QUANTUM VACUUM FLUCTUATIONS, ZERO POINT ENERGY AND THE QUESTION OF OBSERVABLE NOISE

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In this paper we review the unsolved problem surrounding the exact relationship between noise, zero point energy and vacuum fluctuations. We survey the unresolved debate highlighting marked differences of opinion in the literature. Much of the uncertainty is shown to be due to unresolved fundamental issues in quantum mechanics.

1 Introduction

If we consider the thermal noise across a resistor R, loaded by a capacitor C, we can classically calculate noise over the total bandwidth. This has been carried out [1] for the various limiting cases of R and C and the results are displayed in Table 1.

Table 1: Thermal noise over infinite bandwidth for different cases of limiting R and C.

	Classical			Quantum		
	$\langle v_n^2\rangle$	$\langle i_n^2\rangle$	$\langle q_n^2\rangle$	$\langle v_n^2\rangle$	$\langle i_n^2\rangle$	$\langle q_n^2\rangle$
$R\to 0$ Shorted Cap.	0	0	0	0	0	0
$R\to\infty$ Open Cap.	$\frac{kT}{C}$ (dc)	0	kTC (dc)	$\frac{kT}{C}$ (dc)	0	kTC (dc)
$C\to\infty$ Shorted Res.	0	∞	∞	0	$\frac{2}{3hR}(\pi kT)^2$	∞
$C\to 0$ Open Res.	∞	0	0	$\frac{2R}{3h}(\pi kT)^2$	0	0

If we examine the classical solutions in Table 1, the most obvious problem with thermal noise formula $\langle v_n^2\rangle = 4kTR\Delta f$ is that it classically predicts infinite noise voltage for $C \rightarrow 0$ and infinite noise current for $C \rightarrow \infty$. This is an analogous situation to the black-body radiation problem where the Rayleigh-Jean's law suffers from the so-called ultraviolet catastrophe – the divergent black-body curve having infinite area over all frequencies. Anticipating this, Nyquist [2] in 1928 suggested replacing kT with the one-dimensional form of Planck's law

$$\frac{hf}{e^{hf/kT}-1} \tag{1}$$

which reduces to kT as $f \rightarrow 0$ and rolls off for $hf > kT$. This roll-off conveniently imposes a physical limit on the bandwidth and we see for this quantum case, in Table 1, that the infinities in question disappear. The remaining infinity for noise charge, in the quantum case, is not a breakdown of quantum theory but is due to $C \rightarrow \infty$ becoming an infinite store of charge [1]. $C \rightarrow \infty$ can be thought of as being modeled by an ideal voltage source and note, furthermore, that the noise process becomes non-stationary.

So far so good, Nyquist's quantum term successfully removes the unwanted infinities, however introduces a new set of problems. Firstly, this quantum term, alone, is obviously inadequate as it predicts that we can communicate with noiseless channels if $hf > kT$ (ie. in the Tera Hertz band). This is no longer an academic question as gallium arsenide resonant tunneling quantum electronic devices now operate in the THz domain. Gallium arsenide detectors [3] and sources [4] of THz radiation have been reported.

A second problem is that the quantum term, in Eqn. 1, predicts zero energy at $T = 0$ which is a violation of the Uncertainty Principle. As we shall see the solution to this creates a further conundrum.

2 The Quantum Energy Catastrophe

During 1911-12, Planck's 'second theory' produced the following modification to the quantum term [5]

$$\frac{hf}{e^{hf/kT}-1} + \frac{hf}{2} = hf \coth\left(\frac{hf}{2kT}\right). \tag{2}$$

The extra $hf/2$ term is called the *zero-point energy* (ZPE) and in this case, at $T = 0$, the Uncertainty Principle is not violated. This creates a further conundrum in that $hf/2$ is infinite when integrated over all frequencies, which is an apparent return to the type of 'catastrophe' problem we saw in the classical case. One can only assume that Nyquist accordingly did not suggest this form and probably would have been aware of Planck's own misgivings concerning the experimental objectivity of $hf/2$. The inclusion of $hf/2$ in standard noise texts only became popular after 1951 following the classic work of Callen & Welton [6] that produced the $hf/2$ ZPE term as a natural consequence of their generalized treatment of noise in irreversible systems using perturbation theory.

The solution to the catastrophe problem is that $hf/2$, in fact, turns out to be the *ground state* of a quantum mechanical oscillator. If n is the quantum number, which is a positive integer, then the allowed energy states for a quantum oscillator are $(n + \frac{1}{2})hf$ and thus the ground state is given when $n = 0$. As there is no lower energy state than the ground state, there is no energy level transition available to release the ZPE. Therefore it can be argued that $hf/2$ should be dropped before integration of the quantum expression. This procedure is an example of *renormalization*, which basically redefines the zero of energy. Renormalization is a significant area of quantum field theory and is usually presented in a more formal manner. The problem of renormalization is an open question in the theory of gravitation where there is the apparent catastrophe of *total* energy becoming infinite. For most laboratory measurements there is no catastrophe as we are only interested in energy *differences*. It is rather vexing that many basic texts herald quantum theory as removing the classical catastrophe, without admitting to the new set of catastrophe type problems it introduces such as in gravitation – a modern fully covariant theory of renormalization [7] resolves some problems, but the case is not yet fully closed.

The fact that the ground state energy, which we call ZPE, cannot be released means that texts that quote the Callen & Welton $hf/2$ term as an observable noise component are not strictly correct. However, by coincidence it turns out that the mean square of the zero point fluctuation (ZPF) also has the $hf/2$ form [8]. The mean square does not vanish with renormalization, of course, and this ensures the Uncertainty Principle survives renormalization. The mean square fluctuation is a detectable quantity and represents the magnitude of the ZPF. This noise starts becoming significant, just when the thermal noise begins to roll-off, in the THz band, thus preventing the possibility of noiseless communication.

Each mode contributes $hf/2$ towards the mean square fluctuation and, for an infinite number of frequencies, the magnitude is infinite. It is considered that this infinity is not fundamental, since the measurement conditions have not been specified. It can be shown [8] that for any finite observation bandwidth and volume of space the magnitude of the fluctuations of a quantum field is finite – if either the bandwidth is infinite or the measurement is evaluated at a *point* in space then the fluctuations become infinite.

3 The Steak Grilling Debate

In 1982, Grau & Kleen expressed the view that $hf/2$ is both unextractable and unobservable, adding their memorable rejoinder in the *Solid-State Electronics* journal that $hf/2$ is not "available for grilling steaks" [9]. Uncannily, about the same time Koch, Van Harlingen & Clarke (KVC) published noise measurements in superconductors reporting to have observed ZPF [10]. Over the next 3-4 years a number of independent superconductor papers followed, all nonchalantly quoting the KVC interpretation of ZPF as standard. In reply, Kleen (1987) essentially restated his case pointing out an unanswered question in the superconductor measurements [11]. As far as we are aware there has been no published KVC reply. This debate epitomizes the tension in schools of thought between $hf/2$ merely producing a measurement artifact (school of Kleen) and $hf/2$ being a real noise power (school of KVC).[a]

The orthodox position, is that the effects of ZPF are observable such as in the Casimir effect [12]. ZPF also has an orthodox status in explaining the observations of Mullikan [13], Lamb [14] and the nature of liquid helium [15]. On the other hand, consensus is not total as the school of Kleen has some support [16,17], the commonly supposed link between spontaneous emission and ZPF has been criticized [18] and the overall understanding of ZPF is also questioned as expressed, for example, in the following quote [19]:

> "The obvious question, then, is whether the zero-point energy and the vacuum fluctuations are one and the same thing. If they are, why is it that the former can be eliminated from the theory? The answer is not yet clear, and a deeper significance has yet to be discovered. Therefore, we will adopt the view that the zero-point energies are to be formally removed from the theory...., and all physical effects of the type.... discussed are to be ascribed to quantum fluctuations of the vacuum.... It must be admitted that the vacuum is not completely understood, neither physically nor philosophically. Whether or not the vacuum fluctuations are intimately related to the (unobservable) zero-point energy remains an open question."

where the expression "vacuum fluctuations" is an alternative term for ZPF. The view that ZPF cannot give rise to a detectable noise power itself, but can indirectly modulate or induce a detectable noise power has been expounded by Senitzky [20]. As for grilling steaks, the debate still sizzles but has shifted away from electrical noise theory. Controversial attempts to harness ZPE are underway using the concept of system self-organization [21] and presupposing the idea that the ground state is not the actual source of energy but is a 'pipeline'

[a]It is curious to note that KVC consistently always refer to the term 'ZPF' in their papers, whereas Kleen always uses the term 'ZPE' – hence there is the added confusion of semantics entangled with valid points of disagreement.

into some universal background source [22]. In an enterprising decade where there have been controversial attempts to consider superluminal velocity [23] and quantum information theory (promising two bits of information from one physical bit [24] and a form of teleportation [25]), there is no doubt that we have not heard the last of ZPE research. It remains to be seen what concrete results are produced and, if any, what the implications are to noise theory. Until further evidence, the quantum zero-field should be regarded as a conservative field as far as the extraction of energy is concerned. We can illustrate this using the thought experiment of a pair of parallel plates being pulled together by the Casimir effect – we can imagine one of the moving plates attached to a cord over a pulley with a miniscule mass on the end. As the mass is raised, the plate therefore does work and hence a small amount of energy is extracted from ZPF. However, external energy must be put into the system, to separate the plates to restart the process. Hence we have a conservative field. It could be argued that the ZPF is merely releasing externally introduced energy, stored by the system, and this may be a mechanical analogy of Senitzky's view [20].

On the other hand, Jaynes has pointed out [26] that the energy density of the Lamb shift, in a hydrogen atom, caused by ZPF, would give rise to a Poynting vector about three times the power output of the sun. This had led to a view that ZPF has no reality [27]. Hence the level of reality of ZPF, in this example, is in tension with the previous example. This also reflects the tension between KVC and Kleen.

Another consequence of a literal view of ZPE is that via the $E = mc^2$ relation and general relativity, this energy can also act as the source of a gravitational field – call this energy density in space W. Then the Kepler ratio for a planet with mean distance R from the sun and period T is proportional to $m_{\text{sun}} + (\frac{V}{c^2})W$, where V is the volume of the sphere of radius R. To agree with observed ratios for the planets the upper frequency cutoff for W can be no higher than optical frequencies [28]. But any attempt to account for the Lamb shift with ZPF requires a cutoff thousands of times higher, at the Compton wavelength [28]. This gravitational energy would not only disturb the above ratios, but it would radically disrupt the solar system. This *ad hoc* selection of frequencies for the operation of ZPF for the convenience of explanation is problematic.

4 Quantum Cut-Off Experimental Status

Fig. 1 shows a theoretical plot of the quantum term for different temperatures. The $hf/2$ term is plotted to illustrate that at normal working frequencies and temperatures it is vanishingly small, so for these conditions it can be

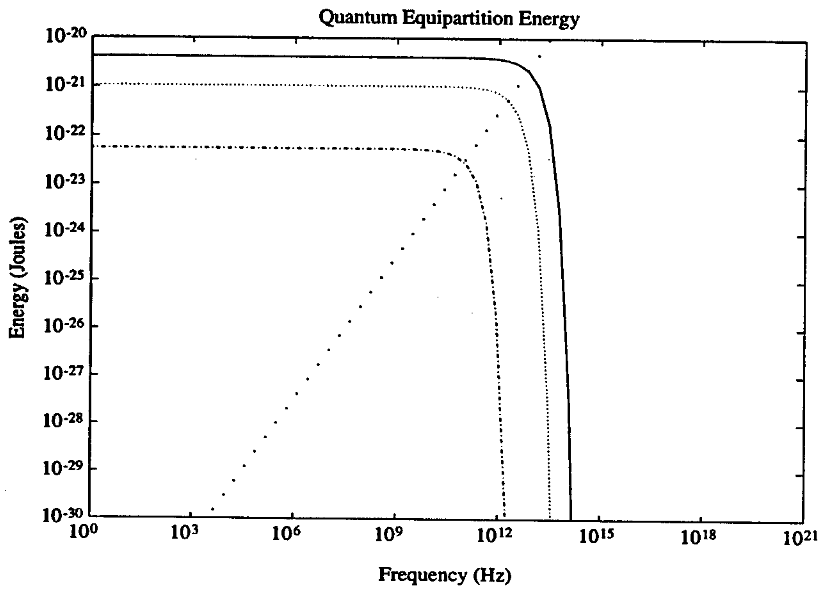

Figure 1: Quantum equipartition energy versus frequency for 300K, 77K and 4K. The line represents the hf/2 term plotted separately.

neglected regardless of the status of debate. It can be seen from the Fig. 1 plot that experimental verification of the quantum cut-off point for electrical noise is rather difficult due to the Tera Hertz frequencies. If the temperature is reduced, to reduce the cut-off frequency, we see that the maximum energy of the curves falls, thus making noise detection more difficult. In 1981, van der Ziel [29] proposed to make measurements in this region, at 100 GHz using Hanbury-Brown Twiss circuits; unfortunately, this research effort was never completed. The only curves we have today, for electrical noise, appear to be those of the type of KVC, which show no cut-off due to ZPF becoming significant. Therefore, as far as we are aware, there are no measurements that directly demonstrate the quantum cut-off for *electrical* thermal noise, to this day. Although the cut-off region, for electrical noise, has so far been obscured by ZPF it may become possible in the future to view at least part of this region, without violation of the Uncertainty Principle, if somehow the concept of *squeezed states* can be successfully employed for the electrical case (eg. [30]).

5 Conclusion

We have reviewed the debates surrounding the objectivity of the influence of ZPF on electrical noise. Although in the literature, terminology is not standard, we suggest to prevent confusion that the unextractable and unobservable groundstate is called ZPE, whereas the vacuum fluctuations themselves are called ZPF. We noted that the mean square fluctuation of ZPF has the form hf/2 and ZPE also has the form hf/2. This has caused some consternation in the literature and we highlighted that these quantities are different. ZPE can be removed by renormalization, whereas the effects of ZPF can be seen in a number of physical phenomena. It is clear that noise measurements are affected by an hf/2 law, as seen experimentally, otherwise communication channels would be noiseless above a certain frequency. However unresolved debate surrounds whether this represents a real noise power or is some quantum disturbance of a measurement (with no power to grill steaks). Also, Senitzky proposed a third option that ZPF cannot do work, but can modulate power from an outside source. All these views have problems: (1) insistence on a measurement artifact, with no work done seems to deny the reality of other observed ZPF effects, (2) whether power is produced or modulated, as per Senitzky, still leaves the problem of potential indefinite increase by hf/2. It seems that vacuum fluctuations are still not fully understood. Solutions could come either from developments in quantum physics or alternatively there is an opportunity to further tackle the problem from the point of view of noise.

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