23
Creation of Universes from Nothing

If inflation is eternal, then the beginning of our local universe, about 14 billion years ago, was preceded by an unknown number of ancestor bubble universes. Although we do not know how far back the chain goes, we now believe that there had to be a beginning (as discussed in Chap. 22). So, how *did* it all begin? Eternal inflation pushes the ultimate beginning so far back into the past that we are unlikely to ever have direct observational evidence helping us to answer this question. Yet it must be addressed. It is arguably the most profound mystery that exists and it is at the core of our cosmological yearning. Here we will try to elucidate the speculative yet scientific attempts to explain how an embryonic seed universe emerged.

23.1 The Universe as a Quantum Fluctuation

We have already learned that the vacuum is a frenzied place filled with virtual particles and fields constantly fluctuating in and out of existence. Vacuum fluctuations live off borrowed energy for exceedingly small time intervals, in accordance with Heisenberg's uncertainty principle. For example, a spontaneously nucleated electron-positron pair will vanish in about a trillionth of a nanosecond. Heavier particle-antiparticle pairs live even briefer lives. If particles and antiparticles can spontaneously appear, why can't a fledgling universe?

This seemingly crazy idea was put forward by Edward Tryon, of the City University of New York, in the early 1970s.[1] Tryon suggested that the entire

[1]At about the same time, a very similar idea was proposed by Piotr Fomin in the Soviet Union.

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Fig. 23.1 The total charge in a closed universe is zero. Field lines emanating from a positive charge at the north pole will converge at the south pole—thus there must be an equal negative charge at the south pole

universe emerged as a quantum fluctuation out of the quantum vacuum. Not surprisingly, this idea was taken as a joke at first—there is a gaping difference between subatomic particles nucleating for about a trillionth of a nanosecond (or less) and a massive universe appearing and lingering for billions of years! Nonetheless, Tryon realized that there are no physical laws that forbid this happenstance. You might be thinking "But what about energy conservation?" Surely Lucretius was correct when he said: "Nothing can be created from nothing". So how can a universe containing at least 10^{53} kg of matter suddenly appear? Here Tryon invoked a well-known fact: closed universes have zero energy. We emphasized several times earlier in this book that gravitational energy is negative. And it follows from general relativity that in a closed universe the negative energy of gravity exactly balances the positive energy of matter, so the total energy is zero. Another conserved quantity is electric charge, and once again it turns out that the total charge must vanish in a closed universe.

The latter statement is easy to understand using a two-dimensional analogy. Imagine a two-dimensional closed universe, which we can picture as the surface of a globe (see Fig. 23.1). Suppose we place a positive charge at the north pole of this universe. Then the lines of the electric field emanating from the charge will wrap around the sphere and converge at the south pole. This means that a negative charge of equal magnitude should be present there. Thus, we cannot add a positive charge to a closed universe without adding an equal negative charge at the same time. The total charge of a closed universe must therefore be equal to zero.

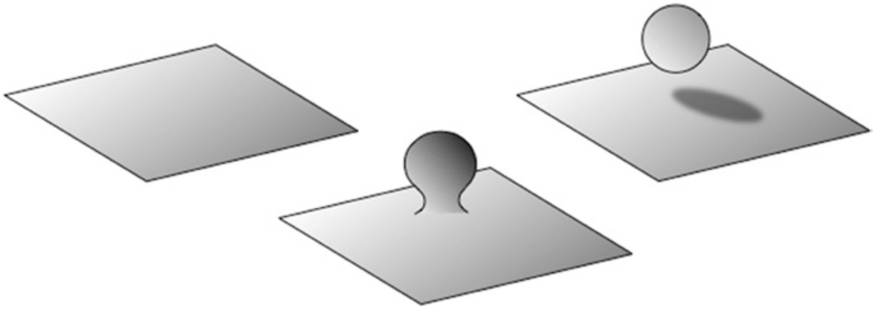

Fig. 23.2 Creation of a closed universe out of the vacuum

The creation of a closed universe out of the vacuum is illustrated in Fig. 23.2. A region of flat space begins to swell, taking the shape of a balloon. At the same time, a large amount of matter is spontaneously created in that region. The balloon eventually pinches off—becoming a closed universe, filled with matter, that is completely disconnected from the original space. Of course, it is very unlikely for such a huge quantum fluctuation to occur. But in quantum theory any process that is not strictly forbidden by conservation laws will happen with some probability. Also, since a nucleated closed universe does not borrow any energy from the quantum vacuum, it can persist for an indefinitely long time without violating the uncertainty principle.

A potential problem with Tryon's idea is that it is hard to understand why such a large universe would appear. It would be much more likely for a Planck sized universe to fluctuate out of the vacuum (as in the spacetime foam picture in Fig. 20.2). Even if we concede that observers require a certain amount of space to evolve, our universe still appears to be much larger than necessary to host observers.

Another, more fundamental issue with Tryon's scenario is that it does not really describe a universe appearing from nothing. The vacuum is what we call empty space. But as we know from Einstein's general relativity, even empty space can bend and warp, and have various geometries, such as the open, closed and flat models we have already encountered. Also, from quantum mechanics we know that the vacuum has energy density and tension, particles and fields. So the vacuum is very much "something", which itself has to be presupposed to exist. As Alan Guth put it, "In this context, a proposal that the universe was created from empty space is no more fundamental than a proposal that the universe was spawned by a piece of rubber. It might be true, but one would still want to ask where the piece of rubber came from". We shall now discuss how Tryon's idea can be extended, to describe quantum creation of the universe from "literally nothing".

23.2 Quantum Tunneling from "Nothing"

Suppose we have a closed spherical universe, filled with a false vacuum and containing a certain amount of ordinary matter. Suppose also that this universe is momentarily at rest, neither expanding nor contracting. Its future will depend on its radius. If the radius is small, then matter is compressed to a high density, and its gravity will cause the universe to collapse. If the radius is large, the vacuum energy dominates and the universe will inflate. Small and large radii are separated by an energy barrier, which cannot be crossed unless the universe is given a large expansion velocity.

This is according to classical general relativity. But quantum physics provides another option: the universe can tunnel through the energy barrier, from a small to a large radius, and start inflating. The tunneling probability depends on the contents of the universe and on its radius. An interesting question is what happens as we let the radius become smaller and smaller. Remarkably, one finds that in the limit of vanishing radius there is still a well-defined, non-zero probability for the tunneling to occur. But a universe with a vanishing radius is no universe at all! One also finds that in this limit the universe that emerges after tunneling contains only vacuum energy and no matter.

Thus, one arrives at a mathematical description for a universe to be spontaneously created out of "nothing". Here "nothing" means a state that contains no matter, and in addition it is also completely devoid of space and time. The "tunneling from nothing" picture was introduced by Vilenkin in 1982 and was later developed by Linde, Valery Rubakov, Alexei Starobinsky, and Yakov Zeldovich.

The tunneling proposal allows for the newborn universe to be filled with different types of vacua. As usual in quantum theory, we cannot tell which of these possibilities is actually realized, but can only calculate their probabilities. The mathematical analysis of the tunneling process shows that the initial radius of the universe right after tunneling is determined by the value of the vacuum energy density ρ_v:

$$R = c\left(\frac{3}{8\pi G\rho_v}\right)^{1/2} \tag{23.1}$$

High-energy vacua correspond to small radii. For example, if the universe emerges with a GUT scale vacuum energy density, its initial size would be $R \sim 10^{-28}$ cm. One also finds that the highest probability is obtained for the universe having the largest vacuum energy and the smallest initial size.[2] Once the universe is formed, it immediately starts expanding, due to the repulsive gravity of the vacuum. This provides the beginning for the scenario of eternal inflation.

At this point you may be wondering: "What caused the universe to pop out of nothing?" Surprisingly, no cause is needed. If you have a radioactive atom, it will decay, and quantum mechanics gives the decay probability in a given interval of time. But if you ask why the atom decayed at this particular moment and not another, the answer is that there is no cause: the process is completely random. Similarly, no cause is needed for a quantum creation of the universe.

Another question you might be asking is: what happened before the tunneling? But we can't meaningfully talk about time before the tunneling. As *St. Augustine* put it centuries ago: "The world was made not in time but simultaneously with time. There was no time before the world". Time only has meaning if something is changing. Without space and matter time does not exist.

23.2.1 Euclidean Time

Quantum creation of universes is similar to quantum tunneling through energy barriers in ordinary quantum mechanics. An elegant mathematical description of this process can be given in terms of the so-called Euclidean time. This is not the kind of time you measure with your watch. It is expressed using imaginary numbers like $i = \sqrt{-1}$ and is introduced only for computational convenience. Making the time Euclidean has a peculiar effect on the character of spacetime: the distinction between time and the three spatial dimensions disappears, so instead of spacetime we have a four-dimensional space. This Euclidean-time description is very useful, as it provides a convenient way to determine the tunneling probability and the initial state of the universe as it emerges from the tunneling.

The birth of the universe can be graphically represented by the spacetime diagram in Fig. 23.3. Here we show one time and one spatial dimension. Time flows from the bottom of the figure upwards—it starts out being Euclidean, and then switches to regular time at the instant labeled

[2] In 1983 James Hartle and Stephen Hawking proposed an alternative model for a quantum description of the creation of the universe, called the no-boundary proposal. We will not discuss this model in detail, except to note that it gives opposite predictions to the tunneling-from-nothing proposal, assigning the highest probability to the smallest vacuum energy and largest initial size of the universe.

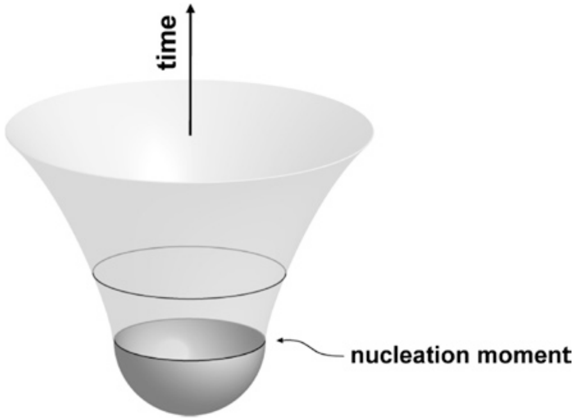

Fig. 23.3 Spacetime diagram of the universe tunneling from nothing. Two out of the three spatial dimensions are not shown. The *dark hemisphere* is the Euclidean region of spacetime, and the *circle* at its boundary represents the spherical universe at the moment of nucleation. The *larger circle* is the universe at a later moment of time

"nucleation moment". The dark hemisphere represents quantum tunneling and the light surface above the nucleation moment is an inflating spacetime. A salient feature of this model is that there are no singularities. A Friedmann spacetime has a singular point of infinite density and curvature at the beginning, where the mathematics of Einstein's equations breaks down (see Fig. 5.5). In contrast, the Euclidean spherical region has no such points; it has the same finite curvature everywhere. It thus gives a mathematically consistent description of how the universe could be born.

23.3 The Multiverse of Quantum Cosmology

As we already mentioned, in the tunneling from nothing proposal a universe can emerge with any one of a variety of values for the vacuum energy and its initial size. Also, although the nucleated universe must have a closed geometry, it need not be perfectly spherical. A range of shapes is allowed. Because of the quantum mechanical nature of the tunneling, we cannot determine which of these possibilities has been realized. All we can do is calculate the probability for a universe to emerge in one of the allowed states. This suggests that there should be a multitude of other universes, which started out differently from our own. We shall refer to this ensemble of universes as the "multiverse of quantum cosmology".

Fig. 23.4 Multiple disconnected closed universes, each capable of producing an unbounded number of open bubble universes

You might imagine that closed universes pop out of nothing like bubbles in a glass of champagne, but this analogy would not be quite accurate. Bubbles pop out in the liquid, but in the case of universes, there is no space outside. Each universe in the quantum cosmology multiverse has its very own space and time, and is completely disconnected from all the others (see Fig. 23.4).

The most probable, and thus the most numerous, universes in the ensemble are the ones with the smallest initial radius and the largest false vacuum energy density. Our best guess, then, is that our own universe also originated in this way. The probability to nucleate larger universes decreases with size, and goes to zero in the limit of an infinite radius. Thus an infinite open universe has a precisely zero chance of nucleating from "nothing", and all the universes in the ensemble are necessarily closed.

Whatever the initial vacuum state of a newborn universe, it will spawn an unlimited number of bubbles (or "bubble universes") filled with other vacua. The entire vacuum landscape will be explored during the course of eternal inflation. Thus, each member of the quantum multiverse ensemble is a multiverse in its own right, including bubble universes of all possible kinds.

23.4 The Meaning of "Nothing"

We have described how an inflating seed could emerge from what seems to be literally nothing—a state with no space, no time, and no matter. However, the birth of the universe by quantum tunneling is described by the same laws of physics that govern its subsequent evolution. So the laws must somehow be "there" prior to the universe. And the laws of physics are definitely not "nothing". This is why we put the word "nothing" in quotation marks.

The notion of "nothing" transmuting into "something" under the spell of abstract laws of nature is deeply mystifying. If there is no time and space, where and how are these laws encoded? After all, the laws of physics have been carefully deduced over centuries by observing and experimenting with matter in space and time. They are supposed to describe our physical reality. Yet if the universe quantum tunneled as prescribed by the laws, then it seems that the laws must be more fundamental than the universe itself. One could become a "matheist" and assert that the laws of physics exist outside of space and time, much like a theist assigns the ultimate first cause to God. Or perhaps the fundamental laws and space and time emerged together?

We have stumbled far into the unknown. But we will press on with the optimistic hope that as the boundaries of scientific enquiry expand, what is currently unknowable might one day be known.

Summary

Quantum theory suggests that a small closed universe could be spontaneously created out of nothing. The newborn universe can materialize with a variety of sizes and can be filled with different types of vacua. The probabilistic nature of the tunneling suggests that an ensemble of universes can nucleate—we call this ensemble the multiverse of quantum cosmology. The most probable universes are the ones having the smallest initial size and the highest vacuum energy. Once such a universe emerges, it starts expanding rapidly because of the repulsive gravity of the vacuum. This provides a beginning for the scenario of eternal inflation.

No cause is needed for the quantum creation of a universe—it is a completely random process, like the decay of a radioactive atom.

Questions

1. What is the total energy of a closed universe? What is its total electric charge?
2. The lifetime of a virtual pair of particles Δt depends on the energy of the particles E. Higher energy particles have shorter lifetimes. Quantitatively, $E \cdot \Delta t \sim \hbar$, where $\hbar$ is the reduced Planck constant. Use this relation to calculate approximately how long it takes for a virtual electron-positron pair to vanish. (The rest mass energy of one electron is 8.187×10^{-14} J and $\hbar = 1.055 \times 10^{-34}$ J s.)

3. Is there a bound to how long a spontaneously nucleated closed universe can live? Why/why not?
4. An important characteristic of elementary particles is their baryon number. This number is equal to 1 for nucleons and -1 for antinucleons. The baryon number is conserved in all particle interactions that have been studied so far. On the other hand, grand unified theories suggest that this conservation law is only approximate and must be violated in high-energy interactions. Assuming that the universe was created from nothing, can you tell whether the baryon conservation law is approximate or exact?
5. How does the quantum vacuum differ from a state of "nothing"?
6. Quantum tunneling from nothing allows a microscopic closed universe filled with false vacuum to pop out of nowhere and to immediately begin inflating. Is it more likely for such a universe to nucleate with a higher or lower false vacuum energy density? Does this make sense to you?
7. A universe which quantum tunnels from nothing must be closed. Does this mean that our local universe has a spherical geometry? Explain your answer. (Hint: See the discussion of bubble geometry in Sect. 18.4.)
8. Why does the tunneling from nothing proposal imply that there should be a multitude of other universes?
9. James Hartle and Stephen Hawking suggested an alternative description for the quantum origin of the universe. In their model, the most probable initial states have the lowest vacuum energy density and the largest radius.
   (a) Do you find this picture intuitively plausible?
   (b) Suppose the initial state of the universe was a large, empty, very low-energy universe, as the Hartle-Hawking model suggests. What would be the following evolution of this universe? (Hint: remember the possibility of bubble nucleation by tunneling "up"; see Sect. 18.3.) Is there any place where we could live in such a universe? Do you think this model can be ruled out observationally?
10. What do we mean by the following terms: observable universe, bubble universe, multiverse, and the multiverse of quantum cosmology?