# Energy nonconservation in collapse theories enables superluminal signaling

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**Abstract**

Energy nonconservation is a well-known feature of collapse theories of quantum mechanics. In this paper, I argue that the heating effect of collapse theories can be used to realize superluminal signaling. Possible implications of this new result are also briefly discussed.

Energy nonconservation is a well-known feature of collapse theories of quantum mechanics including the continuous spontaneous localization (CSL) model and the gravity-related collapse models such as the Diósi-Penrose (DP) model (Ghirardi and Bassi, 2020). The localization of the wavepacket of a quantum system in space amounts to an increase in the energy of the system, and thus conservation of energy is violated (Pearle, 2000). This effect of energy increase or heating has been investigated by analyzing existing experiments and conducting new experiments (Carlesso et al, 2022). Although these experiments constrain the parameter values in the CSL model and the DP model, they do not exclude the possibility of such energy nonconservation. In this paper, I will argue that the heating effect of collapse theories can be used to realize superluminal signaling. Possible implications of this new result will be also discussed.[1]

Consider two ensembles of identically prepared measured systems. In the first ensemble, the wave function of each system is random, being $|0\rangle$

[1]In a previous paper, I argued that collapse theories with a solution to the tails problem in principle permit superluminal signaling (Gao, 2022).

or $|1\rangle$ with the same probability 1/2, where $|0\rangle$ and $|1\rangle$ are two different eigenstates of an observable of the system such as different spin states. In the second ensemble, the wave function of each system is also random, but being $\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$ or $\frac{1}{\sqrt{2}}(|0\rangle - |1\rangle)$ with the same probability 1/2. These two ensembles have the same statistical density matrix $\rho = \frac{1}{2}|0\rangle\langle 0| + \frac{1}{2}|1\rangle\langle 1|$. In standard quantum mechanics, it is impossible to distinguish between these two ensembles.

However, the two ensembles can be distinguished in collapse theories due to the existence of the heating effect. The reason is as follows. When the systems in the first ensemble are input one by one to a measuring device that measures the observable of which $|0\rangle$ and $|1\rangle$ are two eigenstates, no collapse of the wave function happens. While when the systems in the second ensemble are input one by one to this measuring device, the collapse of the wave function will happen. According to collapse theories such as the CSL model or the DP model, the energy of the measuring device will not increase due to the first measurements, but it will increase due to the second measurements. In other words, the first measurements will not lead to the heating of the measuring device, but the second measurements will do. Then, we can distinguish the two measured ensembles by detecting the heating effect in principle.

Here it is worth noting that the (mean) energy of a quantum system will continuously increase over time due to the continuous expansion and collapse of its wave function. This means that the energy of the above measuring device will also increase after the first measurements. However, the second measurements will induce more collapse of the wave function and thus result in more energy increase or heating. Then, the second measurements will still cause more heating of the measuring device than the first measurements. In an extreme case where the measuring time for each measured system is so short that it can be ignored, the first measurements will cause no heating of the measuring device, while the second measurements will cause heating of the measuring device due to the collape of the wave function during the measurements.

Once two ensembles with the same density matrix can be distinguished, superluminal signaling can be realized. Consider a usual Bell-like experiment. There are two observers Alice and Bob who are in their separate laboratories and share an ensemble of EPR pairs of spin 1/2 particles in the spin singlet state:

$$\frac{1}{\sqrt{2}}(|\uparrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\uparrow\rangle_2). \tag{1}$$

Alice measures the spin of particles 1 at angle $z$ or $x$, and Bob measures the spin of particles 2 always at angle $z$. These two measurements are spacelike separated. When Alice measures the spin of particle 1 at angle $z$, the state of spin of particle 2 in the $z$ direction will be either $|\uparrow_z\rangle_2$ or $|\downarrow_z\rangle_2$ with the same probability 1/2. While when Alice measures the spin of particle 1 at angle $x$, the state of spin of particle 2 in the $z$ direction will be either $\frac{1}{\sqrt{2}}(|\uparrow_z\rangle_2 + |\downarrow_z\rangle_2)$ or $\frac{1}{\sqrt{2}}(|\uparrow_z\rangle_2 - |\downarrow_z\rangle_2)$ with the same probability 1/2. Now if these two ensembles of particles 2, which have the same statistical density matrix, can be distinguished, then Alice can send a signal to Bob by measuring particles 1 at angle $z$ or $x$, and Bob can also identify the signal by measuring particles 2 at angle $z$. This means that superluminal signaling can be realized. Since Alice's and Bob's measurements are spacelike separated, the superluminal signaling is instantaneous in a preferred Lorentz frame.

It has been demonstrated that collapse theories prohibit superluminal signaling (see, e.g. Ghirardi et al, 1993). The above analysis is not inconsistent with the existing proofs. The reason is as follows. These proofs consider only the results of measurements represented by the whole post-measurement wave functions and their probability distribution. They do not consider the forms of these post-measurement wave functions. Due to the existence of dynamical collapse process, the form of the post-measurement wave function for a measurement of an eigenstate of the measured observable is different from that for a measurement of a superposition of eigenstates of the measured observable. In particular, the post-measurement wave function in the latter case will contain more high-momentum components than the post-measurement wave function in the former case, although they are both localized, representing the same result of measurement. As argued above, the difference of energies for these two cases can be used to distinguish two ensembles with the same density matrix and further realize superluminal signaling.

It can be seen that besides the heating effect, other non-interferometric tests of collapse models may also be used to realize superluminal signaling (Carlesso et al, 2022). In collapse theories, although interferometric experiments cannot distinguish two ensembles with the same density matrix, non-interferometric experiments can distinguish them. The essential reason is that measurements of an ensemble of random superpositions of eigenstates of the measured observable will induce more collapse of the wave function than measurements of an ensemble of random eigenstates of the measured observable and thus the former will cause stronger non-interferometric effects such as a stronger heating effect than the latter, although the two ensembles have the same statistical density matrix. Note that the above mechanism of superluminal signaling is still based on the stochastic nonlinear evolution of the wave function introduced in collapse theories, and it is not based on the definite nonlinear evolution of the wave function, which can lead to superluminal signaling when combining with wave-function collapse, as already demonstrated by several authors (Gisin, 1989, 1990; Polchinski, 1991; Czachor, 1991).

There are three possible ways to respond to the above result (when assuming the result is valid). The first way is to admit that collapse theories with energy nonconservation permits superluminal signaling and try to conduct new feasible experiments to test this result. Maybe few people will take this way. The second way is to build and test collapse models which satisfy the principle of conservation of energy (see Gao, 2013, 2017, chap.8 for an example). This may be an interesting direction of research for the proponents of collapse theories. However, it is possible that these models may also have other non-interferometric effects that can help realize superluminal signaling. This needs a further deep analysis. The third way is to take this result as a no-go result for collapse theories. Some opponents of collapse theories may choose this way.

It has been recently argued that the many-worlds interpretation of quantum mechanics (MWI) also violates conservation of energy (Carroll and Lodman, 2021). If this is true and this effect of energy nonconservation can also be measured, then it seems that we can also use this effect to realize superluminal signaling in MWI in a similar way as above. But I doubt that their result is valid, since the expectation value of energy cannot be measured for a single quantum system.

To sum up, I have argued that the effect of energy nonconservation in collapse theories of quantum mechanics can be used to realize superluminal signaling. It remains to be seen if one can formulate a collapse model which satisfies conservation of energy and avoids superluminal signaling.

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