Quantum fluctuations of spacetime

Introduction

The realm of applicability of Einstein's General Theory of Relativity is the very large, from about a hundredth of a millimeter to the end of the observable universe. From a purely classical point of view (such as general relativity), it is expected that the flat to gently curved space-time should be found even at very small scales of space and time. However, quantum mechanics revealed an increasingly violent space-time of energy fluctuations and all forms energy and take, including gravity, at smaller distances and time scales. In terms of classical reasoning empty space should not have a gravitational field. Quantum mechanics showed that space-time is far from empty, that the value of gravity fluctuates as a result of quantum fluctuations. At larger scales the fluctuations cancel each other out and we are not aware of fluctuations.

2 Form quantum to cosmos

It is now generally accepted that the universe began some 14 billion years ago from a point smaller than an atom, of enormous energy, density and temperature, governed by the laws of quantum mechanics. Many believe that the Big Bang resulted from a runaway series of quantum fluctuations in a primordial vacuum.

Georgi, Quinn and Weinberg, quoted by Brian Greene calculated that the energies required to penetrate the haze caused by quantum fluctuations in flat space-time were characteristic of the very early universe, 10^{-39} second old at a temperature of 10^{28} Kelvin, when the size of the universe was about 10^{-29} cm. (Greene G. The Elegant Universe. 1999. Random House, London.) Although we do not currently have the technology to probe such a small distance, these theoretical works suggest that the universe consisted of homogeneous plasma in which the electromagnetic force, the weak force and the strong force merged into one force. It is expected that the three forces merge into a single super force in the quantum vacuum at a similar small scale of length. The formation of matter in the early universe was subject to quantum effects.

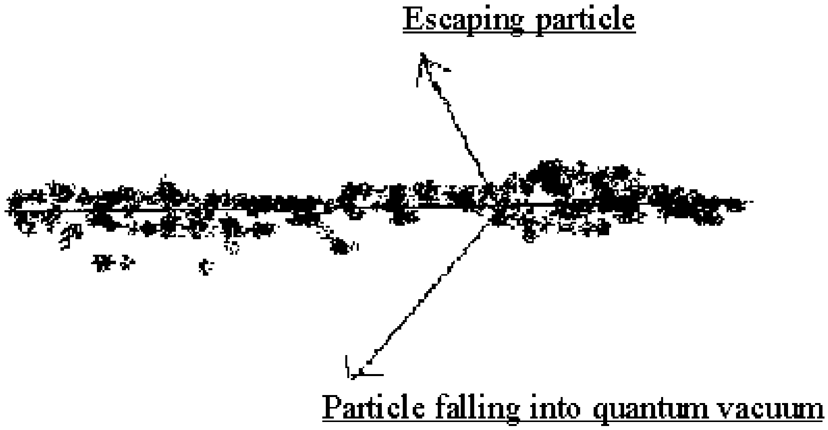
Massive particles, currently not existing in flat spacetime were produced in the very early universe and are expected to be present in the quantum vacuum at similar small scales of distance and time. Hawking found that the same violent fluctuations of energy, gravity and the geometry of space-time were present in the very early universe. (Hawking S. The Universe in a Nutshell. 2001.Transworld Publishers, London)

Extreme fluctuations in gravity and spacetime occur at the quantum level.

3 The quantum vacuum and flat space-time

Since we do not have a full theory of quantum gravity, we have to describe a quantum field according to the semi classical quantum theory including the uncertainty principle and quantum fluctuations, but space-time in terms of the well defined classical theory of general relativity.

The smearing effect of the uncertainty principle makes the boundary between the flat space-time of classical theory and the quantum vacuum ill defined. Virtual particles are created in the quantum vacuum from energy borrowed from flat space-time. The particles annihilate, the borrowed energy is repaid, more energy is borrowed and more virtual particles created in a never ending process of interaction between flat space-time and the quantum vacuum. It is possible that one of the members of the virtual particle pair may escape to flat space-time to become a real particle. The quantum vacuum will gain positive energy if the escaping particle carries negative energy and negative energy if the escaping particle carries positive energy. The escaping particle becomes a “real” particle, annihilation does not happen and the borrowed energy is not repaid. This process is similar to the Hawking radiation at the similarly ill defined event horizon of a black hole.



The strength of attraction between two oppositely charged particles gets stronger as the distance between them decreases. Brian Greene (1999) found that quantum fluctuations in flat space-time play a role if we examine the electric force of an electron or any other electrically charged particle. When we examine the electric force of an electron, we are examining it through a “mist” of energy fluctuations occurring in the region of space-time surrounding the particle. The seething mist of microscopic fluctuations obscures the full force of the electron’s force field. As we get closer to the electron we will have penetrated some of the mist and the strength of the electron’s electric field will increase as we get closer to it. Scientists distinguish between the quantum mechanical increases as we get closer to the electron from that known in classical physics by referring to the intrinsic strength of the electromagnetic force, which increases at shorter distance scales. These effects do not only apply to the electron but to all electrically charged particles. Greene (1999) summarized it by saying that quantum effects drive the strength of the electromagnetic force to get larger when examined on increasingly smaller distance scales.

Surprisingly Gross and Frank Wilczek (Greene 1999) found that the strengths of the other forces of the standard model, the weak and strong forces are being amplified by the cloud of virtual particles flashing into and out of existence. As we examine these forces at smaller distance scales the amplification effect of the “mist” of quantum fluctuation gets less and the strengths of these forces get weaker. Georgi, Quinn and Weinberg (Greene 1999) showed that, when the effects of quantum effects are carefully accounted for, the strengths of the three non gravitational forces are driven together. They further proved that if the three forces are examined at a distance of about 10^{-29} cm. their strengths appear to become equal.

4 Energies at the quantum level

In terms of the uncertainty principle of quantum mechanics the ground state of a quantum field will have a certain minimum amount of energy, called zero point fluctuations. Classical theory implies that the quantum field will have no energy. At shorter distance and time scales quantum fluctuations get increasingly violent. This can also be described as an increasingly violent curvature of space-time. At the extreme energies of the quantum vacuum at distances very close to the Planck length of 10^{-33} cm very massive particles will be produced. Current technology can only probe energies of about 1 000 times the mass of a proton, which is less than a billionth of the Planck energy.

In terms of Einstein’s $E = mc^2$ energies at the quantum level amount to enormous masses, which means enormous strengths of gravity. But if gravity is that strong at the quantum level, why is the curvature of space-time not correspondingly high or infinite? Hawking (2001) showed that the energies of bosons with positive ground state energies and fermions with negative ground state energies cancel each other out. In an unpublished paper in 2004 I have showed that the flow of known forms of energy at the quantum level could be quantized. But this is not the complete answer, because particles do not only interact gravitationally.

5 Quantum weirdness

The ultramicroscopic examination of space-time reveals an unfamiliar world to us. It is a world in which everyday notions we take as self evident become meaningless. The difference between left, right, up, down, back and forth and even the distinction between the past and the future cease to exist. The notion in general relativity of a smooth gently curving space-time is replaced by violent fluctuation of even the curvature of space-time itself.

Hawking (2001) pointed out that the smearing effect of the uncertainty principle in the very early universe and at an examination of space-time at very small scales of distance and time, caused the difference between the time directions and directions in space to disappear. In flat space-time the world line of a photon, traveling at the speed of light is at a 45 degree angle. In the quantum vacuum the uncertainty principle causes the world line of the photon to fluctuate wildly and there is no distinction between space and time.

6 Understanding the quantum vacuum

To understand the quantum vacuum we need to consider quantum fluctuations not only of matter fields but also of space-time itself. The following should be considered:

6.1 The quantum vacuum is far from empty. It is a seething mass of virtual particles flashing in and out of existence and wild fluctuations of energy and all forms energy can take including gravity and fluctuations in the curvature of space-time;

6.2 The quantum vacuum is not separate from flat space-time. It is space-time at very small scales of distance and time;

6.3 The quantum vacuum borrows energy from flat space-time. Virtual particle pairs are created from the borrowed energy, the virtual particles annihilate and the borrowed energy is repaid within a time determined by the uncertainty principle. This is a never ending process of interaction between the quantum vacuum and flat space-time;

6.4 Quantum fluctuations occur in both the quantum vacuum and flat space-time;

6.5 A member of a virtual particle pair may escape into flat space-time to become a real particle in a process similar to the Hawking radiation;

6.6 The smearing effect of the uncertainty principle causes the boundary between the quantum vacuum and flat space-time to be ill defined;

6.7 Quantum fluctuations obscure the value of the field of an electrically charged particle and "amplify" the strengths of the three non gravitational forces; and

6.8 The effects of space-time fluctuations can only be fully explored when we have a complete theory of quantum gravity.

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Suggested reading

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