Quantum vacuum noise in physics and cosmology

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The concept of the vacuum in quantum field theory is a subtle one. Vacuum states have a rich and complex set of properties that produce distinctive, though usually exceedingly small, physical effects. Quantum vacuum noise is familiar in optical and electronic devices, but in this paper I wish to consider extending the discussion to systems in which gravitation, or large accelerations, are important. This leads to the prediction of vacuum friction: The quantum vacuum can act in a manner reminiscent of a viscous fluid. One result is that rapidly changing gravitational fields can create particles from the vacuum, and in turn the backreaction on the gravitational dynamics operates like a damping force. I consider such effects in early universe cosmology and the theory of quantum black holes, including the possibility that the large-scale structure of the universe might be produced by quantum vacuum noise in an early inflationary phase. I also discuss the curious phenomenon that an observer who accelerates through a quantum vacuum perceives a bath of thermal radiation closely analogous to Hawking radiation from black holes, even though an inertial observer registers no particles. The effects predicted raise very deep and unresolved issues about the nature of quantum particles, the role of the observer, and the relationship between the quantum vacuum and the concepts of information and entropy.
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The manifestation of quantum vacuum noise in macroscopic systems comes about because of the peculiar amplifying properties of gravitational fields. For some decades it has been known that a rapidly expanding universe will produce particles from the vacuum. This was followed by Hawking's famous discovery that the catastrophic collapse of a star to form a black hole leads to the production of a steady flux of heat radiation from the vacuum state in the vicinity of the hole. A similar, and somewhat simpler, phenomenon arises when a reflecting boundary undergoes nonuniform acceleration. The changing boundary conditions effectively amplify the vacuum noise and create a flux of radiation, which may or may not be thermal. These topics have important implications for the thermodynamics of black holes and other gravitating systems, in particular whether there exists a "gravitational entropy" to complement ordinary entropy, and whether information that flows into black holes disappears from the physical universe. Related to these matters is the existence of negative energy in quantum field theory, and the possible use of negative energy fluxes to violate the second law of thermodynamics. In this paper I review the foregoing topics, and also discuss some recent advances in laboratory techniques that may permit the measurement of some of the unusual vacuum effects mentioned. Finally, I propose a new class of experiment to observe vacuum viscosity, and briefly mention the role of "environmental noise," i.e., decoherence in quantum mechanics.

I. A NOISY QUANTUM BIRTH OF THE COSMOS

In April 1992 the world's newspapers carried a picture of the sky showing a mish-mash of red and blue splodges. One enthusiastic journalist described the pattern as the fingerprint of God. Essentially, the picture is a thermal map of the universe obtained by the satellite COBE (for Cosmic Background Explorer), which surveyed the cosmic microwave background radiation. This radiation is the fading afterglow of the hot big bang that gave birth to the cosmos between 10 and 20 billion years ago, and it bathes the universe at a temperature of about 2.7 K. The red and blue regions of the map indicate hot and cold fluctuations, respectively, and they form a snapshot of what the universe was like only 300 000 years after the big bang. The irregularities are at a level of a few parts in 10^6; otherwise the radiation is incredibly and mysteriously smooth.

The cosmic temperature fluctuations discovered by COBE are the first glimmerings of large-scale structure in the universe. What caused them? The conventional view is that the COBE "ripples" are actually produced by quantum vacuum noise, hugely amplified, and writ large on the sky. When we look at those temperature fluctuations we are in effect seeing a type of frozen relic of the quantum vacuum as it was a mere 10^{-34} s after the universe began. One of the major unsolved problems of noise—perhaps the biggest in

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terms of its literally cosmic significance, and the huge research budgets involved—is to determine accurately, and then explain, the power spectrum of these fluctuations over a range of angular sizes. COBE was a teaser, but its resolution is too crude to tell us much. A new generation of observations, including the forthcoming satellites Planck and MAP, combined with ground-based observations,[1] will do for the microwave background what the Hubble Space Telescope did for optical astronomy. The challenge to theory will be to derive not only the observed power spectrum, but to account for the manner in which quantum noise has been transformed into classical density perturbations.

It has long been known by cosmologists that galaxies would not form in the time available since the big bang if the universe began in a perfectly smooth state. Only if there existed primordial irregularities would there be sufficient gravitating power to accrete material to make galaxies and thereby stars. If these density inhomogeneities were too large, the cosmic material would collapse instead into gigantic black holes. If they were too small, the expansion of the universe would disperse the material faster than it could aggregate, and galaxies and stars may never form. In this sense the emergence of life as we know it depends crucially on the universe starting out in a state of almost but not quite perfect order. Fortuitously, quantum vacuum fluctuations in the very early universe produced precisely such a state, by bestowing density irregularities of roughly one part in 10^5, which is just what was needed for the emergence of galaxies, stars, planets and—eventually, on one planet at least—cosmologists. We may thus trace our very existence to the action of quantum vacuum noise in the first split second after the cosmic origin.

Most cosmologists now accept that the universe originated in some sort of quantum process.[2] In most interpretations of quantum cosmology, the birth of the universe from nothing is considered to be the result of some sort of existence of noise, which gives a curious new twist to the biblical proclamation that ''in the beginning was the word.'' As Hu and Matacz[3] have expressed it, ''not only is noise good, it is absolutely essential.'' A satisfactory account must await a fully consistent quantum theory of gravitation. Meanwhile, it is possible to draw some remarkable conclusions from a hybrid model in which gravitation is treated classically, but the curved space–time that describes the gravitational field constitutes a type of container for various quantum fields. Researchers tend to think in terms of the electromagnetic field as the prototype quantum field, but most of what I shall report here involves calculations with massless scalar fields. A review of the subject is given in Ref. 4.

We know that a perfect vacuum is not just inert empty space. In fact, it teems with quantum activity in the form of ephemeral virtual particles. This vacuum activity leads to a number of well-known observable effects, such as the Lamb shift and the Casimir force, that have been thoroughly discussed in the literature.[5] Although most observable quantities average to zero in the quantum vacuum, there can be nonzero fluctuations about the expectation value, and these fluctuations can produce a range of interesting physical phenomena. One of these may be the COBE ripples.

According to the now-standard big bang theory known as the inflationary universe scenario, the universe jumped in size by an enormous factor shortly after its origin.[6] In the simplest models, this so-called inflationary episode is described by an exponential growth in the size of the universe. The COBE fluctuations may be envisaged, crudely, as quantum vacuum fluctuations from the very early universe inflated to a vast scale of size. The behavior of the quantum vacuum in an exponentially expanding space (known technically as de Sitter space) is very similar to that of ordinary Minkowski space, since both have an equal number of geometrical symmetries. For this reason, the spectrum of quantum vacuum fluctuations has no in-built length scale, which accords with the roughly scale-free spectrum that COBE detected, and implies that the universe is spatially flat (i.e., the spatial geometry is Euclidean on a large scale). But whether this simple picture will survive improved observations remains to be seen. The most recent ground-based observations[1] do indeed support the hypothesis that the universe is flat.

II. VACUUM VISCOSITY AND PARTICLE CREATION BY THE EXPANDING UNIVERSE

As pointed out by DeWitt,[7] the quantum vacuum is in some respects reminiscent of the aether, and in what follows it may be helpful to think of space–time as filled with a type of invisible fluid medium, representing a seething background of vacuum fluctuations. Although the mechanical properties of this medium can be strange, and the image should not be pushed too far, it is sometimes helpful to envisage this ''quantum aether'' as possessing a type of *viscosity*.

To illustrate the concept, consider the behavior of a quantum field in an expanding universe. This problem was originally tackled by Parker in the late 1960s.[8] He found that one effect of the expansion was to disturb the quantum vacuum and bring about the creation of particles. Physically, one can think of this either as an external disturbance (the expansion) ''promoting'' virtual quanta from the vacuum into real quanta, or as due to the viscosity of the vacuum generating heat as the ''fluid'' is expanded. In the case that the expansion is homogeneous and isotropic, this corresponds to so-called bulk viscosity. If the universe expands anisotropically, then shear viscosity of the quantum ''aether'' also plays a role, and the particle production is much more prolific.[9] In both cases, the backreaction of the particle production serves to damp the cosmological motion, and so acts as a genuine viscous drag. Although the discovery of cosmological particle creation was important conceptually, it is not clear that this process was ever physically very significant, since other quantum particle effects, such as the decay of false vacuum states, probably overwhelmed it.[2]

From the point of view of quantum field theory, to see why an expanding universe creates particles, consider the (admittedly artificial) example[10] of one space dimension, where the expansion is homogeneous and the cosmological scale factor has the form shown in Fig. 1. Note that in this model there is no big bang. Instead, the universe starts out as conventional flat space–time (Minkowski space), then expands smoothly for a period, and ends up as flat space–time,

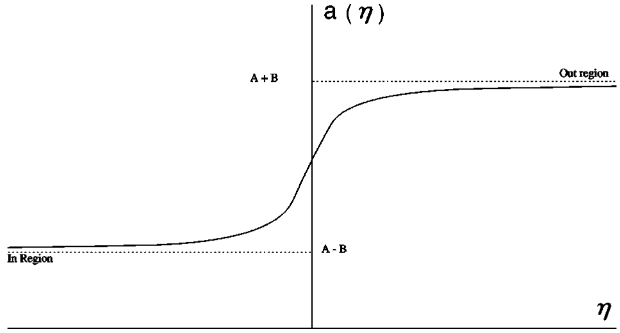

FIG. 1. The scale factor of an expanding universe with asymptotically static in and out regions.

but with any given initial region of the universe expanded in size by a fixed factor. It is possible to solve the wave equation for a massless scalar field exactly in this model for certain functions of the expansion factor $a(t)$. For example,

$$a(\eta)=\sqrt{A+B\ \tanh(\rho\eta)}$$
$$\eta=\int\frac{dt}{a(t)}, \tag{1}$$

where $A,\ B,\ \rho$ are constants.

One may then write down a complete set of field modes that reduce to standard exponential modes in the "in" region (i.e., when $t\rightarrow-\infty$):

$$\begin{aligned}u_k^{\text{in}}&=(4\pi\omega_{\text{in}})^{-1/2}\exp\{ikx-i\omega_+\eta-(i\omega_-/\rho)\\&\quad\times\ln[2\cosh(\rho\eta)]\}{}_2\mathbf{F}_1(1+(i\omega/\rho),i\omega_-/\rho;\\&\quad 1-(i\omega_{\text{in}}/\rho);\tfrac{1}{2}(1+\tanh(\rho\eta))\\&\underset{\eta\rightarrow-\infty}{\rightarrow}(4\pi\omega_{\text{in}})^{-1/2}e^{ikx-i\omega_{\text{in}}\eta},\end{aligned} \tag{2}$$

where ${}_2\mathbf{F}_1$ is a hypergeometric function and

$$\begin{aligned}\omega_{\text{in}}&=\sqrt{k^2+m^2(A-B)},\\\omega_{\text{out}}&=\sqrt{k^2+m^2(A+B)},\\\omega_\pm&=\tfrac{1}{2}(\omega_{\text{out}}\pm\omega_{\text{in}}).\end{aligned} \tag{3}$$

I use units $\hbar=c=1$ throughout. Note that $t\propto\eta$ when $t\rightarrow\pm\infty$.

The modes [Eq. (2)] may be used to define particle states and a Fock space in the Heisenberg picture in the conventional way. In particular, the field ϕ may be expanded

$$\phi=\sum_k\ (a_k u_k^{\text{in}}+a_k^\dagger u_k^{\text{in}*}) \tag{4}$$

and a vacuum state defined by

$$a_k|0_{\text{in}}\rangle=0. \tag{5}$$

In the "in" region, $|0_{\text{in}}\rangle$ coincides with the standard definition of a quantum vacuum of normal Minkowski space quantum field theory. However, in the "out" region, where $t\rightarrow\infty$ the modes [Eq. (2)] are not simple exponentials, but more complicated functions of time.

Alternatively, one may find a complete set of modes of the field that reduce to simple exponentials in the "out" region but not the "in" region, and use them to define an "out" vacuum state:

$$\begin{aligned}u_k^{\text{out}}&=(4\pi\omega_{\text{out}})^{-1/2}\exp\{ikx-i\omega_+\eta-(i\omega_-/\rho)\\&\quad\times\ln[2\cosh(\rho\eta)]\}{}_2\mathbf{F}_1(1+(i\omega/\rho),i\omega_-/\rho;\\&\quad 1-(i\omega_{\text{out}}/\rho);\tfrac{1}{2}(1+\tanh(\rho\eta))\\&\underset{\eta\rightarrow+\infty}{\rightarrow}(4\pi\omega_{\text{out}})^{-1/2}e^{ikx-i\omega_{\text{out}}\eta}.\end{aligned} \tag{6}$$

These modes are complicated functions of time in the "in" region. Again, the field may be expanded in terms of these "out" modes, and an "out" vacuum state defined:

$$\phi=\sum_k\ (b_k u_k^{\text{out}}+b^\dagger u_k^{\text{out}*}), \tag{7}$$

$$b_k|0_{\text{out}}\rangle=0. \tag{8}$$

The significance of "out" modes is that they correctly describe the standard definition of vacuum and particle states in the "out" region (but not in the "in" region).

The crucial observation is that the "in" and "out" modes are different, and hence the two vacuum states $|0_{\text{in}}\rangle$ and $|0_{\text{out}}\rangle$ are not the same. That is, the "in" vacuum contains "out" particles and vice versa. Since in the Heisenberg picture the state remains unchanged, if we assume the universe is in the "in" vacuum state, i.e., there are no real particles present initially, then there *will* exist particles in the out region. In other words, physically speaking the effect of the period of expansion is to create particles, which are detectable in the "out" region. To find out how many, one simply solves the wave equation to determine the form of the "in" modes in the "out" region, expands them in terms of the "out" modes, and uses the coefficients to determine the so-called Bogoliubov transformation:

$$u_k^{\text{in}}(\eta,x)=\alpha_k u_k^{\text{out}}(\eta,x)+\beta_k u_{-k}^{\text{out}*}(\eta,x), \tag{9}$$

where

$$\alpha_k=\sqrt{\frac{\omega_{\text{out}}}{\omega_{\text{in}}}}\frac{\Gamma(1-i\omega_{\text{in}}/\rho)\Gamma(1-i\omega_{\text{out}}/\rho)}{\Gamma(1-i\omega_+/\rho)\Gamma(1-i\omega_+/\rho)}, \tag{10}$$

$$\beta_k=\sqrt{\frac{\omega_{\text{out}}}{\omega_{\text{in}}}}\frac{\Gamma(1-i\omega_{\text{in}}/\rho)\Gamma(1-i\omega_{\text{out}}/\rho)}{\Gamma(1-i\omega_-/\rho)\Gamma(1-i\omega_-/\rho)}. \tag{11}$$

Hence the expectation value for the number operator of mode k "out" particles in the "in" vacuum state is

$$\langle 0_{\text{in}}|b_k^\dagger b_k|0_{\text{in}}\rangle=|\beta_k|^2=\frac{\sinh^2(\pi\omega_-/\rho)}{\sinh^2(\pi\omega_{\text{in}}/\rho)\sinh^2(\pi\omega_{\text{out}}/\rho)}, \tag{12}$$

which gives the spectrum of created particles for the particular expansion factor [Eq. (1)].

In case this definition of particles seems arbitrary, one may check that if a model particle detector is switched on (slowly) in the "out" region, it will indeed respond to the "in" vacuum state in exactly the same way as it would if placed in a conventional quantum state with particle spectrum defined by Eq. (12). I shall return to the subject of particle detectors in Sec. V. One of the unsolved problems with this type of calculation is how to define particle and vacuum states when there are no asymptotically static ''in'' and ''out'' regions. In particular, in the more realistic case where the universe expands from a singular origin, the notion of an initial vacuum is obscure. Over the years there have been many proposals to define ''instantaneous'' vacuum states from epoch to epoch as the universe expands,[11] but these definitions have an unappealing ad hoc character. Nor can one use model particle detectors to provide a definition, since these can behave oddly (see Sec. V) when not at rest in Minkowski space, and in any case they suffer from spurious transient effects if switched on abruptly (e.g., at the big bang).

III. MOVING MIRRORS

A changing gravitational field (i.e., a nonstatic space–time) is not the only way to disturb the vacuum. A moving reflecting boundary (mirror) may also create real particles from the quantum vacuum. Crudely speaking, if a mirror suddenly moves, the news of this change does not reach a distant place until at least the light travel time from the mirror surface to that location, so the vacuum ''fluid'' in the intervening space is compressed. Vacuum viscosity then leads to heat being generated in the form of particles. (Usually, however, the spectrum is not thermal.)

In the case of a one-dimensional mirror (reflecting point) moving in one space dimension, the problem is exactly soluble for a massless scalar field[12,13] in terms of the energy flow from the mirror, though the particle spectrum normally requires a numerical treatment. For a mirror trajectory

$$x=z(t),\qquad z(t)=0,\quad t<0, \tag{13}$$

the energy flux is given by

$$\frac{-1}{12\pi}\,\frac{\sqrt{1-v^2}}{(1-v^2)^2}\,\frac{da}{d\tau}, \tag{14}$$

where v is the mirror velocity, a the proper acceleration, and τ is the proper time. In the general case the energy flux need not be positive at all times. When the acceleration is increasing to the right, the energy flow to the right is negative (see Fig. 2). The significance of this is not clear. There are several scenarios in quantum field theory where negative energy fluxes are possible, and there is a large literature examining the implications of this for the second law of thermodynamics.[13–20] For example, can the entropy of an oven or a black hole be reduced by directing a sustained negative energy beam into it to cool it down? The answer seems to be ''usually not.'' Ford and Roman have shown[19,20] that the duration of a negative energy flux is normally strictly circumscribed by an uncertainty principle type inequality which prevents the entropy from going down significantly. However, there are scenarios involving black holes in which the inequality is evaded[20] and there is as yet no general proof that the second law is immune from negative energy effects.

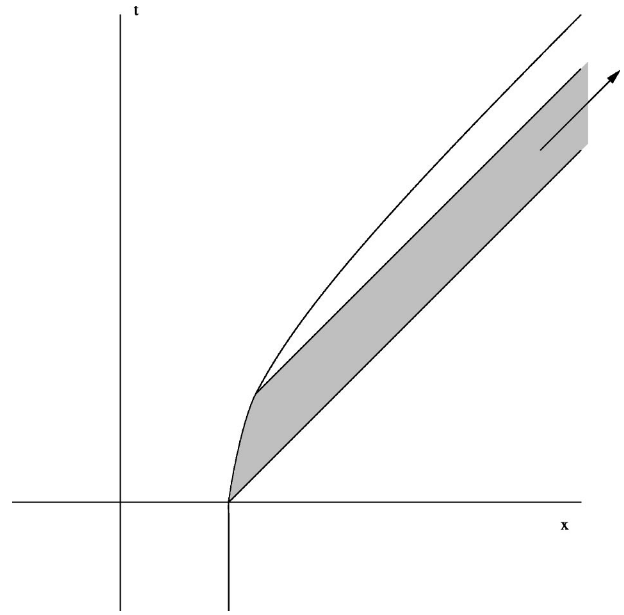

FIG. 2. The world lines of a mirror that is static for $t<0$, and accelerates nonuniformly to the right for $t>0$. The motion excites the quantum vacuum and causes a flux of radiation to flow from the mirror's surface. Initially the acceleration increases to the right with time, leading to the energy flux associated with the radiation to be negative. This is depicted by the shaded region.

Another startling consequence of negative energy fluxes discussed by Ford and Roman[21,22] occurs when the flux is directed at a black hole with maximal electric charge. It is well known that this is a limiting case: If the mass of such a black hole is reduced by even an infinitesimal amount, the event horizon vanishes, and the black hole is converted into a naked singularity. As a result, the universe is no longer causally closed. Ford finds that the singularity inside a black hole can indeed be briefly exposed by directing a negative energy flux at it, but the situation is rapidly restored by the next burst of positive energy. Ford calls this fluctuating horizon ''cosmic flashing.'' In effect, the causal influences that might emanate from the singularity are masked by the noise of the fluctuating horizon. But this is not random noise, because the negative energy flux has a predictable form dependent on the mirror motion. It is an open question whether under these circumstances information about the singularity can get out. Roger Penrose has coined the term ''cosmic censorship'' for the hypothesis that singularities are never naked or exposed, so the open question is whether negative energy fluxes can violate cosmic censorship, at least in a statistical way.

Moving mirror radiation is exceedingly feeble unless the accelerations involved are colossal, and there remains doubt over whether it can be detected. However, there have been attempts to attribute sonoluminescence to moving mirror radiation.[23] This phenomenon occurs when sound is passed through water, causing flashes of light to appear. It is thought that they are generated when small bubbles collapse with enormous rapidity. Treating the bubble as a cavity containing quantum vacuum, and the bubble surface as a partially reflecting mirror, the implosion effectively compresses the quantum vacuum and generates photons. Although the theory remains incomplete, opinion is now swinging against moving-mirror radiation as the principal explanation.[24]

In a Casimir situation, with two parallel mirrors, amplification of the moving mirror radiation is possible if one mirror oscillates in resonance with the light travel time across the cavity. Recent calculations[25] suggest this may bring moving mirror radiation into the realm of the detectable.

IV. BLACK HOLES

Some of the most interesting unsolved problems of quantum vacuum noise are associated with black holes. Again, vacuum viscosity can offer heuristic interpretations. Imagine a rotating black hole. Einstein's general theory of relativity predicts that near a rotating body a gyroscope should precess due to an effect called the dragging of inertial frames. In effect, the gravitational field of the rotating body has a ''magnetic'' component that tries to pull nearby objects around with it, causing them to co-rotate. The vacuum ''aether'' is dragged around too, but differentially—the effect falls away with distance. The shearing of the vacuum in this manner creates particles (entropy), which flow away into the surrounding space, taking angular momentum with them. Eventually this radiation would cause the black hole to spin down. The theory for this ''rotation radiation'' was worked out by Starobinski[26] and Unruh,[27] who treated the problem as one of vacuum instability. An unsolved problem is whether a rotating star would also produce such radiation.[28]

Shortly after the Starobinski–Unruh effect was discovered, Stephen Hawking made his famous prediction that nonrotating black holes also emit radiation.[29] This time the mechanism is different. An imploding spherical star drags the vacuum ''fluid'' with it down a black hole, and the resulting heat generated is precisely thermal. Hawking derived this result by following the sort of procedure I outlined in Sec. II for a cosmological model, that is, he decomposed the quantum field in ''in'' and ''out'' modes, and expanded the ''in'' vacuum in terms of ''out'' states. Here the ''in'' region corresponds to the (almost) flat space–time prior to collapse, and the ''out'' region refers to the space–time far from the black hole long after the collapse phase is over. Hawking evaluated the Bogoliubov transformation between these two sets of modes, and found for the case of a spherical uncharged black hole a thermal spectrum with temperature

$$T=\frac{1}{8\pi GM}, \tag{15}$$

where G is Newton's gravitational constant and M is the total mass of the black hole.

Hawking concluded that a black hole is not black, but radiates like a blackbody. For a solar mass black hole the temperature is a tiny 10^{-8} K, but a curious feature of quantum black holes, clear from Eq. (15), is that they have a negative specific heat. That is, as the hole loses energy, hence mass, it gets hotter. The Hawking effect is therefore unstable, and the black hole radiates faster and faster until its mass approaches zero.

One of the big unsolved problems of quantum gravity—indeed, of the whole of physics—is what happens in the end. As the hole's mass and radius shrink towards zero, will the object just disappear, or leave behind some exotic remnant? At the center of a black hole lies a space–time singularity—an edge or boundary of space and/or time at which the curvature approaches infinity. The surface of the black hole is an event horizon that envelops the singularity and prevents it being seen from afar. It also ensures that no causal influences from the singularity will get out and invade the universe. Since a singular boundary represents a breakdown of causality (any influence at all may emerge), this ''cosmic censorship'' is crucial. However, if the black hole evaporates by the Hawking effect, the prospect arises that a singularity, albeit massless, will eventually be exposed.

A key issue relating to this conundrum concerns information. Since the radiation emitted by the hole is thermal, and (for a spherical hole at least) depends only on the total mass, it is not possible to tell from the outside what a given black hole consists of. A black hole made from antimatter, for example, is identical to one made from the same mass of matter. Therefore the information content of the object that imploded to form the black hole is irreversibly lost. Indeed, any information flowing across the event horizon into the hole cannot return to the outside universe, since information cannot exceed the speed of light, and light itself is trapped. That is why the Hawking radiation is thermal: it has maximum entropy, representing the total loss across the event horizon of the information of the material that went to build the black hole.

You might imagine that if the hole itself subsequently disappears, the information must somehow find its way out again. This is one of the big unsolved problems of quantum gravity. Hawking's original answer is that the information is completely lost into the singularity. Any matter or radiation that intersects the singularity, having fallen into the hole, will effectively disappear from the physical universe. Even if the black hole itself evaporates away, it is too late to recover the information—it has vanished into the singularity! On the strength of this, Hawking asserted that quantum gravity introduces a fundamental microscopic irreversibility into nature, and that a pure quantum state will not in general remain pure in the presence of gravitational structures like black holes and wormholes.[30] In other words, the universe is subject to a pervasive decohering ''cosmic noise'' generated by the fundamentally ''leaky'' topological structure of spacetime!

However, Hawking's position has been challenged.[31,32] Some physicists have argued it is a basic principle of nature that information is conserved at the microscopic level. Somehow, an evaporating black hole must give back, via the Hawking process, all the information that it swallows. There is no agreement on precisely how this might happen. One suggestion appeals to the properties of the event horizon. The entropy of the black hole is proportional to the horizon area A, and given by the expression

$$S=kA/4. \tag{16}$$

In quantum gravity, the smallest meaningful spatial size is the Planck length $\sqrt{G\hbar/c^3}=10^{-33}$ cm. If the event horizon area is divided into cells of one square Planck length, and each cell stores one bit of information, then the entropy of the black hole is given by Eq. (16). This is numerically the same as the total information attached to the horizon—one bit per Planck area. A proposal of Susskind and others[32] is that when a ball of matter collapses under gravity to form a black hole, the information content of the matter gets smeared over the horizon surface. Although it is for all practical purposes inaccessible to an outside observer (the horizon looks totally black), the information can still escape in the Hawking process by ''tunneling out'' quantum mechanically.

The apparent loss of information down black holes raises some deep issues. Note that the situation is very different from the information loss associated with normal thermodynamic entropy rise, which comes about because of coarse graining. When a book is thrown on a bonfire, the information content of the book is certainly made inaccessible to human eyes, but at the microscopic level it is still there, encoded in the correlations of the atoms and photons that issue from the bonfire. The information is lost in practice because the microscopic information content is jumbled up in an immensely complicated manner. But in principle at least, all the information is retrievable. By contrast, the loss of information down a black hole seems to be absolute, for the theory of relativity forbids one from reaching across an event horizon to retrieve it, even in principle.

So the issue boils down to whether the radiation from a black hole really is pure thermal noise, or whether it encodes via subtle correlations the entire description of the erstwhile star, or other body, that imploded to form the hole. Existing calculations using string theory to model the matter suggest it can.[32] Other evidence comes from the work of Hu[33] applying quantum statistical mechanics to the black hole evaporation problem. Hu finds evidence that there is a continual shifting of information from the black hole to the higher correlations in the field modes of the Hawking radiation as the system evolves. This suggests that when the hole has completely evaporated the initial information content will be preserved in a highly nonlocal manner among the higher correlations of the field modes—in effect, spread across the universe in a way that makes the information inaccessible to a local observer. However, it is unlikely that this issue will be resolved until a fully consistent theory of quantum gravity is available.

The role of science is to explain the universe in terms of rational principles. A central tenet of science is the principle of sufficient reason, which states that events do not occur reasonlessly, but have causes or explanations in something else. Quantum mechanics proves so vexatious because it seems to challenge the principle of sufficient reason by permitting spontaneity and indeterminacy (hence Einstein's famous lament that God does not play dice with the universe). However, although individual quantum events may be unpredictable, the wave function itself evolves unitarily, i.e., it obeys a causal equation. Another way of saying this is that information is conserved as the wave function evolves. It is fundamental to the nature of rational explanation that information should not enter the universe from beyond space–time, for that is tantamount to a miracle. How could science proceed if new physical influences popped up from nowhere? It would render the universe ultimately absurd. Because the laws of physics are time symmetric, the same considerations require that information should not disappear from the universe. Hawking asserts[34] that not only does God play dice with the universe, he sometimes throws the dice where they cannot be seen (i.e., down black holes). The question then is whether such a universe in which the wave function does not always evolve unitarily, so that information comes and goes, can be given a complete rational description, or whether it is a recipe for ultimate cosmic absurdity.

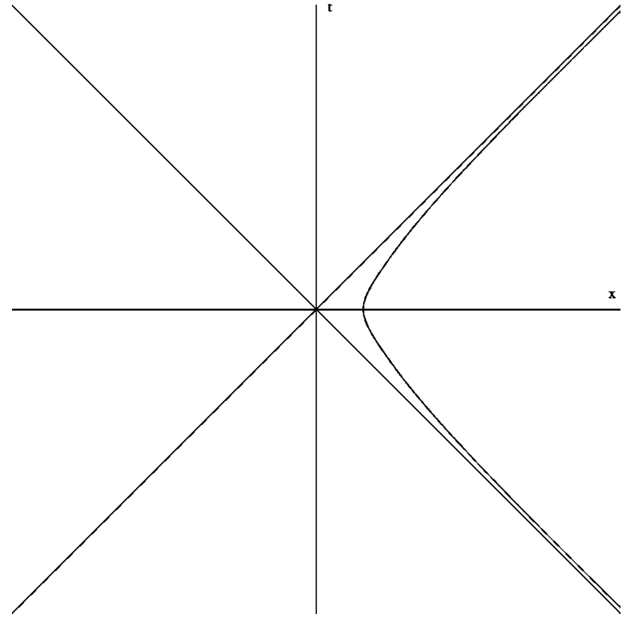

FIG. 3. The hyperbola shows the world line of a uniformly accelerating particle detector.

V. ACCELERATED OBSERVERS

One of the most dramatic and much-publicized examples of vacuum noise effects concerns accelerated observers. Some years ago, Unruh and I independently predicted[35,36] that a uniformly accelerated observer moving through a quantum vacuum would perceive a bath of thermal radiation with a temperature

$$T=a/2\pi k, \tag{17}$$

where a is the proper acceleration. Unruh,[36] and later DeWitt,[7] showed that a model particle detector in its ground state would respond, when accelerated, in exactly the same way as if immersed at rest in thermal radiation at the temperature given by Eq. (17). In effect, the quantum vacuum fluctuations when viewed in an accelerated reference frame become thermal fluctuations. The situation closely resembles Hawking's black hole radiation effect. In fact, the Bogoliubov transformations are identical in both cases. The trajectory of a uniformly accelerated observer is a hyperbola in Minkowski space, as shown in Fig. 3. The asymptotes lie along the light cone through the origin, which play a role analogous to the event horizon in the black hole.

There has been much discussion about the conservation of energy of an accelerated detector. Since the detector becomes excited, it must gain energy. On the other hand, consider the standpoint of a stationary observer. The quantum field begins in a vacuum state, so any transition of the detector to an excited state must involve a transition in the field too, and in first order perturbation theory the only transition from the vacuum state possible is the emission of a quantum. Thus in the frame of the detector energy is absorbed, but in the unaccelerated frame it is emitted!

The paradox is resolved when it is realized that the initial state of accelerated detector + vacuum is not a total energy eigenstate. In an individual transition, therefore, energy is not conserved. Consider an ensemble of accelerated two-level detectors that have their energies measured at the end of some time interval. Since in the accelerated frame there is an apparent thermal bath, some detectors will be excited, others will be in the ground state, with energies distributed according to the usual Boltzmann factor determined by Eq. (17). For those detectors that are excited, the expectation value of the energy will have gone up, but for the unexcited ones the expectation value will have gone down. It turns out that the total energy expectation value remains unchanged.[37]

A related effect is also of interest. If an observer rotates with constant angular velocity, they will also perceive a bath of radiation, but in this case it does not have a thermal spectrum.[38] Although this represents work still in progress[39,40] the energetics seem to be different from the case of linear acceleration. It appears that, in the nonrotating frame, when a rotating detector becomes excited it emits a quantum into the field that carries angular momentum away and serves to damp the motion of the detector. This is therefore another vacuum friction effect. This time, however, there is a net energy loss from the detector to the field. To sustain the rate of angular motion, energy must be continuously fed into the system.

Some people have suspected a deep link between quantum vacuum noise, accelerated observers, and inertia.[41] Mach's principle seeks to treat acceleration as motion relative to distant matter in the universe. In the foregoing examples of accelerated particle detectors, the rest of the universe is (initially) devoid of matter. A rotating observer in such an empty universe could establish the rotation by inspecting a particle detector to see if it is excited. In this respect, quantum field theory seems to contradict Mach's principle, which is perhaps no surprise since, as I remarked earlier, the quantum vacuum does mimic some aspects of the aether.

The magnitude of ''acceleration radiation'' is disappointingly feeble. An acceleration of 10^{21} g is needed to generate an effective temperature of just 1 K. Nevertheless Bell and Leinaas[42,43] claim to have seen a positive effect in the spin depolarization of electrons in a particle accelerator ring.

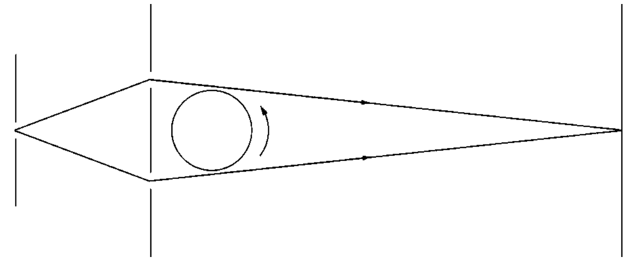

FIG. 4. Modified atom interference experiment. The rotating cylinder positioned near the slits exerts a differential vacuum viscosity on the passing atoms, which serves to both shift the interference pattern and decohere it.

VI. DECOHERENCE AND DISSIPATION IN QUANTUM MECHANICS

My final example of vacuum friction is much closer to experimental study than the foregoing. Moreover, it involves frictional forces in a very familiar context. Imagine a Casimir situation in which one plate moves, not orthogonal to the plane of the plates as I discussed at the end of Sec. III, but in the plane of the plate, i.e., one plate ''slides across'' the other. If the plates were perfectly conducting, nothing would happen because of Lorentz invariance; put simply, the plates would not know they were in relative motion because they lack any markers. However, real plates are not perfect conductors/reflectors. They are composed of dissipative materials. As a result, there will be a frictional force experienced that acts to damp the relative motion. Its magnitude has been calculated by Pendry.[44] Since the region between the plates is a quantum vacuum, the friction is entirely a vacuum effect. No real photons are involved.

The phenomenon is at its most striking in the case of a single atom moving parallel to, but some distance from, an imperfectly conducting plate. The atom also experiences a velocity-dependent damping force due to vacuum friction. The kinetic energy of the atom appears as heat in the plate; virtual photons transfer the energy from the atom to the plate. One way to envisage the phenomenon is as follows. An atom located near a reflecting surface sees an image of itself, and will experience an effective van der Waals attractive force. In the case of a transversally moving atom, the image moves parallel to it, but the dissipation in the plate causes the image to lag slightly behind the atom. As a result, the effective attractive force between the atom and the image has a small component parallel to the plate that acts to retard the motion. This example of ''friction-at-a-distance'' is reminiscent of the moon's motion around the earth. Friction heats the tidal bulge in the rotating earth, and the resulting lag in the bulge relative to the moon's motion creates a retarding force that causes the moon to lose energy and slow down in its orbit.

This example of vacuum friction suggests some novel thought experiments which may soon be doable. For example, if an atom is dropped vertically down the center of a metal cylinder, it should reach a terminal velocity due to vacuum friction with the material of the cylinder. Another experiment involves interference. Suppose a standard two-slit experiment is performed with atoms, but a rotating metal cylinder is inserted between the slits (see Fig. 4). There should then be a shift in the interference pattern, because the atoms moving through one slit will be accelerated while those moving through the other slit will be retarded. Furthermore, since the cylinder material will be dissipative, there will be some loss of phase coherence, which will serve to reduce the overall degree of interference. By adjusting the conductivity and rotation rate of the cylinder, these two effects can be independently tuned. The effects will also be sensitive to the dielectric properties of the cylinder, which would provide an additional variable. There is considerable interest in the study of decoherence in quantum mechanics, related to solving the so-called collapse of the wave function problem.[45] A dissipative environment provides a very strong source of decoherence, but the relationship between the decoherence time and the dissipation time is a subtle one. The experiment proposed previously could be used to investigate the interweaving of these two fundamental effects, one controlling the emergence of classicality in the universe, the other the emergence of an arrow of time.

VII. CONCLUSION AND OPEN QUESTIONS

The quantum vacuum is an inescapable source of noise in the universe. Normally quantum vacuum effects are tiny, but under some circumstances they may become hugely amplified and lead to macroscopic—indeed cosmic—effects. Heuristically, many vacuum effects can be envisaged as produced by a type of quantum aether with frictional properties. A major challenge on the experimental front is to detect some of the quantum vacuum effects described here, such as acceleration radiation and moving mirror radiation. Although the predicted effects are extremely small, they test key properties of quantum vacuum noise inaccessible in any other way. Further observations of ultrahigh energy cosmic rays may also allow us to start probing the quantum gravity regime experimentally.

The relationship between quantum noise, thermodynamics, and gravitation remains murky. The grandest of these concerns the manner in which our universe (and perhaps others too) came into existence from nothing as a result of a quantum fluctuation. This required clarification of the nature of the vacuum state in which fluctuations may occur. This is not simply the empty space vacuum of normal quantum field theory, but a vacuum state of space–time itself, a concept that makes sense only within the framework of a proper quantum theory of gravitation, and probably only within a completely unified theory of physics, of the sort that M theory now promises.[46]

At a more modest—but still challenging—level of difficulty, there remain many open questions concerning particle creation in strong gravitational fields treated classically, in particular the problem of the final state of black hole evaporation. Some of these problems are at the level of adequate definitions of such things as particle states, observers, etc. A major focus of research concerns the emergence of an almost-uniform universe with a superimposed spectrum of low-amplitude fluctuations from a quantum big bang. Unfortunately, existing models are highly artificial, and the quantum to classical transition mechanism needs to be clarified. The problems of accelerating/rotating observers and particle detectors, and associated effects involving negative energy fluxes, continue to hint at deep links between the quantum "aether" and gravitational thermodynamics, but in the absence of an agreed definition of gravitational entropy, the subject is incomplete. At a more down-to-earth level, the possibility of laboratory observations of vacuum friction effects promises to open up a new class of experiments to test the foundations of quantum mechanics.

A further set of unsolved problems concerns the deeper significance of the relationship between acceleration and quantum vacuum noise. Does the existence of "acceleration radiation" suggest a link between the quantum vacuum and inertia? Haisch *et al.*[41] claim that the very existence of inertia can be traced to the activity of vacuum noise on an accelerating particle. Although this claim has not received widespread support, it is tempting to believe that the distinction between inertial and accelerated motion provided by acceleration radiation is telling us something fundamentally new about the principles of dynamics.

Finally, the key open questions can be summarized as follows.

(1) Can quantum vacuum noise explain the large-scale structure of the universe? What is the spectrum of primordial fluctuations? How does a quasiclassical world emerge from the chaos of space–time foam?
(2) Can negative energy fluxes be used to suppress quantum vacuum noise in such a way as to lower entropy or violate cosmic censorship?
(3) What is the relationship between vacuum noise, entropy, and gravitation?
(4) What is the end state of an evaporating black hole? Where does the information go?
(5) Is the universe intrinsically noisy in the very structure of space–time itself, or is microscopic information ultimately conserved?

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