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EMERGENCE OF CLASSICAL TIME FROM A UNIVERSAL WAVE FUNCTION

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Abstract: The concepts of time, entropy and observation are discussed on the basis of Hawking's universal wavefunction. I conclude that there is no observable reversal of cosmic expansion.

Hawking's recent suggestion of a simple symmetric initial condition for the quantum state of the universe [1,2] has caused broad interest in quantum gravity. Although the general formalism of quantum gravity has been thoroughly studied since the pioneering work of DeWitt [3], the deep problems of its interpretation, which have been emphasized especially by Wheeler [4], still prevail. Most important among them are the lack of an external concept of time and of an external observer or measurement device required for the conventional probability interpretation. Another fundamental problem that may be decidable on the basis of Hawking's proposal is that of the relation between the thermodynamic and cosmologlcal arrows of time [5]. These, in turn, seem to be connected with the time arrow of quantum measurement and the reduction of the state vector [6].

The Schrödinger equation for a closed quantum universe, the Wheeler-DeWitt equation [3,4], being of the form $H\psi = 0$, turns out to be of the hyperbolic type. This allows the formulation of an initial value problem with respect to an intrinsic (dynamical) time-like variable. Explicit models so far have been based on mini superspace, the two-dimensional configuration space of an isotropic and homogeneous universe classically described by the expansion parameter $a(t)$ and a massive scalar field $\phi(t)$.

This model may be called ”quantum-friedmannian”, a property essentially distinguishing it from our (supposedly) approximately ”macro-friedmannian” universe. The difference might become clear on comparing a macroscopic, spherically symmetric body with an intrinsically symmetric microscopic object, such as a spherical nucleus. The former shows rotational motion with moments of inertia given by its mass distribution, while the latter cannot rotate around any symmetry axis, reflecting a vanishing moment of inertia, as its intrinsic state is an eigenstate of the unitary symmetry transformations. In fact, the concept of *intrinsically* deformed nuclei (in particular for states of zero angular momentum) presented problems even to some of the founders of quantum theory, as reported by their discoverer, Hans Kopfermann [7]. Angular momentum eigenstates of nuclei or molecules can be constructed from deformed states as superpositions of their different orientations [8]. In particular, spin-zero states are totally symmetric in spite of describing correlations in orientation between the individual nucleons. Macroscopic objects, however, will unavoidably be “measured” by their environment, and in this way become correlated with it, and potentially with some final observer. This correlation with the environment will locally destroy all coherence between different orientations [9], while correlation with the observer corresponds to what is usually considered the reduction (collapse) of state into a certain (“classical”) orientation [10]. If one could imagine an observer inside an intrinsically deformed nucleus, he would necessarily be correlated with “his” nucleus and therefore experience its orientation in an angular momentum wave packet representing the intrinsic state (its “relative state” with respect to his own state).

This picture may form an appropriate analogy for interpreting the wave function of our universe. Hawking’s state vector is a superposition of essentially all possible spacetime geometries correlated with certain matter wave functions. Joos [11] recently argued that matter measures curvature very efficiently, in this way assuming the role of an environment to spacetime geometry. The same is true for possible intrinsic properties (symmetry transformations) of the vacuum. Curvature must therefore not be regarded as a separate, unitarily evolving quantum system. It should instead obey some kind of master equation, as described in Ref. [9] for other macroscopic systems. Such (with respect to the time-like expansion parameter a) irreversible dynamics may be readily derived in lowest approximation from the linear coupling of higher multipoles of matter and geometry on the Friedmann three-sphere to the minisuperspace variables. According to Halliwell and Hawking [12], the corresponding wavefunction may be conveniently written as

$$\psi(a,\phi,\{x_n\}) = \psi_0(a,\phi)\prod_{n>0} f_n(a,\phi;x_n) \quad , \tag{1}$$

where $\psi_0(a,\phi)$ is the minisuperspace solution, and x_n represents the amplitudes of all n-th multipoles. Hawking's initial condition requires the multipoles to start out of their ground states $f_n^{(0)}(x_n)$,

$$f_n(a,\phi;\{x_n\}) \approx f_n^{(0)}(x_n) \quad \text{for small a} \quad . \tag{2}$$

Growing amplitudes x_n are understood as indicating increasing entropy [5].

The universal wave function appears to have been interpreted by most authors so far as describing probabilities for classical paths of the WKB approximation or their corresponding wavepackets [12,13]. However, the concept of a universal wavefunction is a hypothetical though natural [10] extrapolation from conventional quantum theory, and its interpretation should thus follow the conventional interpretation as much as possible. Hence, a classical path (for example in mini superspace) should arise by "continuous measurement", just as is the case with an α-particle track in a Wilson chamber [14]. "Continuous" can here only refer to the intrinsic time variable a. The mini superspace density matrix derived from (1) reads

$$\begin{aligned}\rho(a,\phi;a',\phi') &= \mathrm{Tr}_{\{x_n\}}|\psi\rangle\langle\psi| \\ &= \psi_0(a,\phi)\psi_0^*(a',\phi')\prod_{n>0}\int dx_n f_n^*(a',\phi';x_n) f_n(a,\phi;x_n) \quad ,\end{aligned} \tag{3}$$

where $\mathrm{Tr}_{\{x_n\}}$ means partial trace with respect to all multipoles $n>0$. For small a and a' the integrals give unity, but for growing a or a' they are smaller than one except for $a=a'$ and $\phi=\phi'$. Because of the large number of multipoles, the product then approaches a narrow gaussian,

$$\rho(a,\phi;a',\phi') \approx \psi_0(a,\phi)\psi_0^*(a',\phi')\, \mathrm{e}^{-\mathrm{k_a}(\mathrm{a}-\mathrm{a}')^2}\mathrm{e}^{-\mathrm{k}_\phi(\phi-\phi')^2} \quad , \tag{4}$$

with k_a and k_ϕ growing with a. Therefore, no interference between different values of "cosmological time" a or background field ϕ can be observed by a material observer. These quantities appear classical except "for very small age (size)" of the universe (already a classical notion). This may render the factor ordering problem [3] irrelevant for this purpose. The model is of course still unrealistic in not describing the important "measurement" of higher curvature multipoles by matter [11], since the multipoles are here assumed not to interact. It would require the complete four geometry to define proper times along the spacetime orbits of all local material systems (such as clocks and observers).

Hawking's wavefunction is extended over all minisuperspace, although causal relationships travel essentially along classical paths, thereby defining classical histories for a and ϕ, wherever the WKB approximation is valid. If the minisuperspace dynamics were unitary, this would allow classically travelling wavepackets. As Page has pointed out [13], the individual paths need not be time symmetric even though the total wavefunction is. In addition, the wavepackets would spread in one or the other direction of the orbit, depending on their construction.

However, this appears quite irrevelant for a consistent quantum interpretation as, for example, that due to Everett [15]. In particular, it would not be meaningful to extend classical paths beyond the WKB region, where they all become causally connected with one another. If the wavefunction may still be understood as a probability amplitude, there are probabilities *for* cosmological time a - not probabilities *in* time. Hence there is no issue of probability conservation for the total wavefunction [16], and the concept of "tunneling" loses its conventional meaning.

Eq. (4) means that probabilities for other quantities (described by their corresponding eigenfunctions or wavepackets) are meaningful only if conditioned to "given" values of a and ϕ. In particular, the Laplace transform of $\psi(a, \phi)$ by itself is meaningless. These conditioned probabilities do not define a direction of classical paths, because there is no external time. If observers (in some yet unspecified sense) occur with some probability, they should only remember their "past" (corresponding to smaller values of a) as a consequence of the thermodynamical arrow contained in the universal wavefunction. For the same reason, Everett's "branching" of the state vector – correponding to a "reduction" or "collapse", and describing the information gain of an observer, should become more fine-grained with increasing complexity of the conditioned wavefunction (hence with increasing a), because of the fundamental locality of an observer [6,17,18]. The wavepackets in configuration space which describe classical worlds are not fixed (evolving unitarily with respect to a), but are created by the ongoing reduction or branching [9]. If the direction of the orbits were kept fixed, the wave packets would have to recohere on their way towards the Big Crunch in order to fulfill the boundary condition. A Copenhagen-like interpretation based on probabilities for the "coming into existence" of classical quantities (including a) would presuppose such a direction of time. There is no "continued existence of the observer" (referred to by Page) in this universal quantum description. There are only particularly strong causal links connecting states of the "same" observer at different times. And there can be no observation of a reversal of cosmic expansion, as there is none in quantum gravity. This conclusion appears avoidable only if the state vector collapse were a fundamental dynamical law defined with respect to some re-introduced concept of external time.

In order to discuss the role of entropy, one has to keep in mind that physical entropy is defined with respect to *branches* of the universal wavefunction. In particular, the density matrix (4) would not be understood to define a "thermal" ensemble for a and ϕ. Instead, these variables are considered given (within the widths of the gaussians resulting from decoherence). The same holds for other quasi-classical quantities. In fact, what is usually regarded as "physical entropy" (distinguished from that measuring a "lack of information") refers to a set of "given" quantities on which all observers in one branch could agree [19] (objectivity in the weak sense of d'Espagnat [10,20]). In this way, entropy becomes a *function* of (local) macroscopic variables, and thus an extensive quantity [6]. This concept corresponds to an objectivization of the collapse (branching) with its much discussed artificial problems of "superluminal effects". It is important to observe that measurement-like processes transform physical entropy into lack of information (about macroscopic quantities). The former may thereby in principle be lowered [18] in violation of Brillouin's negentropy principle [21]. The latter would be reduced by factual observation ("reading of the pointer"). Processes of this kind may be of quantitative importance under special circumstances, such as a symmetry-violating phase transition of the vacuum [22-24], or for an Everett branching leading from Hawking's extended wavefunction into a wavepacket representing a certain geometry.

The homogeneous expansion parameter a may be expressed by means of the volume measure, $a = {}^{(3)}g^{-1/6}$, where ${}^{(3)}g$ is the determinant of the spatial metric. If the connection between volume measure and the thermodynamical arrow also held locally – as suggested by Hawking –, this arrow should be reversed inside black holes [5,25,26]. Consistency of the boundary conditions might then require "conspiratorial" phenomena to occur close to black holes, including the possibility of local singularities not being formed at all. When discussing these possibilities, the branching of the wavefunction related to observations has to be carefully taken into account. This branching may be quite different for observers on different sides of the event horizon [26], hence eroding the very concept of objectivization between them, since the observation of phenomena may very much depend on the inertial status of the observer [27]. Answering these questions would require not only the investigation of the universal wave function far beyond the linear approximations of Halliwell and Hawking, but also a better understanding of the observation-related branching (the nature of the "observer basis" [18]). Thereby the remarkable thermodynamical role of black holes [28] might be expected to offer further surprises.

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