Is superluminal signaling possible in collapse theories of quantum mechanics?

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Abstract

It is a received view that superluminal signaling is prohibited in collapse theories of quantum mechanics. In this paper, I argue that this may be not the case. I propose two possible mechanisms of superluminal signaling in collapse theories. The first one is based on the well-accepted solution to the tails problem, and the second one is based on certain assumptions about the minds of observers. Finally, I also discuss how collapse theories can avoid such superluminal signaling.

1 Introduction

In standard quantum mechanics, it is postulated that when a quantum system is measured by a measuring device, its wave function no longer follows the linear Schrödinger equation, but instantaneously collapses to one of the wave functions that correspond to definite measurement results. As a result, there are no measuring devices and observers being in a superposition of different result states. However, such special superpositions exist in collapse theories of quantum mechanics (Ghirardi and Bassi, 2020). In collapse theories, due to the imperfectness of wave-function collapse, the post-measurement state is a superposition of all possible result states, although the modulus squared of the amplitude of one result branch is close to one typically. Besides, since the collapse time of a single superposed state is a random variable, whose value can range between zero and infinity, there always exist certain measurements with a small probability, for which the collapse time is much longer than the normal measuring time so that the post-measurement state is a general superposition of result states (Ghirardi et al, 1993). In this paper, I will argue that the existence of these special superpositions in collapse theories permits superluminal signaling. Concretely speaking, I will propose two possible mechanisms of superluminal signaling, one of which is based on the well-accepted solution to the tails problem, and the other of which is based on certain assumptions about the minds of observers. I will also discuss how collapse theories can avoid such superluminal signaling.

2 Superluminal signaling: First mechanism

In collapse theories, 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 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). In the following, I will argue that collapse theories with this well-accepted solution to the tails problem permit superluminal signaling.

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

However, 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 $\sqrt{p_0}\,|0\rangle_S |0\rangle_M + e^{i\phi}\sqrt{p_1}\,|1\rangle_S |1\rangle_M$ or $\sqrt{p_0}\,|0\rangle_S |0\rangle_M - e^{i\phi}\sqrt{p_1}\,|1\rangle_S |1\rangle_M$

already obtains the definite result “1”. Then, the above two ensembles can be distinguished; 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 $\sqrt{p_0}\,|0\rangle_S\,|0\rangle_M + e^{i\phi}\sqrt{p_1}\,|1\rangle_S\,|1\rangle_M$ or $\sqrt{p_0}\,|0\rangle_S\,|0\rangle_M - e^{i\phi}\sqrt{p_1}\,|1\rangle_S\,|1\rangle_M$ already obtains the definite result “1”, since the low-density matter in the tail branch $|0\rangle_S\,|0\rangle_M$ is inaccessible to the observer. Then, the two ensembles 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”.

It is worth noting that a measuring device or an observer is always entangled with the measured system (and the environment) after a measurement due to the existence of tails in collapse theories. And when a measuring device or an observer is in an entangled superposition with tails such as $\sqrt{p_0}\,|0\rangle_S\,|0\rangle_M + e^{i\phi}\sqrt{p_1}\,|1\rangle_S\,|1\rangle_M$, collapse theories require that the measuring device or the observer already obtains a definite result; otherwise these theories would not agree with experience. Moreover, these theories also permit that the result 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, and this 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 can be used to realize superluminal signaling. Suppose there is an ensemble of random entangled states of a particle and a measuring device (as resources for signaling), each of which is $\sqrt{p_0}\,|0\rangle_S\,|0\rangle_M + e^{i\phi}\sqrt{p_1}\,|1\rangle_S\,|1\rangle_M$ or $\sqrt{p_0}\,|0\rangle_S\,|0\rangle_M - e^{i\phi}\sqrt{p_1}\,|1\rangle_S\,|1\rangle_M$ with the same probability 1/2, where $|0\rangle_S$ and $|1\rangle_S$ are two different states of the particle, $|0\rangle_M$ and $|1\rangle_M$ are two different result states of the measuring device, $p_0 + p_1 = 1$, and p_0 is small enough so that the measuring device already 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 in the $\{|0\rangle_S\,,|1\rangle_S\}$ basis with her measuring device. It is required that Alice’s measurement makes the dynamical collapse of each entangled state so fast that the post-measurement state is almost $|0\rangle_S\,|0\rangle_M$ or $|1\rangle_S\,|1\rangle_M$ (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 after Alice makes her measurements, there is another different ensemble of random states, each of which is $|0\rangle_S |0\rangle_M$ with probability p_0 or $|1\rangle_S |1\rangle_M$ with probability p_1. As argued above, the two ensembles before and after Alice's measurements, which have the same statistical density matrix, can be distinguished in collapse theories. For the first ensemble, all devices obtain the result "1", while for the second ensemble, some devices obtain the result "0", and the probability is p_0. Then the signal sent by Alice can be received by the devices that obtain the result "0" in Bob's lab.[1] In a preferred Lorentz frame (where the collapse of the wave function is simultaneous in different regions of space), the signaling is instantaneous, while in other Lorentz frames the signaling is not instantaneous but still superluminal.

Similarly, one can also use an ensemble of random entangled states of a particle and an observer to realize superluminal signaling. The particles are in Alice's lab, and the observers are in Bob's lab. In this case, if Alice does not make her measurements, all observers will obtain the result "1", while if Alice makes her measurements, some observers will obtain the result "0", and the probability is p_0. Then the superluminal signal sent by Alice can be received by the observers who obtain the result "0" in Bob's lab.

3 Superluminal signaling: Second mechanism

The above mechanism of superluminal signaling uses special superpositions with tails. In this section, I will further argue that superluminal signaling may be also realized using general superpositions, which, as noted before, exist after certain measurements with a small probability. The mechanism does not rely on the solution to the tails problem, and it is based on certain assumptions about the minds of observers.

Consider an observer M being in a general entangled superposition:

$$\alpha |1\rangle_P |1\rangle_M + \beta |2\rangle_P |2\rangle_M , \tag{1}$$

[1]Bob can also receive the superluminal signal by looking at the devices in his lab if his observation of the result of a device does not further collapse the entangled superposition of the device significantly so that the superposition is still a result "1" state with the tail being the result "0" state, namely immediately after Bob's observation of the result of a device the state of the whole composite system including Bob is close to the state $\sqrt{p_0} |0\rangle_S |0\rangle_M |0\rangle_B + e^{i\phi}\sqrt{p_1} |1\rangle_S |1\rangle_M |1\rangle_B$ or $\sqrt{p_0} |0\rangle_S |0\rangle_M |0\rangle_B - e^{i\phi}\sqrt{p_1} |1\rangle_S |1\rangle_M |1\rangle_B$. In this case, if Alice does not make her measurements, Bob will observe the result "1" for all devices, while if Alice makes her measurements, Bob will observe the result "0" for some devices.

where $|1\rangle_P$ and $|2\rangle_P$ are the wave functions of the pointer of a measuring device being centered in positions x_1 and x_2, respectively, $|1\rangle_M$ and $|2\rangle_M$ are the wave functions of the observer M who observes the pointer being in positions x_1 and x_2, respectively, and α and β, each of which is nonzero and not necessarily small enough, satisfy the normalization condition $|\alpha|^2+|\beta|^2 = 1$.

We first assume that the observer M being in this superposition still has a well-defined mental state. The question then is: what is her mental content? There are two possibilities. The first one is that the mental content of M is related to the values of α and β (Gao, 2019). The second one is that the mental content of M is constant for all (nonzero) values of α and β. There are three further possibilities for the second case: (1) The mental content of M is "observing the pointer being in position x_1"; (2) The mental content of M is "observing the pointer being in position x_2"; (3) The mental content of M is constant for all nonzero values of α and β, but it is neither "observing the pointer being in position x_1" nor "observing the pointer being in position x_2".

We further assume that M can report her mental content about the measurement result. Then, for the first possibility, the output of M will contain the information about (nonzero) α and β. As a result, some non-orthogonal states such as $|1\rangle_P |1\rangle_M$ or $|2\rangle_P |2\rangle_M$ and $\alpha |1\rangle_P |1\rangle_M + \beta |2\rangle_P |2\rangle_M$ or $\alpha |1\rangle_P |1\rangle_M - \beta |2\rangle_P |2\rangle_M$ can be distinguished. For the former, the output of M does not contain the information about α and β, while for the latter, the output of M contains the information about α and β. Similarly, for the second possibility, the above non-orthogonal states can also be distinguished. For example, for the third sub-possibility in this case, the output of M for $|1\rangle_P |1\rangle_M$ or $|2\rangle_P |2\rangle_M$ is "observing the pointer being in position x_1" or "observing the pointer being in position x_2", while the output of M for $\alpha |1\rangle_P |1\rangle_M + \beta |2\rangle_P |2\rangle_M$ or $\alpha |1\rangle_P |1\rangle_M - \beta |2\rangle_P |2\rangle_M$ is neither "observing the pointer being in position x_1" nor "observing the pointer being in position x_2".

Once the non-orthogonal states $|1\rangle_P |1\rangle_M$ or $|2\rangle_P |2\rangle_M$ and $\alpha |1\rangle_P |1\rangle_M + \beta |2\rangle_P |2\rangle_M$ or $\alpha |1\rangle_P |1\rangle_M - \beta |2\rangle_P |2\rangle_M$ can be distinguished, we can realize superluminal signaling using the same method as given in the last section. In fact, we may use only one system, not an ensemble of many systems, to realize superluminal signaling this time. Suppose an observer and the pointer of a measuring device are in the entangled state $\alpha |1\rangle_P |1\rangle_M + \beta |2\rangle_P |2\rangle_M$. The pointer is in Alice's lab, and the observer is in Bob's lab. Then, Alice may send a superluminal signal to Bob's lab by measuring the pointer on her side with her measuring device. Before Alice's measurement, the observer is in a superposed state $\alpha |1\rangle_P |1\rangle_M + \beta |2\rangle_P |2\rangle_M$, while after Alice's measurement, the superposed state collapses to $|1\rangle_P |1\rangle_M$ or $|2\rangle_P |2\rangle_M$. Since the observer can distinguish between these two non-orthogonal states, she can receive the superluminal signal sent by Alice.

4 Further discussion

It has been demonstrated that collapse theories prohibit superluminal signaling (see, e.g. Ghirardi et al, 1993). The above result is not inconsistent with the existing proofs. These proofs implicitly assume that the same density matrix that describe two different ensembles always gives the same empirical predictions. As argued above, however, this assumption may be not universally true in collapse theories. Once two ensembles with the same density matrix can be empirically distinguished, superluminal signaling is possible.

There is a reason why two ensembles with the same density matrix may be distinguishable in the two mechanisms of superluminal signaling. It is that they both violate the strict Born rule for some states.[2] In the first mechanism of superluminal signaling, the solution to the tails problem assumes that a measuring device or an observer being in a typical post-measurement superposition with tails already obtains a definite result. This violates the Born rule, according to which a measuring device or an observer being in a post-measurement superposition such as $\sqrt{p_0}\,|0\rangle_S |0\rangle_M + e^{i\phi}\sqrt{p_1}\,|1\rangle_S |1\rangle_M$ (where p_0 is small enough) should not obtain the result "1" with certainty, but obtain the result "1" with probability $p_1 < 1$.

Similarly, in the second mechanism of superluminal signaling, an observer being in a general superposition such as $\sqrt{p_0}\,|0\rangle_S |0\rangle_M + e^{i\phi}\sqrt{p_1}\,|1\rangle_S |1\rangle_M$ already obtains a definite result (no matter what the result is), while this also violates the Born rule, according to which the observer being in this superposition should not obtain a definite result with certainty, but obtain the result "0" with probability p_0 and obtain the result "1" with probability p_1. If the Born rule is violated for some states, the same density matrix that describe two different ensembles will not always give the same empirical predictions, and thus superluminal signaling is possible.

The final question is: can we avoid superluminal signaling in collapse theories? This seems possible for the second mechanism of superluminal signaling. This mechanism is based on two key assumptions about the minds

[2]This means that these two mechanisms of superluminal signaling are different from the mechanism of superluminal signaling in nonlinear quantum mechanics (Gisin, 1989, 1990; Polchinski, 1991; Czachor 1991). Note also that such superluminal signaling is practically unrealizable due to either the extremely small tails or the extremely small possibility of the existence of general superpositions of different result states.

of observers. One is that an observer being in a general superposition of different result states has a well-defined mental state, and the other is that the observer being in this superposition can report her mental content about the result. If an observer being in such a superposition cannot report her mental content, then this mechanism of superluminal signaling will not work.

It seems more difficult to avoid superluminal signaling for the first mechanism, since it is based on the well-accepted solution to the tails problem. If the post-measurement states have tails, then it seems that one must assume that a measuring device or an observer being in such a post-measurement superposition already obtains a definite result; otherwise collapse theories will be inconsistent with experience. We obtain a definite result after each measurement after all. It seems to me that the only way out is to use the compact support collapse functions in collapse models so that the post-measurement state has no structured tails, although these models are plagued by other relativistic problems (see Mcqueen, 2015). This solution will also invalidate the second mechanism of superluminal signaling.

To sum up, I have argued that superluminal signaling is possible in collapse theories of quantum mechanics. In particular, the well-accepted solution to the tails problem in principle permits the distinguishability of two ensembles with the same density matrix and the existence of superluminal signaling. It remains to be seen if one can formulate a collapse theory which solves the tails problem and also avoids superluminal signaling.

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