VACUUM RADIATION, ENTROPY AND THE ARROW OF TIME

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Abstract

The root mean square perturbations on particles produced by vacuum radiation must be limited by the uncertainty principle, i.e., $< d\, x^2 >^{1/2} < d\, p_x^2 >^{1/2} = \hbar / 2$, where $< d\, x^2 >^{1/2}$ and $< d\, p_x^2 >^{1/2}$ are the root mean square values of drift in spatial and momentum coordinates. The value $< d\, x^2 >^{1/2} = (\hbar t / m)^{1/2}$, where m is the mass of the particle, can be obtained both from classical SED calculation and the stochastic interpretation of quantum mechanics. Substituting the latter result into the uncertainty principle yields a fractional change in momentum coordinate, $< d\, p_x^2 >^{1/2} / p$, where p is the total momentum, equal to $2^{-3/2} (\hbar / Et)^{1/2}$, where E is the kinetic energy. It is shown that when an initial change $< d\, p_x^2 >^{1/2}$ is amplified by the lever arm of a molecular interaction, $< d\, p_x^2 >^{1/2} / p \geq 1$ in only a few collision times. Therefore the momentum distribution of a collection of interacting particles is randomized in that time, and the action of vacuum radiation on matter can account for entropy increase in thermodynamic systems.

The interaction of vacuum radiation with matter is time-reversible. Therefore whether entropy increase in thermodynamic systems is ultimately associated with an arrow of time depends on whether vacuum photons are created in a time-reversible or irreversible process. Either scenario appears to be consistent with quantum mechanics.

1. Introduction

In this paper we will see that entropy increase in thermodynamic systems can be accounted for by vacuum radiation, and then discuss the relationship between vacuum radiation and the arrow of time.

The problem in accounting for entropy increase has always been that dynamical interactions which occur at the molecular level are time-reversible, but thermodynamic processes associated with entropy increase, such as diffusion and heat flow, only proceed in one direction as time increases. In the past it was often held that entropy increase is only a

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macroscopic phenomenon, which somehow appears when a coarse-grain average is taken of microscopic processes. But no averaging of time-reversible processes has ever been shown to account for phenomena which are not time-reversible.[1]

Nowadays entropy increase is often viewed as coming from effects of the environment, such as walls of a container or thermal radiation, not taken into account in the description of a system. Unruh and Zurek [2] have given examples in which entropy increase is produced in this way.

However, the second law of thermodynamics specifies that entropy increase must also occur in an isolated system. So if we are to hold that entropy increase is produced by a physical process at the microscopic level, we must also understand how it can be produced in this way in an isolated system.

Any explanation must satisfy the basic assumptions of statistical mechanics. Classical statistical mechanics has only one assumption:

> *At equilibrium it is equally probable that the system will be in any (classical) state which satisfies the thermodynamic constraints*.

Quantum statistical mechanics has two basic assumptions. The first is essentially the same as for classical, except that states are now counted quantum mechanically. Thus:

> *At equilibrium it is equally probable that the system will be in any (quantum) state which satisfies the thermodynamic constraints*.

The second assumption of quantum statistical mechanics is:

> *At equilibrium the relative phases of the eigenvectors describing the system are random.*

Once these fundamental assumptions are made, one can then define entropy as *k*log(number of states), where *k* is Boltzmann's constant. It is always also assumed that the number of molecules, and therefore the number of states, is extremely large. One can then develop the physics of the microcanonical ensemble in the usual way, by requiring that different parts of an isolated system be in equilibrium with each other at temperature *T*. By placing the system in equilibrium with a heat bath one can then derive the physics of the canonical ensemble, and so forth.[3]

In order to talk about entropy, we must specify the context in which we refer to the ensemble of all possible states. In the coarse-grain view we would use an ensemble of states with all possible initial conditions, and then argue that because the number of states is very large, the only states we are apt to see are the most probable ones (and not ones in which all molecules are clustered in a corner of a box, for instance). Thus equilibrium merely refers to the most probable state in a large collection of systems. In the view in which entropy is produced at the microscopic level, we start with a single system which has specified initial conditions (classical or quantum mechanical) and look for a process which produces many random perturbations and by this means places the individual system into its most probable state.

In order to inquire about an isolated system, let us consider the system to be comprised of not only the interacting molecules under consideration, but also the walls of their container, any heat bath surrounding them, and all the thermal radiation which might affect them. It would seem that we have taken into account all interactions which could possibly affect the system. What then could serve as an "environment" which would account for entropy increase?

Let us ask if an interaction could take place within the limits of the uncertainty principle which would affect molecules randomly? If this interaction could randomize the momentum of each molecule and (when quantum mechanical description is needed) randomize the quantum phases of the eigenvectors describing the system, this process would then account for entropy increase. Yet the interaction itself could not be detected in measurements of the system.

Vacuum radiation acts at the limits of the uncertainty principle, and clearly it would perturb molecules in a random way. But are these effects large enough? A thermodynamic system goes to equilibrium in a few molecular collision times.[3] So in order to account for entropy increase, vacuum radiation would have to randomize the momentum of a system and the quantum phases of its eigenvectors in that short time. Let us first take up the question of momentum.

2. Randomization Of Momentum By Vacuum Radiation

2.1. DRIFT IN SPATIAL COORDINATE

It has been shown by Rueda [4] in a classical stochastic electrodynamics (SED) calculation that the coordinate drift produced on a free particle by vacuum radiation can be described by diffusion constant $D = \hbar/2m$, where m is the mass of the particle. A quantum mechanical calculation of this effect of vacuum radiation has not been done. However, when only energy and momentum transfer are involved and not anything specifically quantum about the nature of the radiation involved, it is reasonable that an SED calculation will give the same result as a quantum mechanical one.[5,6]

Rueda showed that vacuum radiation moves electrons in a random walk at relativistic speeds and that this motion accounts for nearly all of their mass, with step length varying from the Compton wavelength to the de Broglie wavelength. The radiation acts on hadrons at the quark level and moves the hadrons at sub-relativistic velocity.[4]

We note that the stochastic interpretation [7] of the Schrödinger equation, which has no direct connection to vacuum radiation, but attributes a quantum brownian motion to particles, yields the same diffusion constant. In a similar vein, the stochastic action of particles, with the same range of step lengths as above, can be derived directly from the uncertainty principle in the following way. Suppose that we have an ensemble of particles, labeled 1, 2, ... Each is subject to a series of position measurements at equal time intervals. Particle 1 is measured with resolution Δx_1, particle 2 with resolution Δx_2, and so forth, with $\Delta x_1 > \Delta x_2 > ....$ According to the uncertainty principle, as measurement resolution becomes increasingly fine, particle momentum is increasingly more uncertain, and the path is more erratic. Using this point of view, a particle can be described as following a continuous, non-differentiable path of fractal dimension two, which corresponds to brownian motion.[8] Further analysis shows that the step lengths vary from the Compton wavelength to the de Broglie wavelength.[9]

The above diffusion constant yields a root mean square spatial drift $< d\, x^2 >^{1/2} = (2Dt\,)^{1/2}$ [10], so

$$< d\, x^2 >^{1/2} = \left[\frac{\hbar\, t}{m} \right]^{1/2} . \qquad (1)$$

The above result can be confirmed experimentally using a tightly collimated beam of low energy electrons. For instance, if a beam of 100 ev electrons has $v_y/v_x = 10^{-5}$ (where x is the forward direction of travel), the spread in beam width due to the above process will be larger than the spread due to diffraction in the first 19.5 cm of travel.[11] This experiment has not presently been done, however.

2.2. RANDOMIZATION OF MOMENTUM

Vacuum radiation acts at the limits of the uncertainty principle, so we write $< d\, x^2 >^{1/2} < d\, p_x^2 >^{1/2} = \hbar / 2$, where $< d\, p_x^2 >^{1/2}$ is the root mean square shift in momentum component of the particle produced by vacuum radiation. It is then easily found that

$$\frac{< d\, p_x^2 >^{1/2}}{p} = \frac{1}{2^{3/2}} \left[\frac{\hbar}{E\, t} \right]^{1/2} , \qquad (2)$$

where p is the total momentum of the particle and $E = p^2/2m$ is the energy. We see that $< d\, p_x^2 >^{1/2}$ is proportional to $t^{-1/2}$, so momentum is conserved as time becomes large.

Perturbations in momentum of a particle will change its original value, and when $< d\, p_x^2 >^{1/2} / p > 1$, momentum has been completely randomized. We wish to know how long this will take. In order to have a concrete example, let us start with air at standard conditions. At the end of one collision time (i.e., the time to travel a mean free path), $< d\, p_x^2 >^{1/2} / p = 1.186 \times 10^{-3}$.[11] However, any change in momentum is multiplied by a lever arm $A = l/r$, where l is the mean free path and r the molecular radius, during the next collision.[11] In air at standard conditions $A = 1.005 \times 10^4$.[11] Therefore, the momentum distribution of the molecules has been randomized in two collision times.

The product $A < d\, p_x^2 >^{1/2} / p$ is proportional to $(kT)^{1/4} / (s\, P^{1/2})$.[11] Therefore, momentum is randomized in a few collision times for all gases except those at very high pressures (> 100 atm, or higher if the temperature is substantially more than 300 K). In solids and liquids many particles interact simultaneously, so it is reasonable to suppose that momentum will randomize within a few collision times in these also.[11]

3. Randomization Of The Phases Of The Eigenvectors

In order to fulfill the second fundamental assumption of quantum statistical mechanics, it is necessary to show that vacuum radiation can randomize the relative phases of the eigenvectors describing the system within a few collision times. We make no calculation here, but simply show that this is likely to be the case.

First, we note that perturbation theory tells us that components of eigenvectors added to a system because of a perturbation are out of phase with the original state vector.[12] Furthermore, because vacuum radiation will produce many small, independent effects, we can see by considering either a coordinate or a momentum representation of the eigenvectors that these effects would affect different eigenvectors differently. So we would expect the relative phases of the eigenvectors to be randomized.

The above does not tell us how quickly this randomization would occur. However, Unruh and Zurek [2] have shown in various examples that when an environment perturbs a system, the off-diagonal elements of the density matrix go to zero in a much shorter time scale than effects involving spatial and momentum distributions. Thus it seems likely that vacuum radiation can diagonalize the density matrix in a shorter time than it takes to randomize momentum.

4. The Arrow Of Time

The dynamical laws of physics are time reversible, i.e., for any given trajectory described by them, the time reversed trajectory is also a solution of the equations. And in nearly all cases, both the process described by these equations as time moves forward and the process described when time is reversed can be observed to occur. But curiously, there are a few exceptions to this rule. The decay of K-mesons violates CP and therefore (assuming CPT holds) is not time symmetric. Electromagnetic waves emanate from a source out to infinity, but do not converge from infinity to a source. Collapse of the wave function is a one-way process.[13,14] And as Prigogine and co-workers have shown, in systems which are so unstable that they cannot be described analytically in an ordinary dynamical framework, process can go in only one direction.[15] Such processes can be called *irreversible*, and they are accounted for by saying they are governed by an *arrow of time*. It is not known what an arrow of time is, what it has to do with the rest of physics, or whether any of the above arrows of time have anything to do with each other.

It has been shown herein that entropy increase in thermodynamic systems is produced by the interaction of vacuum radiation with matter. This interaction is time reversible. However, we can go back a step and ask how vacuum radiation is produced. Whether an arrow of time is ultimately involved in entropy increase depends on the answer to this question, as we will see.

In examining this issue, let us start with a classical (SED) analysis. Puthoff [16] has shown that if vacuum radiation with its frequency-cubed spectrum once exists, then random interactions with matter in which radiation is absorbed and matter accelerates and reradiates maintain this frequency-cubed spectrum indefinitely. From this perspective, the random nature of the interaction of vacuum radiation with any given particle is caused by the random distribution in position and momentum of other particles the radiation previously interacted with. All interactions are time-reversible, and it is not necessary to invoke an "arrow of time" to explain entropy increase in thermodynamic systems.

In quantum mechanics photons exist in quantized units of energy hn . However, the average energy per photon of vacuum radiation is $1/2\ hn$. For that reason it is commonplace to explain the average energy by supposing that photons spontaneously and causelessly arise out of the vacuum, exist for the time allotted by the uncertainty principle, and then annihilate themselves back into the vacuum. In this scenario information describing the state of the newly created vacuum photon arises from nothing, the photon interacts with matter and modifies the information describing its state according to this interaction, and this modified information is then destroyed when the photon annihilates itself.

The dynamical information which is introduced in the creation of virtual photons is purely random. However, the information which is removed is no longer random (or potentially is not because the virtual photons could have interacted with an ordered system). Thus the beginning and end points are inherently different, and an arrow of time is defined. According to this view, entropy increase is therefore ultimately associated with an arrow of time.[11]

On the other hand, it would seem that quite different views of the arising and disappearance of photons are possible. The basic equations of QED and quantum field theory do not tell us how vacuum photons (or other virtual particles) arise. And creation and annihilation operators, although they have evocative names, simply describe mappings from one state to another in Hilbert space, the same as any other operators. The idea that vacuum photons arise spontaneously out of the vacuum is basically a pictorial device to account for the average energy per photon of $1/2\ hn$. Alternatively, one can conceive that, comparably to the classical picture, vacuum photons arise and disappear through constructive and destructive phase interference of a large number of photons traveling in different directions. To be consistent, one would have to view all other virtual particles as also arising and disappearing through constructive and destructive interference of quantum phase, perhaps through interaction with negative energy particles. But the appearance and disappearance of virtual particles could perhaps occur in this way. Another possibility is that the seemingly random appearance and disappearance of virtual particles comes about through interactions in the extra dimensions provided by string theory. In each of these cases processes would be entirely time-reversible, and no arrow of time would be involved.

We can put this issue another way by asking: Is the universe a continuous source of random dynamical information, creating virtual particles which can interact with matter and then return some of the previous dynamical information describing this matter to the vacuum? Or does the universe merely transform dynamical information, with virtual particles arising and disappearing through a process such as the above? At present there is no answer to these questions and, given quantum indeterminacy within the limits of the uncertainty principle, there may never be any conclusive answer.

5. Conclusion

As vacuum radiation interacts with particles, it exchanges momentum with them. The fractional change in momentum of a particle $<d\,p_x^2>^{1/2} / p$ after one collision time, when multiplied by the lever arm of succeeding molecular interactions, becomes greater than one in only a few collision times. Therefore, particle momentum is randomized during that time, and vacuum radiation can account for entropy increase in thermodynamic systems.

Vacuum radiation interacts with matter in a time-reversible process. Therefore, whether entropy increase in thermodynamic systems should be viewed as ultimately connected with an arrow of time depends on whether the arising and disappearance of vacuum photons should be considered as a time-reversible or irreversible process. Either possibility appears to be consistent with quantum mechanics.

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