function of each device is also random, being $\sqrt{p_0}\,|0\rangle + \sqrt{p_1}\,|1\rangle$ or $\sqrt{p_0}\,|0\rangle - \sqrt{p_1}\,|1\rangle$ with the same probability 1/2. These two ensembles have the same statistical density matrix $\rho = p_0|0\rangle\langle 0| + p_1|1\rangle\langle 1|$. In quantum mechanics, it is impossible to distinguish between these two ensembles.

On the other hand, when p_0 is small enough, the two ensembles can be distinguished in collapse theories. For example, according to the fuzzy-link principle (Albert and Loewer, 1996), when p_0 is small enough, a device being in the superposition $\sqrt{p_0}\,|0\rangle + \sqrt{p_1}\,|1\rangle$ or $\sqrt{p_0}\,|0\rangle - \sqrt{p_1}\,|1\rangle$ already obtains the definite result 1. Then, the above two ensembles can be distinguished;[2] for the first ensemble, the result of each device is not always "1", and it may be "0" with a nonzero probability p_0, while for the second ensemble, the result of each device is always "1".

When the measuring devices are replaced by observers, the analysis is similar. For example, according to the principle of inaccessibility (Ghirardi et al, 1995), when p_0 is small enough, an observer being in the superposition $\sqrt{p_0}\,|0\rangle + \sqrt{p_1}\,|1\rangle$ or $\sqrt{p_0}\,|0\rangle - \sqrt{p_1}\,|1\rangle$ already obtains the definite result "1", since the low-density matter in the tail branch $|0\rangle$ is inaccessible to the observer. Then, the two ensembles of observers can also be distinguished in collapse theories; for the first ensemble, an observer does not always obtain the result "1", and she may obtain the result "0" with a nonzero probability p_0, while for the second ensemble, every observer obtains the result "1".

Note that collapse theories with a solution to the tails problem also permit that the results obtained by a measuring device or an observer can be verified by other devices or observers. When verifying the result obtained by a measuring device or an observer being in a post-measurement superposition, the state of another device or observer is entangled with this superposition,

[1] Note that these principles can solve the so-called structured tails problem by assuming that the result of a measuring device or the mental state of an observer is determined by the whole post-measurement superposition, not only by the high mod-square result branch (cf. McQueen, 2015). The bare theory is another example of solving the structured tails problem by this assumption (Albert, 1992). My analysis in this paper is independent of the concrete solutions to the tails problem.

[2] Similarly, the first ensemble and another ensemble with an identical reduced density matrix can also be distinguished. This will be analyzed in more detail later.

and the device or observer will also record the same result by the fuzzy-link principle or the principle of inaccessibility.

The distinguishability of two ensembles with the same density matrix in quantum mechanics can be used to realize superluminal signaling. Suppose there is an ensemble of entangled states of a measuring device and a particle $\sqrt{p_0}\,|0\rangle_A|0\rangle_B + \sqrt{p_1}\,|1\rangle_A|1\rangle_B$, where p_0 is small enough so that the device only records the result "1". The particles are in Alice's lab, and the devices are in Bob's lab. Alice may send a signal to Bob's lab by measuring the particles on her side. It is required that Alice's measurement makes the dynamical collapse of each entangled state so fast that the post-measurement state is almost $|0\rangle_A|1\rangle_B$ or $|1\rangle_A|0\rangle_B$ (i.e. the sum of the amplitudes of the tails is much smaller than p_0 so that these tails can be omitted relative to the original state). Then before Alice makes her measurements, Bob has an ensemble of entangled states $\sqrt{p_0}\,|0\rangle_A|0\rangle_B + \sqrt{p_1}\,|1\rangle_A|1\rangle_B$, while after Alice makes her measurements, Bob has an ensemble of random states, each of which is $|0\rangle_B$ with probability p_0 or $|1\rangle_B$ with probability p_1. For the first ensemble of entangled states, all devices obtain the result "1", while for the second ensemble of random states, some devices obtain the result "0", and the probability is p_0. Then the devices in Bob's lab can receive the superluminal signal. Bob can also get the superluminal signal by looking at the results of the devices.[3] In a preferred Lorentz frame, the superluminal signaling is instantaneous.

It has been shown that collapse theories prohibit superluminal signaling (see, e.g. Ghirardi et al, 1993). The above analysis is not inconsistent with the existing proofs. These proofs apply to the cases in which the time for dynamical collapse approaches infinity. In these ideal cases, any two ensembles with the same density matrix cannot be distinguished as in standard quantum mechanics. While the above analysis applies to the cases in which the time for dynamical collapse is finite. In these realistic cases, collapse theories with a solution to the tails problem permit that two ensembles with the same density matrix can be distinguished, which further permits superluminal signaling. In the final analysis, collapse theories violate the superposition principle and introduce definite nonlinear evolution at the macroscopic level such as for measuring devices or observers via their solution to the tails problem.[4] Al-

[3]Here it is assumed that Bob's observation does not collapse the entangled superposition of each device significantly. Alternatively, we may also use an ensemble of observers being in the post-measurement state $\sqrt{p_0}\,|0\rangle_A|0\rangle_B + \sqrt{p_1}\,|1\rangle_A|1\rangle_B$ in Bob's lab to receive the superluminal signal.

[4]One may argue that for measuring devices the fuzzy-link principle is only "a proposal for how to use language" (Lewis, 2006). But for observers their mental states are real, and thus the violation of the superposition principle is also real for observers.

though the effect of definite nonlinear evolution is extremely small, it can in principle lead to superluminal signaling when combining with wave-function collapse, as already argued by some authors (Gisin, 1989, 1990; Polchinski, 1991; Czachor 1991). Certainly, it is arguable that this mechanism of superluminal signaling is practically unrealizable due to the extremely small tails and the existence of environmental noises.

To sum up, I have argued that superluminal signaling is possible in collapse theories of quantum mechanics. In order to solve the tails problem, these theories have to assume that a measuring device or an observer being in a post-measurement superposition already obtains a definite result. However, this will in principle permits the existence of superluminal signaling. It remains to be seen if one can formulate a collapse theory which can solve both the tails problem and the problem of superluminal signaling.

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