Quantum cosmology

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Abstract

It is not my intention to give an in depth description of quantum cosmology. Rather a short overview of the history of quantum cosmology and the latest developments with emphasis on the scientific breakthroughs. Quantum mechanics is an indispensable tool in describing the origin of the universe and to understand inflation, the small scale anisotropies in the Cosmic Microwave Background Radiation (CMBR) and homogeneity and isotropy of the universe at large distances. The origin of the universe is described using quantum tunnelling. Quantum tunnelling (or tunnelling) is a well known phenomenon in quantum mechanics which, when applied to the early universe, predict the exponential expansion of the universe. To arrive at quantum tunnelling the quantum field theory is applied to the very early universe.

1. Background

The physical laws governing the universe describe how the initial state evolves with time. If the initial state is known exactly the motion of the system will be completely predictable. Cosmology attempts to describe the behaviour of the entire universe using these physical laws. In applying these laws to the universe we immediately encounter a problem. What is the initial state that these laws should be applied to?

Einstein's General Theory of Relativity including the λ (lambda) factor described a static unchanging universe. When Edwin Hubble proved to Einstein that the universe is expanding Einstein said the inclusion of the λ factor was the biggest blunder of his life. The equations of

General Relativity without the λ factor can be used to trace the evolution of the universe back in time. This shows that the universe is getting smaller as we go back in time until the universe was as small as a quantum object. At this point the equations of general relativity break down as it cannot describe gravity at the quantum level. A theory of quantum gravity is needed to describe the quantum effects of extreme density and temperature of the early universe. We do not yet have a theory of quantum gravity, but when quantum tunnelling is applied it describes a universe evolving in what we observe today. The approach of tracing the evolution of the universe back in time has proved to be very successful but it has taken us back to the question: “What were the initial conditions?”

2. Initial conditions

   There are two important candidates to explain initial conditions in the very early universe. These are inflation and the application of quantum cosmology to the entire universe. For inflation to have occurred the universe must have been formed containing some matter in a highly excited state. Inflation does not address the question why this matter was in such an excited state. To answer this question we must have a theory of the pre-inflationary initial conditions. The first is the chaotic inflation proposed by Andrei Linde of Stanford University. According to this theory the universe started of in a completely random state. In some regions there will be more energetic matter than in other regions and inflation could ensue producing the universe we see today.

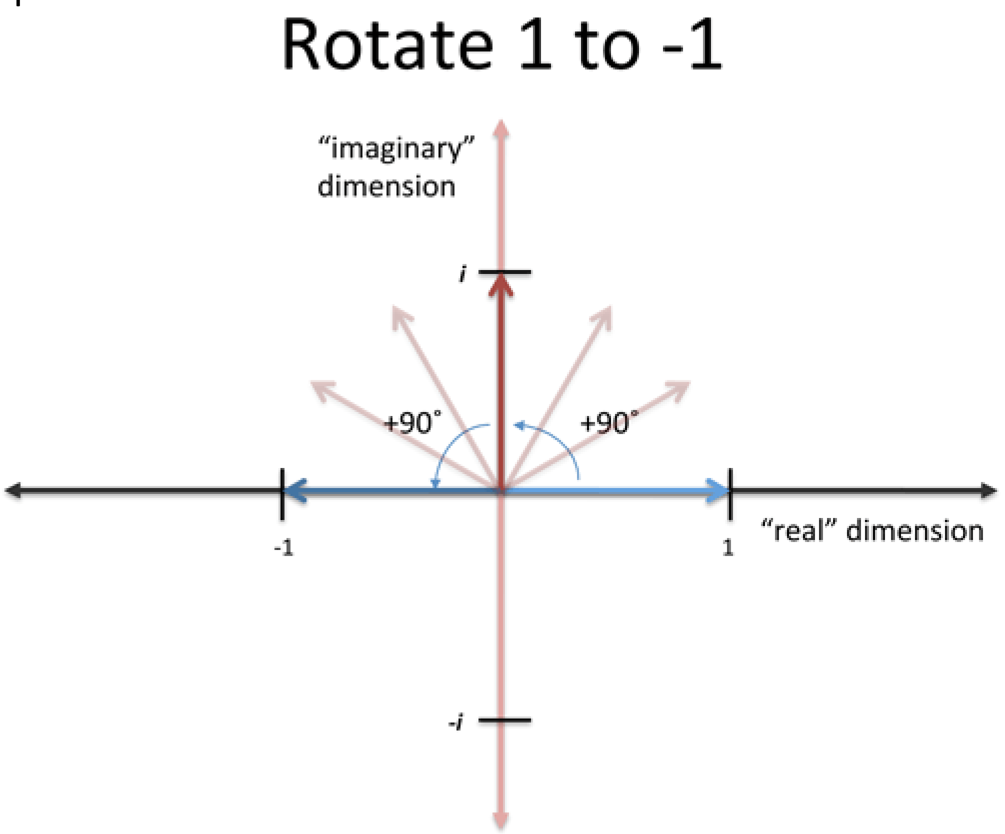
   The second candidate of initial conditions is quantum cosmology, the application of quantum theory to the entire universe. This sounds impossible since large systems, such as the universe obey classical laws, not quantum laws. Einstein’s general theory of relativity is a classical theory that describes the evolution of the universe from a first fraction of its existence until now. However this theory is inconsistent with the principles of quantum theory and cannot describe the extreme conditions at very small scales at the quantum level. For this we need a quantum theory of gravity. In non-gravitational physics the approach to the quantum theory that has proved very useful is the path integrals introduced by Richard Feynman. In the path integral approach, the probability that the initial state A will evolve to a final state B is given by adding up a contribution from every possible history of the system that starts in A and ends in B. The path integral approach is therefore often referred to as 'sum over histories'.

The Schrödinger equation (see below) describes the state of a quantum system as a wave function ψ. It is time dependant and describes the change in a quantum system as time goes on (in this case the quantum size very early universe). The difficulty here is a conceptual one, interpreting the mathematics in terms of physical processes often far removed from the physical processes at large scales.

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} + V(x)\Psi(x,t) \equiv \tilde{H}\Psi(x,t),$$

3. No-boundary proposal

Quantum theory can predict how the universe began since it introduces a new idea, that of imaginary time. Imaginary time is a well known scientific concept. Real time can be imagined as a horizontal line. On the left is the past and on the right the future. Imaginary time is in the vertical direction. The three directions in space and one direction of imaginary time make up a Euclidean space-time that is finite in extent.



http://hawking.org.uk/text/public/bot.html) By taking imaginary time together with space, James Hartle and Stephen Hawking found that the universe will indeed be finite in extent but with no boundary. This will be like the surface of the Earth. The absence of boundaries means that the laws of physics hold everywhere in imaginary time. The no-boundary proposal means that the universe started at a point but with no singularity at that point. It will be like any other point. As the universe expanded it would have borrowed energy from the gravitational field to create matter.

4. Cosmic inflation

Cosmic inflation, usually called Inflation, the exponential expansion of the quantum size universe, is now accepted as a standard for the explanation of several cosmological problems. It is the key to to the understanding of the early universe and early universe cosmology.

Alan Guth has found that the early universe may have been in a highly excited state from which space expanded exponentially. This is possible when the hypothesis of the quantum tunnelling is accepted to describe the exponential expansion of the very early universe. The exponential expansion of the very early universe provides an explanation to a series of otherwise unexplained features of the large scale universe such as the horizon problem, the flatness problem and the relic particle abundances. The most important role of inflation is that it provides a quantitative theory for the density perturbations in the universe from which large scale structures eventually formed.

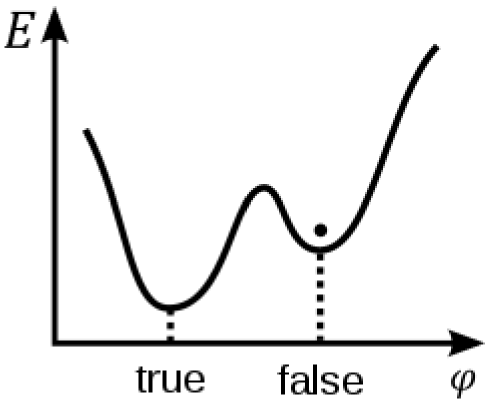
Although Guth realized inflation provides a solution to several cosmological problems such as the horizon problem and the flatness problem, it was the monopole problem was particularly uppermost in his thinking.1) In his book *The Inflationary Universe,* Guth stated that it was only through publicising the discovery as a way of solving the monopole problem that he became aware of the other problems.

As mentioned above inflation does not address the question of why matter was in such a highly excited state. A theory of pre-inflationary conditions is needed to answer these questions. There are two candidates for such a theory. The first is a proposal by Andrei Linde called chaotic inflation. According to this the universe started of in a completely random state. Some regions of the universe will be more energetic than others and inflation could take place.

The second proposal for initial conditions is quantum cosmology. This is the application of the quantum theory to the entire universe. This might sound absurd since the large scale universe obey the laws of physics of large scale systems, quantum cosmology is applied to the very early universe to describe features we observe today.

5. Quantum cosmology

The main feature of quantum cosmology is the universe came into being via a quantum tunnelling event.   Applying the uncertainty principle of quantum mechanics a particle behaves like a particle/wave, not a particle or a wave. In this case it ius the wave function of the universe. This allows us to use the quantum tunnelling effect of the false vacuum to describe the evolution of the quantum size early universe. In the quantum field theory a false vacuum is described as a metastable part of space which is unstable due to instanton effects that may tunnel to a lower energy state. The tunnelling is caused by quantum fluctuations or the creation of high energy fluctuations. The false vacuum is not in the lowest energy state but can remain stable for some time. A barrier prevents the transition of the false vacuum to a lower state and the transition must be stimulated by either high energy particles or quantum tunnelling.



Credit Wikipedia.

During the epoch of the very early universe, both quantum mechanics and gravity, known as the quantum gravity regime are important. The theory of quantum gravity and gravity as described by general relativity are inconsistent with one another. The two are, however applied to very different physical regimes, the former applied to the very early universe and at the singularity at the centre of a black hole. An example of the incompatibility is that quantum mechanics is formulated in a fixed space time while in general relativity space time is dynamic with no preferred definition of time. At this stage it is unclear how quantum mechanics and the theory of gravity in general relativity can be unified. What is clear that quantum mechanics are successfully applied to describe the evolution of the very early universe into the universe we see today.

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1) Guth, A. (1997) The Inflationary Universe. Jonathan Cape, London.