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МОЖЕТ ЛИ ВСЕЛЕННАЯ БЭРРОУ СТАТЬ ПРОТИВОЯДИЕМ ОТ КОСМОЛОГИЧЕСКИХ СИНГУЛЯРНОСТЕЙ?

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Работа посвящена приложению метода квантования многих взаимодействующих миров (MIW), предложенному М. Холлом, Д.-А. Декертом и Г. Вайзманом в работе [1] к решению старой проблемы космологических сингулярностей. В работе приведён краткий экскурс в историю вопроса теории Де Бройля-Бома, её развития в формализме MIW и приложение этого формализма к фридмановской космологии в виде модели многих взаимодействующих вселенных (MIU). Далее, используя рассуждения Д. Бэрроу о физичности нулевых решений уравнения Фридмана $a(t) = \dot{a} = 0$ мы приходим к необходимости учёта таких решений в подходе MIU, который в свою очередь приводит к теореме о запрете возникновения космологических сингулярностей вида $a \to 0$ для всех остальных (ненулевых) фридмановских вселенных при выполнении некоторых физически осмысленных условий. Также приведены несколько простых примеров, иллюстрирующих эту Теорему.

Ключевые слова: космология, квантовая механика, теория де Бройля-Бома, теория многих взаимодействующих миров, нулевая вселенная Бэрроу.

COULD THE BARROW UNIVERSE BE AN ANTIDOTE FOR COSMOLOGICAL SINGULARITES?

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The article is dedicated to the Many Interacting Worlds (MIW) quantization approach, initially proposed by M. Hall, D.-A. Deckert and H. Wiseman in [1], as it is applied to the old problem of emergent cosmological singularities. We begin by discussing the history of de Broglie-Bohm theory and its evolution into the MIW formalism, followed by the direct application of MIW approach to Friedman cosmology in the model of Many Interacting Universes (MIU). After that we recall John D. Barrow's idea about the physical nature of zero solutions $a(t) = \dot{a} = 0$ for the Friedman equations and surmise the necessity for including such solutions into the framework of MIU. This works like a charm, as it directly leads to the Theorem 1 which, under some physically sensible assumptions, prohibits the remaining Friedman cosmological solutions from reaching zeroes, thereby preventing the formation of cosmological singularities. In conclusion we discuss some exact solutions to illustrate the aforementioned Theorem.

Keywords: cosmology, quantum mechanics, de Broglie-Bohm theory, Many Interacting Worlds interpretation, Barrow zero universe.

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Introduction

In this article we are going to tackle an old problem of cosmological singularities. Ever since the initial foray into the General Relativity by Karl Schwarzschild [2] has decidedly placed the gravitational singularity (located in the center of what we now call Schwarzschild black hole) on the map of contemporary physics, the scientists have been trying to understand them – and, if possible, eliminate. These attempts were made even more pertinent after the discovery of cosmological singularities of Big Bang/Big Crunch by Alexander Friedman [3] and George Lemaître [4] in the 1920-s. Coupled with the discovery of the Hubble law in 1929 [5] (see also [6]), the conclusion reached by the cosmologists was unmistakable: the very early observable universe must have been extremely dense and had a scale factor $a \to 0$ around 13.8 billion years ago. All attempts to avoid this conclusion, such as the controversial model of steady-state universe by Hermann Bondi, Thomas Gold and Fred Hoyle [7], [8], were ultimately unsuccessful in explaining the observable astronomical phenomena (most importantly the cosmic microwave background radiation). It was looking more and more likely that the gravitational singularities were all but unavoidable. Eventually, the set of theorem proved by Roger Penrose and Steven Hawking and collectively known as Penrose–Hawking singularity theorems [9], [10], [11] have confirmed these growing suspicions: the singularities were firmly established as being here to stay. However, a set of very recent discoveries and developments in our understanding of quantum mechanics might reopen this old question for reexamination. In particular, in this article we will demonstrate that the new approach to quantization dubbed the Many Interacting Universes model [1], coupled with an interesting hypothesis of late John Barrow and under some natural physical assumptions, ensures that the cosmological solutions to the Friedman-Lemaître-Robertson-Walker equations will be completely devoid of cosmological singularities.

The article is structured as follows: we begin Sec. 1 by discussing the classical de Borglie-Bohm (dBB) interpretation of quantum mechanics, followed by introduction of the Many Interacting Worlds approach and its relationship to both the dBB and the Many-Worlds interpretation. After that we proceed to Sec. 2, where the MIW formalism is applied to cosmology in the shape of Many Interacting Universes (MIU) model [12]. Finally, in Sec. 3 we add the final ingredient, the Barrow zero universe [13], and then proceed to formulate the Main Theorem 1. We conclude by discussing three analytic examples aimed at illustrating the key result of the Theorem.

1. From de Broglie-Bohm interpretation to the Many Interacting Worlds approach

One of the most perplexing problems one encounters while studying the elusive quantum phenomena is simply a question of interpretation. While the mathematical foundations of the quantum mechanics are well understood – and have been ever since late 1930-s – the question of the actual *physical explanation* of said mathematics remains a hotly contested area. The earliest interpretation, developed by Niels Bohr, refuses to allot physical meaning to spin, momentum and coordinate of a particle unless a classical measurement is performed, thereby *collapsing* a wave function of said quantum particle and turning it into a classically comprehensible one. This approach, dubbed a Copenhagen interpretation by Werner Heisenberg [14], while providing correct predictions pertaining to the behavior of particles, loses its clarity when we include the macroscopic objects, leading to such bizarre ideas as that of a Schrödinger's cat [15] or the paradox of Wigner's friend [16]. The first physicist who proposed a way to dispense with the troublesome concept of wave function's collapse, was Louis de Broglie, who proposed that the complex-valued wave function $\psi = P^{1/2} \cdot \mathrm{e}^{iS}$ of a given quantum particle with mass m must be treated as a physical field, upon which the momentum $\vec{p}$ of said particle explicitly depends, i.e. that $\vec{p} = m\vec{v}(\psi)$. If we then use such properties of the solutions of Schrödinger equation as: 1) invariance w.r.t multiplication by a constant, 2) invariance w.r.t. simultaneous transformations $t \to -t$ and $\psi \to \psi^*$, and 3) Galilean invariance, we'll arrive at the following relationship [17]:

$$\vec{p} = \nabla S, \tag{1}$$

a time derivative of which produces a very interesting equation

$$\dot{\vec{p}} = \nabla S_t = -\nabla V - \nabla\left(-\frac{\hbar^2}{2m}\,\frac{\Delta P^{1/2}}{P^{1/2}}\right) = -\nabla V - \nabla Q, \tag{2}$$

where V is the classical potential. In other words, we have a standard second Newton's Law with an additional *quantum potential* Q. These calculations can also be performed for a set of K particles, aptly called a *world-particle*, which can be shown to satisfy the $3K$-dimensional analogue of (2). This observation is now known as the de Broglie-Bohm interpretation, which states that the quantum mechanics can be completely reduced to a classical Newtonian physics with an additional all-pervasive quantum potential Q. It is this quantum potential that distorts the trajectories of the particles, which in turn gives rise to all known quantum phenomena.

Of course, de Broglie-Bohm interpretation has its own set of problems, most important of which is the seeming detachment of field Q from the actual particles it controls. What could be a possible source of this field? This question remained unanswered for almost ninety years, until in 2014 M. Hall, D.-A. Deckert and H. Wiseman have found a way to marry the de Broglie-Bohm approach with the Everett's Many World Interpretation [1]. Their idea was very simple and goes like this: since by de Broglie-Bohm the quantum behavior of a particle (or a world-particle) can be explained by existence of a certain force, the particle must interact with something external to it. The Many World Interpretation postulates that every physical observation produces multiple version of our particle/world-particle, and that they don't interact with each other after the observation. But what if they actually *do* interact, and it is this interaction that we interpret as the de Broglian potential?.. Indeed, consider an ensemble of N particles/world-particles, serving as doppelgangers of each other, and then assume that these world-particles interact with each other. This interaction will manifest itself as a new potential – which would immediately explain what the quantum potential is. Furthermore, since we do not know which world-particle of this ensemble is ours, we must have a probability distribution, which for sufficiently large N should converge to the known function P. Using this idea it is easy to show that the actual *quantum interaction potential* for an ensemble of N copies of a particle with mass m must have a form [1]:

$$U_N \approx \sum_{j=1}^{N} \frac{\hbar^2}{8m}\left|\frac{\nabla P(\vec{x}_j)}{P(\vec{x}_j)}\right|^2, \tag{3}$$

where $\vec{x}_j$ stands for a position of j-th particle from the ensemble. This formula gets much simpler if we consider a one-dimensional case, where the particles are ordered by their positions: $x_1 < x_2 < x_3 < ... < x_N$: in this case (3) turns into [1]:

$$U_N = \frac{\hbar^2}{2m}\sum_{j=1}^{N}\left(\frac{1}{x_{j+1}-x_j} - \frac{1}{x_j - x_{j-1}}\right)^2, \tag{4}$$

where for the sake of simplicity we have introduced auxiliary parameters $x_0 = -\infty$ and $x_{N+1} = +\infty$. This formula can be shown to converge to the quantum potential Q from (2), and it has a number of very interesting consequences. It describes a new repulsive potential which gets stronger the closer the copies of the particles gets together – and quickly vanishes when said copies depart, thus explaining why the quantum effects (all of them controlled by U_N!) are so fragile and fleeting. It also shows that, contrary to Copenhagen interpretation, whether or not an object might behave quantum-mechanically is determined not by its *size*, but by the amount of degrees of freedom the object has: the fewer there are, the higher would be the chance that a least one of its doppelgangers gets close enough in the phase space for the potential U_N to get physically relevant. And, in fact, there exists a class of macroscopic objects that are uniquely designed to feel such a potential: the Friedman universes!

2. Cosmology steps in: Many Interacting Universes model

We have shown in [12] that it is indeed very easy to add a quantum interaction to the Friedmann-Lemaître-Robertson-Walker (FLRW) equations. Consider a homogenous isotropic universe with a curvature $\kappa = 0, \pm 1$, filled by fields of matter with density ρ and pressure p. Such a universe lies in thrall of a single parameter – scale factor a, which satisfies the FLRW equations:

$$\begin{aligned} \ddot{a} &= -\frac{1}{2}\left(\rho + \frac{3p}{c^2}\right)a, \\ \frac{\dot{a}^2}{2} - \frac{4\pi G}{3}a^2\rho &= -\frac{\kappa c^2}{2}, \end{aligned} \tag{5}$$

hereby making it a perfect target for a *quantum interaction.* To figure out how it will manifest itself in FLRW, we shall use the same approach as in [1]. First, we assume that there exists a set of N universes with scale factors a_n, which are scale factor-ordered: $a_1 < a_2 < ... < a_N$. Next, we upgrade a Hamiltonian of a system of many interacting universes (MIU) by adding the potential of quantum interaction U:

$$\begin{aligned} \mathcal{H}_N = &\sum_{n=1}^{N} \frac{\mathbf{p}_n^2}{2} - \frac{1}{2}\sum_{n=1}^{N} \rho_n(a_n)a_n^2 + \\ &+ U(a_1, .., a_N) + \frac{1}{2}\sum_{n=1}^{N} \kappa_n = 0, \end{aligned}$$

The quantum interaction potential will be of a familiar form:

$$U(a_1, .., a_N) = \alpha^2 \sum_{n=1}^{N} \left(\frac{1}{a_{n+1} - a_n} - \frac{1}{a_n - a_{n-1}}\right)^2, \tag{6}$$

where $a_0 = a_{N+1} = \infty$ and the constant $\alpha^2 = 8\pi\hbar G/3c = (L_{PL}c)^2$ [12]. Using inverse Legendre transform, we then derive the Lagrangian, which could then be plugged into the Euler-Lagrange equation. This results in a newly modified Friedmann equations:

$$\ddot{a}_n = -\frac{1}{2}(\rho_n + 3p_n)a_n - (L_{PL}c)^2 \frac{\partial}{\partial a_n} \sum_{k=1}^{N} \left(\frac{1}{a_{k+1} - a_k} - \frac{1}{a_k - a_{k-1}}\right)^2, \tag{7}$$

plus an additional constraint:

$$\sum_{n=1}^{N} \left(\frac{1}{2}\dot{a}_n^2 - \frac{4\pi G}{3}\rho_n a_n^2 + \frac{c^2}{2}k_n\right) + (L_{PL}c)^2\, U(a_1, ..., a_N) = 0, \tag{8}$$

The equation (7) describes the dynamics of N interacting universes which in the semi-classical limit $L_{PL} \to 0$ reduces to N classic FLRW equations. It has, however, one peculiarity: there is nothing to prevent the solutions of (7) from becoming singular (i.e. approach the limit $a_i \to 0$) with *no growth in the quantum potential*, simply because there happen to be no doppelganger universes in a sufficiently close neighborhood at the moment. This is a problem, because the phase directly preceding the cosmological singularity is the one when the universe should start experiencing the effects of quantum gravity – in other words, the quantum potential must necessarily become larger the closer we get to the singularity. One possible solution to this conundrum was proposed in [12], where we have assumed that (at least in the vicinity of cosmological singularity) the scale factors of all universes must be proportional to each other: $a_i(t) = \mu_i\ a(t)$ for $\forall i$, where the universal (or *multiversal*) function $a = a(t)$ is what we have called a *master-factor* and $\mu_i > 0$. This allowed us to derive a number of interesting solutions for (7), (8) where the quantum interaction with other universes produced the effects similar to those produced by dark matter and dark energy [12]. However, a question remained on the actual necessity of this *ad hoc* assumption and on whether or not it might be bypassed. Interestingly, a possible way to do this has been proposed in one of the last articles of late great John Barrow [13], in which he argued for the necessity of existence of very strange solutions he has dubbed "zero universes".

3. Barrow zero Universe to the rescue: The Main Theorem

John Barrow in [13] has pointed an existence of a number of often neglected analytic solutions for the FLRW equations (5) – particularly those that describe a stationary universe with $a = \dot{a} \equiv 0$ – and has argued that we must take such solutions into account if we are at all serious about accepting the FLRW equations themselves. We would not go deep into the core of Barrow's arguments – but for the purposes of this article we must point out the if his hypothesis is correct, then the MIU formalism will require us to add such a universe to a general ensemble of interacting universes as a first (leftmost) universe with $a_1 \equiv 0$. Once added, it is possible to show that (under some simple assumptions) such a universe would act as a deterrent to the collapse of the remaining ensemble! To be more precise, a following theorem can be proven (the proof is rather direct and is therefore left for the reader):

Theorem 1 *Consider an ensemble of N ordered universes with scale factors $\{a_n\}_{n=1}^N$, interacting with each other via the quantum potential* (6) *as satisfying the following conditions:*

1. *At some time $t = t_0$ (for simplicity we will henceforth assume that $t_0 = 0$) the values of all scale factors of the universes are ordered according to their index numbers:*

$$a_n(0) > a_{n-1}(0).$$

2. *The first (and therefore the smallest) universe in the ordered list of scale factors $\{a_n\}$ is the Barrow's zero-universe with:*

$$a_1(t) = \dot{a}_1(t) = 0, \qquad \forall\, t. \tag{9}$$

3. *The second universe with a scale factor a_2 is an entirely quantum universe containing no fields of matter:*

$$\rho_2 = p_2 = 0. \tag{10}$$

4. *The fields of matter in the rest of the universes with $n > 2$ satisfy the standard energy conditions employed in the theorems about the singularities [11]. In particular, we assume that ρ_n has but one special point that occurs only when $a_n \to 0$.*

Then the solutions of the system (7) *and (8) are strictly positive for all $n > 1$.*

In other words, by adding a single ingredient, a "zero universe", we can actually remove any threat of standard cosmological singularities; the second ("quantum") universe with $\rho = p = 0$ serves as a "damper" for a special case when the parameter of state $w > 1/3$ in at least one of the universes in the ensemble, and can otherwise be dispensed with. Thus, the prediction of Theorem 1 can be easily tested on simple models containing just 2 or 3 universes. For example, if an ensemble consists of just two universes: a Barrow zero universe and a universe filled by the baryon matter (a.k.a. the "dust") with $\rho(x) = D^2/x^3$ (in this case $w = 0$ and we can omit the third assumption of Theorem 1), we'll get the following three singularity-free cases:

(i) A closed model, $k = +1$. The exact solution has the form

$$\begin{aligned} x(\eta) &= \mu + \sqrt{\mu^2 - 4L_{PL}^2}\,\sin\eta, \\ t(\eta) &= t_0 + \frac{1}{c}\left(\mu\eta - \sqrt{\mu^2 - L_{PL}^2}\,\cos\eta\right), \end{aligned} \tag{11}$$

with $\mu = 4\pi G D^2/(3c^2)$. If we take a limit at $\hbar = 0$, this solution turns into a familiar Friedman solution for a closed universe filled with dust. In general, though, our solution contains no final singularity; instead, it describes an eternally oscillating universe with periodic rebounds occurring at $\eta = -\pi/2 + 2\pi m$ followed by the stages of expansion lasting until $\eta = \pi/2 + 2\pi m$. The maximal expansion of the universe is $x_{max} = \mu + \sqrt{\mu^2 - L_{PL}^2}$ and the minimal possible value for the scale factor is $x_{min} = \mu - \sqrt{\mu^2 - L_{PL}^2}$. It is also interesting to note that the period of oscillations does not depend on L_{PL}^2 and is equal to $2\mu\pi/c$.

(ii) An open model, $k = -1$. In this case the solution has the following parametric form:

$$x(\eta) = \sqrt{\mu^2 + 4L_{PL}^2}\cosh\eta - \mu,$$
$$t(\eta) = t_0 + \frac{1}{c}\left(\sqrt{\mu^2 + L_{PL}^2}\sinh\eta - \mu\eta\right). \qquad (12)$$

At $L_{PL} = 0$ (12) we again get a well-known Friedman solution and it is singular at $t = t_0$ ($\eta = 0$); it no longer is if $L_{PL} > 0$.

(iii) A flat model, $k = 0$:

$$\pm t = t_0 + \sqrt{\frac{2}{\mu c^2}}\left(\frac{1}{3}\left(x - \frac{2L_{PL}^2}{\mu}\right)^{3/2} + \right.$$
$$\left. + \frac{6L_{PL}^2}{\mu}\left(x - \frac{2L_{PL}^2}{\mu}\right)^{1/2}\right). \qquad (13)$$

Once again, (13) has no singularities ($x_{\min} = 2L_{PL}^2/\mu$), and at $2L_{PL} = 0$ reduces to a familiar solution: $x \propto t^{2/3}$.

Conclusion

We have discussed how the novel approach to quantization due to Hall, Deckert and Wiseman, applied to the cosmology at large and coupled with a commonly neglected trivial solution to Friedman equation (a.k.a. the Barrow zero universe) produces a starkly unexpected result: a cosmological multiverse of many interacting universes might completely lack standard cosmological singularities of Big Bang and Big Crunch. We would like to emphasize here, that this result does not require any new exotic fields of matter or any additional assumptions aside from the physically sensible ones. There are, of course, two interesting questions that we haven't touched in this article: first of all, whether or not the solutions we have constructed are perturbative with respect to $\hbar$ (in our case to L_{PL})? Secondly, is it possible for the Theorem to remain effective if we lift some of the restriction in Theorem 1, imposed upon the fields of matter? And, while we are on the subject, can our model prevent some other types of singularities, such as Big Rip? We believe that the answers to all of this question are positive, and they will both be addressed in the follow up article.

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