On the Initial State of the Universe

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Abstract

It is argued that the initial state of the universe is neither a high-entropy equilibrium state nor a special low-entropy state, but a quantum superposition of high-entropy states and low-entropy states, and the sum of the squared amplitudes of the low-entropy states is most likely close to zero. In this case, the thermodynamic arrow of time in our universe can still be accounted for by the many-worlds interpretation of quantum mechanics. This provides a new solution to the puzzle of the arrow of time.

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 propose a new solution to the puzzle of the arrow of time. It is argued that the initial state of the universe is neither a high-entropy equilibrium state nor a special low-entropy state, but a quantum superposition of both high-entropy states and low-entropy states. In this case, the many-worlds interpretation of quantum mechanics (MWI) can still account for the observed thermodynamic arrow of time in our universe, although the single-world quantum theories can hardly do.

In classical statistic mechanics, a particle has definite position and momentum, and thus a system composed of classical particles is in one definite point in the phase space at each instant, and its macro-state also has definite entropy, either high or low, depending on the values of certain macroscopic quantities such as the total energy, total number of particles and total volume of the system. Since quantum mechanics is different from classical mechanics, there are two quantum effects in quantum statistic mechanics. The first one is related to quantization or the uncertainty principle for position and momentum, which requires that there are minimal $\Delta x \Delta p$ cell in the phase space. The second one is related to identical particles, which leads to the Fermi-Dirac statistics or the Bose-Einstein statistics, rather than the Maxwell-Boltzmann statistics in classical statistic mechanics.

However, few people has noticed that there is a third quantum effect, which, as we will see, may be important when analyzing the thermodynamic arrow of time in our universe. As we know, for a system of classical particles dominated by gravity, the natural, high-entropy states are clumpy states in which the gravitational force has caused the particles to aggregate together in lumps, while the states in which the particles have a homogenous and even distribution in space are special and they have low entropy (Price, 1996). In quantum statistic mechanics, since the wave function of each particle spreads throughout the whole space in general, the clumpy states cannot have definite entropy, and it must be a superposition of high-entropy states and low-entropy states in which the sum of the squared amplitudes of low-entropy states is close to zero, or in other words, it must be a superposed high-entropy state with low-entropy tails.

Let the state of the early universe at an initial instant t_0 be a general 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 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 classical and familiar. When considering the classical macro-states with definite entropy, most states in the state space of the early universe are high-entropy 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 state, not a low-entropy state. In other

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

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 one concerns the quantum nature of the initial state we have discussed. 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 superposition of high-entropy states and low-entropy states in which most amplitudes a_i and b_j are not zero. Moreover, since the total dimension of low-entropy macro-spaces is much smaller than the total dimension of high-entropy macro-spaces, 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 is the most probable initial state of the universe.

In the following, I will analyze whether the observed thermodynamic arrow of time can be accounted for when assuming the universe begins with the most probable initial state, namely a superposed high-entropy state with low-entropy tails.[2] First, consider the single-world unitary quantum theories such as the de Broglie-Bohm theory. According to the Born rule, these theories predict that the universe today will be in a high-entropy, equilibrium state with probability very close to one, and it will be in a low-entropy 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. This result means that in single-world unitary quantum theories the observed thermodynamic arrow of time can hardly be accounted for when assuming the universe begins with a superposed high-entropy state with low-entropy tails.

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 branch at the initial instant (this is the requirement of typicality), and they will stay in the branch later due to the separation of different entropy branches in configuration space with time. Then, the de Broglie-Bohm theory predicts that the universe today will be in a high-entropy, equilibrium state.

Next, consider the single-world non-unitary quantum theories or collapse theories. According to these theories, the initial superposed state will collapse to a high-entropy state 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 with probability very close to one. Note that there are also solutions to the tails problem of collapse theories which admit the many worlds ontology but are not accepted by the proponents of collapse theories. In that

[2]According to the above analysis, no matter what the initial quantum state of the universe is, it must contain the low-entropy branches. As we will see below, this is enough for solving the puzzle of the arrow of time.

case, the prediction of collapse theories will be the same as that of MWI (see below).

Lastly, consider the many-worlds theory or MWI. According to MWI, there will be many worlds today, in most of which the universe will be in thermal equilibrium. But there are still very small portion of these worlds, in which the universe begins with an extreme low-entropy condition and there are a thermodynamic arrow of time and observers in this universe today, just as the past hypothesis assumes and tries to explain. This means that MWI can account for the observed thermodynamic arrow of time in our universe when assuming the universe begins with a superposed high-entropy state with low-entropy tails. In this case, one may say that we are living in the tails of the wave function of the universe. Note that due to the separation of different entropy branches in configuration space with time, the decoherence and branching happening in the low-entropy tails are enough for explaining our quasi-classical world.[3]

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 most likely evolves from a high-amplitude branch of the initial universal wave function. While MWI predicts that our universe may be atypical, and it may evolve from a low-amplitude branch of the initial universal wave function. In other words, according to single-world quantum theories, the probability of our universe (evolving from the early superposition) being atypical is close to zero. But according to MWI, the probability of our universe (evolving from the early superposition) being atypical may be one.[4] This probability is equal to the probability of existence of atypical universes multiplied by the probability of us living in an atypical universe today. The former probability is one, and the latter probability is also one if we are living in an atypical universe today. Then, 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 these properties will support MWI and disfavor the single-world quantum theories. Besides the thermodynamic arrow of time, the matter-antimatter asymme-

[3]Note that most high-entropy branches will be full of macroscopic black holes, and they are also quasi-classical.

[4]It is worth emphasizing that the probability here is different from the probability of an observer obtaining a certain result after a measurement, which is close to zero for an atypical result.

try might 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.[5]

To sum up, I have argued that the initial state of the universe is a superposition of high-entropy states and low-entropy states, and the sum of the squared amplitudes of the low-entropy states is most likely close to zero. In this case, although the single-world quantum theories can hardly account for the observed thermodynamic arrow of time in our universe, the many-worlds interpretation of quantum mechanics can do. It remains to be seen if this new solution to the puzzle of the arrow of time is complete and fully satisfyinng.

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References

[1] Albert, D. Z. (2000). Time and chance. Harvard University Press.

[2] Albrecht, A. and Sorbo, L. (2004). Can the universe afford inflation? Phys. Rev. D 70, 063528.

[3] Callender, C. (2009). The past hypothesis meets gravity. In G. Ernst and A. Hutteman (Eds.), Time, Chance and Reduction: Philosophical Aspects of Statistical Mechanics, Cambridge. Cambridge University Press. Available online at http://philsci-archive.pitt.edu/archive/00004261.

[4] Callender, C. (2021). Thermodynamic Asymmetry in Time. The Stanford Encyclopedia of Philosophy (Summer 2021 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/sum2021/entries/time-thermo/.

[5]Note that this argument for MWI, unlike the argument based on the thermodynamic arrow of time, is not plagued by the Boltzmann brain problem (Albrecht and Sorbo, 2004; Norton, 2015; Carroll, 2017); the dynamical fluctuations may not account for the matter-antimatter asymmetry of the universe today, and even if we are Boltzmann brains, our observation of the matter-antimatter asymmetry in the universe today still favors MWI.

[5] Carroll, S. M. (2014). In what sense is the early universe fine-tuned? arXiv:1406.3057.

[6] Carroll, S. M. (2017). Why Boltzmann Brains Are Bad. arXiv:1702.00850.

[7] Earman, J. (2006). The past hypothesis: not even false. Studies in History and Philosophy of Modern Physics 37, 399-430.

[8] Friederich, S. (2018). Fine-Tuning. The Stanford Encyclopedia of Philosophy (Winter 2018 Edition), Edward N. Zalta (ed.), https://plato.stanford.edu/archives/win2018/entries/fine-tuning/.

[9] Norton, John D. (2015) You are not a Boltzmann brain. http://philsci-archive.pitt.edu/17689/.

[10] Penrose, R. (1989). The Emperor's New Mind: concerning computers, brains and the laws of physics. Oxford: Oxford University Press.

[11] Price, H. (1996). Time's Arrow and Archimedes' Point. Oxford: Oxford University Press.

[12] Price, H. (2004). On the Origins of the Arrow of Time: Why There is Still a Puzzle about the Low-Entropy Past. in Christopher Hitchcock (ed.), Contemporary Debates in the Philosophy of Science, Oxford: Blackwell, 219-232.

[13] Wallace, D. (2010). Gravity, Entropy, and Cosmology: In Search of Clarity. British Journal for the Philosophy of Science, 61, 513-540.

[14] Wallace, D. (2011). The logic of the past hypothesis. http://philsci-archive.pitt.edu/8894/.