Time's Arrow Points to Many Worlds

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August 15, 2021

Abstract

It is argued that when assuming the initial state of the universe is not a special low-entropy macro-state, but a general superposition of both low-entropy states and high-entropy states, the observed thermodynamic arrow of time will provide strong evidence for the existence of many worlds.

It is widely thought that in order to account for the observed thermodynamic arrow of time in the universe, one must assume that the entropy of the early universe is very low compared to the current entropy of the universe (Penrose, 1989; Price, 1996; Albert, 2000; Wallace, 2011; Callender, 2021). This assumption has been called the past hypothesis (Albert, 2000). However, the extreme low-entropy condition of the early universe is as a deep puzzle as the arrow of time (Penrose, 1989; Price, 2004; Callender, 2021). In this paper, I will argue that the past hypothesis is not necessary, and the initial state of the universe may be a general superposition of both low-entropy states and high-entropy states. In this case, the many-worlds interpretation of quantum mechanics (MWI) can still account for the thermodynamic arrow of time, although the single-world quantum theories cannot.

Let the state of the early universe at an initial instant t_0 be a superposition of macrostates with different entropy:

$$\Psi(t_0) = \sum_i a_i \psi_i^L + \sum_j b_j \psi_j^H \tag{1}$$

where ψ_i^L are low-entropy macro-states (that leads to the observed thermodynamic arrow of time), ψ_i^H are high-entropy macro-states (that does not lead to the observed thermodynamic arrow of time), a_i and b_j are the corresponding amplitudes, and they satisfy the normalization relation

$\sum_i |a_i|^2 + \sum_j |b_j|^2 = 1$. Note that with a proper definition of the macro-variable entropy,[1] the total Hilbert space of the early universe can be orthogonally decomposed into macro-spaces with definite entropy (and definite total energy being zero). The states ψ_i^L and ψ_j^H are certain normalized bases in these macro-spaces. The precise forms of these states are not relevant to my following analysis.

For the past hypothesis, we have $a_i = 1$ for a particular i, and $a_i = 0$ for all other i, and $b_j = 0$ for all j. This is a very special state in two senses. The first one is familiar. When considering the macro-states with definite entropy, most states in the state space of the early universe are high-entropy macro-states that are in thermal equilibrium. Then, if the initial state of the universe is randomly choosen from these states, then it will be typically a high-entropy macro-state. In other words, the initial state of the universe will be not the state in which $a_i = 1$ for a particular i, but the state in which $b_j = 1$ for a particular j. The second sense concerns the quantum nature of the initial state. If the initial state is randomly choosen from all superpositions of macro-states with definite entropy, then typically it will be not a macro-state with definite entropy, either high entropy or low entropy, but a superpositions of high-entropy macro-states and low-entropy macro-states in which most amplitudes a_i and b_j are not zero.

A further analysis may help find the most probable initial state of the universe. First, when assuming that no basis in the superposition (1) is special and they have the same contribution to the superposition, the squared amplitudes will be the same, namely $|a_i|^2 = |b_j|^2 = 1/d$ for all i and j, where d is the dimension of the total Hilbert space. It is possible that the values of the squared amplitudes have a small deviation from $1/d$, but a large deviation is in want of a reasonable explanation of why the corresopnding basis is very special. Next, since the total dimension of low-entropy macro-spaces is much smaller than the total dimension of high-entropy macro-spaces, which is close to the dimension of the total Hilbert space, we have $\sum_i |a_i|^2 \ll \sum_j |b_j|^2$, or $\sum_i |a_i|^2 \approx 0$ and $\sum_j |b_j|^2 \approx 1$.

This result is within expectation. In the classical case, the most probable initial state of the universe will be a high-entropy state. While in the quantum case, the most probable initial state of the universe will be a superposed state, the bulk of which are high-entropy macro-states, and the tails of which are low-entropy macro-states. In other words, the initial state of the universe is almost a high-entropy state, but with low-entropy tails.

In the following, I will analyze whether the observed thermodynamic arrow of time can be accounted for when assuming the universe begins with the suggested initial state.First of all, I will argue that decoherence occurs during the time evolution of almost all initial states of the universe. It is

[1] This is not easy to do for the early universe when considering gravity (Earman, 2006; Callender, 2009; Wallace, 2010).

usually thought that decoherence only occurs when there is room for entropy to increase (Wallace, 2012; Carroll, 2021). One reason is that "if a set of histories is decoherent then its time reverse is not." (Wallace, 2012, p.325) This reason is certainly true, but it arguably does not lead to the conclusion that decoherence depends on the increase of entropy. In my view, the issue is just like that in the case of the second law of thermodynamics. That if the entropy increases during a process then the entropy will decrease during the time reverse of the process does not imply the second law of thermodynamics is wrong. The key, as is well known, is to find the number of micro-states in the macro-spaces. In the case of decoherence, it is to find the number of states for decoherence and re-coherence. It is obvious that for a subsystem of the universe, the number of states of the environment for decoherence is much more than the number of states of the environment for re-coherence in general. For example, only if the states of all particles in the environment overlap in space, can re-coherence occur, while the probability of this situation occuring is extremely small. Then, by means of the same argument for the second law of thermodynamics, we will obtain a similar law for decoherence, which says that decoherence occurs for almost all initial states, no matter the entropy increases or decreases in the process.

Now I will first consider the single-world unitary quantum theories such as the de Broglie-Bohm theory. According to the Born rule, these theories will predict that the universe today will be in a high-entropy macro-state or in thermal equilibrium with probability very close to one, and it will be in a low-entropy macro-state with probability very close to zero. Note that each branch with definite entropy is also an eigenstate of the total Hamiltonian of the universe, and thus the modulus squared of the amplitudes corresponding to these branches do not change with time. Since there is only one universe and the prediction is for one event, this result is equivalent to say that the universe today will be in a high-entropy macro-state or in thermal equilibrium (see later for more analysis about the equivalence). This means that in single-world unitary quantum theories the observed thermodynamic arrow of time cannot be accounted for when assuming the universe begins with the suggested initial state.

Take the de Broglie-Bohm theory as an example. According to the theory, the Bohmian particles of the universe will reside in one high-entropy macro-state branch at the initial instant (this is the requirement of typicality), and they will stay in the branch later due to decoherence. Then, the de Broglie-Bohm theory will predict that the universe today will be in a high-entropy macro-state or in thermal equilibrium.

Next, consider the other type of single-world quantum theories, collapse theories. According to these theories, the initial superposed state will collapse to one high-entropy macro-state with tails much earlier than today with probability very close to one. Then, similar to the single-world unitary quantum theories, these theories also predict that the universe today will be in thermal equilibrium. Note that there are also solutions to the tails problem which admit the many worlds ontology but are not accepted by the proponents of collapse theories. In that case, the prediction of collapse theories will be the same as that of MWI (see below).

Lastly, consider MWI. As argued above, decoherence and branching will occur during the time evolution of the suggested initial state of the universe.[2] Thus, according to MWI, there will be many worlds today, in most of which the universe will be in thermal equilibrium, while there are still very small portion of these worlds in which the thermodynamic arrow of time can be observed as in our universe. This means that MWI can account for the observed thermodynamic arrow of time in our universe when assuming the universe begins with the suggested initial state. In this case, one may say that we are living in the tails of the wave function of the universe.

The above analysis may help answer a more general question: how can we test the different predictions of single-world quantum theories and MWI? Admittedly it is a very difficult task to do these tests in laboratories using currect technology. However, these tests may be possible by observing the state of the universe. The key is to notice that single-world quantum theories predict that our universe is typical, and it evolves from a high-amplitude decoherent branch of the initial universal wave function which has a large squared amplitude. While MWI predicts that our universe may be atypical, and it may evolve from a low-amplitude decoherent branch of the initial universal wave function which has a very small squared amplitude. In other words, in single-world quantum theories, the probability of our universe being atypical is close to zero, while in MWI this probability may be equal to one. Then, the observation of whether the universe is typical or atypical can be used to test these quantum theories.

Now increasing evidence shows that our universe is fine-tuned in many aspects (Friederich, 2018). If some of these fine-tuned properties come from the above atypicality, namely our universe indeed evolves from a low-amplitude branch of the initial universal wave function, then our observation of the these properties will strongly support MWI and disfavor the single-world quantum theories. Besides the thermodynamic arrow of time, the matter-antimatter asymmetry may be another example. It is possible that the initial universal wave function is a superposition of different particle numbers with various ratios of matter and antimatter, and the branches in which there are approximately equal amounts matter and antimatter have the largest squared amplitude close to one. Then our observation of the matter-antimatter asymmetry in the universe today will also favor MWI and disfavor the single-world quantum theories. These cosmological tests for MWI, if they are valid, are stronger than the quantum suicide thought

[2] Note that most high-entropy macro-state branches will be full of macroscopic black holes, and they are already quasi-classical.

experiment, in which the experimenter can only convince herself (not us) that MWI is true (Tegmark, 1998).

One may object that our universe may also be atypical, evolving from a low-amplitude branch of the initial universal wave function according to single-world quantum theories, and thus the above analysis is problematic. The key lies in how small the squared low-amplitude is. If the squared low-amplitude or the corresponding probability is $1/10$ or $1/10^2$ or even $1/10^{10}$, then we can say that our universe may evolve from such a low-amplitude branch or a similar event may occur in a single-world quantum theory. But when the squared low-amplitude or the probability of an event is as small as $1/10^{10^{123}}$ (Penrose, 1989; Carroll, 2014), then I think a reasonable person will admit that such events do not occur. Similarly, our universe cannot evolve from a low-amplitude branch whose squared amplitude is as small as $1/10^{10^{123}}$ in a single-world quantum theory. This is an example of Borel's Law, which says that events with a sufficiently small probability never occur.[3]

In addition, it is worth noting that if one does not accept this argument and holds that events with a non-zero probability can always occur and the occuring of such events is quite understandable, then any improbable initial state of the universe is normal and the thermodynamic arrow of time will be not a puzzle any more. This is against the widely accepted view.

Finally, I will briefly discuss the Boltzmann brain problem (Albrecht and Sorbo, 2004). My proposal for the initial state of the universe, unlike the past hypothesis, may be consistent with the existence of Boltzmann brains. In MWI, these Boltzmann brains may exist in the high-amplitude worlds, and it is also possible that we are Boltzmann brains living in these worlds. This means that if we are indeed Boltzmann brains, then my argument for MWI will be invalid. This is the Boltzmann brain problem for my proposal.[4]

One way to solve the problem is to argue that we are not Boltzmann brains. According to Norton (2015), we are most likely not Boltzmann brains, since the latter have chaotic memories of irregular pasts and equally chaotic beliefs about the veracity of ordinary memories (see also Carroll, 2017). Another way is to avoid the problem; the Boltzmann brain problem may not appear for other similar arguments relating not to entropy.

[3]Borel illustrated this law by referring to the classic example of the monkeys who happen by chance to produce the complete works of Shakespeare by randomly hitting the keys of a typewriter. In Borel's words: "Such is the sort of event which, though its impossibility may not be rationally demonstrable, is, however, so unlikely that no sensible person will hesitate to declare it actually impossible. If someone affirmed having observed such an event we would be sure that he is deceiving us or has himself been the victim of fraud." (Borel, 1962, p.3)

[4]Note that the past hypothesis also has the Boltzmann brain problem. If we are Boltzmann brains, then the hypothesis will be wrong. In fact, they are two mutually exclusive solutions to the puzzle of time's arrow; one concerns the initial condition, and the other concerns the dynamics.

For example, the dynamical fluctuations may not account for the matter-antimatter asymmetry of the universe today. In this case, a similar argument for MWI based on the matter-antimatter asymmetry, if it is valid, is not plagued by the Boltzmann brain problem; even if we are Boltzmann brains, our observation of the matter-antimatter asymmetry in the universe today still favors MWI.

To sum up, I have argued that the initial state of the universe may be a general superposition of both low-entropy states and high-entropy states. In this case, the many-worlds interpretation of quantum mechanics (MWI) can still account for the thermodynamic arrow of time, although the single-world quantum theories cannot.

Acknowledgments

I am grateful to Jeff Barrett, Sean Carroll, Don Page and Paul Tappenden for helpful discussion. This work is supported by the National Social Science Foundation of China (Grant No.16BZX021).

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