Extracting energy and heat from the vacuum

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Relatively recent proposals have been made in the literature for extracting energy and heat from electromagnetic zero-point radiation via the use of the Casimir force. The basic thermodynamics involved in these proposals is analyzed and clarified here, with the conclusion that, yes, in principle, these proposals are correct. Technological considerations for actual application and use are not examined here, however.

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Nearly a decade ago Forward [1] raised the possibility of extracting energy from the electromagnetic zero-point (ZP) fields that are predicted by quantum electrodynamics to be present in all of space. He described a means of accomplishing this task via a mechanical device consisting of a charged foliated conductor. By using the attractive Casimir force between metal layers to overcome a repulsive electrostatic force, the foliated conductor can be greatly compressed, thereby storing charge at a high electrostatic potential energy.

More recently, one of us (Puthoff) has again raised the possibility of energy extraction from the vacuum [2], while also emphasizing that the energy density of the electromagnetic ZP energy has conservatively been estimated to be equal to or greater than nuclear energy densities [3]. Puthoff suggested a potentially more practical and plentiful means for energy extraction, namely, a method involving a charged plasma. His discussion included the idea of generating heat from the vacuum.

Here we do not comment further on devising practical methods for enabling the vacuum to become a viable, economical alternative to more conventional sources of energy, except to say that, without a doubt, considerable technological effort might need to be expended to adequately harness such energy. Instead, here we will concentrate on the issue of whether fundamental thermodynamic laws are being violated in even considering this possible source of energy. In particular, certainly the "vacuum" should be considered to be a state of thermal equilibrium at the temperature of $T=0$. How then can energy be extracted, and even heat generated, at $T=0$?

Some relatively recent articles by one of us (Cole) provide a starting point for this discussion. These articles analyze the thermodynamics of quasistatic displacement operations on fluctuating electric dipole harmonic oscillators [4–7] and on conducting parallel plates [8]. The operations involve, respectively, the microscopic van der Waals force between atomic systems, and the macroscopic Casimir force between parallel plates. Due to the fundamental thermodynamic definition of $T=0$, no heat flow should occur at $T=0$ during quasistatic displacements of these systems. Indeed, for these two systems, as treated via classical physics, only one electromagnetic thermal radiation spectrum was found to ensure that no heat would flow: namely, the classical electromagnetic ZP radiation spectrum, which has the same spectral form as the ZP spectrum predicted to exist via QED. The existence of this radiation results in van der Waals and Casimir forces at $T=0$, thereby yielding a tight connection between the required spectrum and the resulting forces.

At first thought, a contradiction appears inevitable between the analysis yielding "no heat flow at $T=0$" and "heat extraction at $T=0$." However, the contradiction becomes resolved upon recognizing that two different types of thermodynamic operations are being discussed. The quasistatic operations are thermodynamically reversible, so here no heat flow occurs at $T=0$. In contrast, the heat generation process discussed in Ref. [2] is thermodynamically irreversible, so heat can be produced, even when the initial temperature is $T=0$.

The following analysis will cover both the $T=0$ and $T\neq0$ cases. Indeed, although the proposals in Refs. [1,2] discussed only the very idealized $T=0$ case, they can be shown to be valid also at $T\neq0$. Our analysis will use classical physics arguments, as in Refs. [4–8].

The mechanism for heat generation is illustrated in the following thought experiment, which clearly is an impractical process, yet it embodies the necessary points. Suppose there exists a large number of uncharged parallel plate capacitors. The plates of each capacitor will be attracted to each other by the fluctuating, yet correlated, induced charge distributions in each plate, that arise on account of the fluctuating ZP plus thermal radiation fields. If each pair of plates is allowed to collide, some of the kinetic energy generated will be converted into heat. Collecting the useable portion of the heat, discarding each pair of plates, and then colliding the next set, in turn, thus yields a means for heat generation. The "fuel" here is the supply of capacitors; the used up capacitors are analogous to the exhaust from gasoline engines or the "waste" from nuclear fuel.

To analyze this process more deeply, the physical description of colliding systems needs to be addressed. In particular, whether we consider macroscopic materials attracted via Casimir forces, or individual atoms attracted together via van der Waals forces, other interatomic interactions need to be considered when the systems come very close to each other. To avoid such complications, let us consider only the situation where, for example, two plates, or two atoms, are initially held apart, then released, and then "grabbed" or blocked by an external force or medium, before the systems collide.

Upon releasing the two attractive systems, they will move toward each other, thereby acquiring kinetic energy. If we then seize them with probes in such a way that the probes should move, or if a material "stop" placed in the path of the system is displaced somewhat, then work will be done upon the probe or stop. Likewise, when making the quasistatic displacements in Refs. [4–8], work could be done on the probes by the displaced systems by making the displacements along the directions of the van der Waals or Casimir forces. In this way, energy is "extracted" by having such systems perform work.

However, heat extraction is quite different than energy extraction, where by energy extraction we henceforth specifically mean the act of having systems perform positive work. During reversible operations, such as are discussed in Refs. [4–8], work will, in general, either be done by or on these systems. However, only for $T \neq 0$ can heat also be generated during these displacements, where heat, here, consists of energy in the form of electromagnetic radiation that flows from the region surrounding the system in question.

In contrast, for irreversible operations, heat will in general be produced. Upon releasing two plates or particles and then stopping them before they collide, not all of the kinetic energy will typically be transformed into work done upon the material stops. Indeed, in the case of a hypothetical infinitely massive stop, no work will be done. Instead, kinetic energy must be converted into electromagnetic radiation energy. The emitted radiation, or perhaps more appropriately, the radiation that results after interacting with randomizing entities, such as an idealized carbon particle [9,8], would then constitute the heat that flows from the system. In an open system this energy will radiate away and the final state of the system would be the same as if we quasistatically brought the particles together, where work is now done in displacing the material stops that hold the particles.

To show that there are no contradictions with these ideas, we next compare two related thought experiments consisting of an irreversible and a reversible operation, as indicated in Figs. 1(a) and 1(b), respectively. The small darkened circles labeled X and Y represent systems that might be neutral conducting plates, dipole oscillator particles, or other more complicated systems attracted together due to van der Waals forces. The rectangles with crosshatched lines represent material stops used to hold the systems in place. In Fig. 1(a), three stops labeled A, B, and C are displayed, while in Fig. 1(b), only two stops A and C are shown. The left and right sides of both figures represent the initial time t_i and final time t_f, respectively, of the two operations to be discussed.

Starting with Fig. 1(a), let stop A be slightly displaced to the left, so that the system is no longer in mechanical equilibrium. A negligible amount of work can be assumed to be done when making this displacement. Subsequently, X will accelerate toward Y and increase its kinetic energy until it hits B. If stop B is not displaced much, or more precisely if $\int_{t_i}^{t_f} \mathbf{F}_B(t)\cdot\mathbf{v}_B(t)dt$ is small, where $\mathbf{F}_B(t)$ is the force from X acting on stop B at time t, and $\mathbf{v}_B(t)$ is the velocity of stop B at time t, then most of the kinetic energy of the system will be converted into electromagnetic energy. If we assume that the box drawn around the system represents a perfectly conducting container that acts to retain all radiation, then this electromagnetic energy cannot escape. Imagining that a small, idealized carbon particle is introduced into the system, then the character of the radiation will again return to a thermal radiation form. The temperature of the system must therefore increase as a result of this sequence.

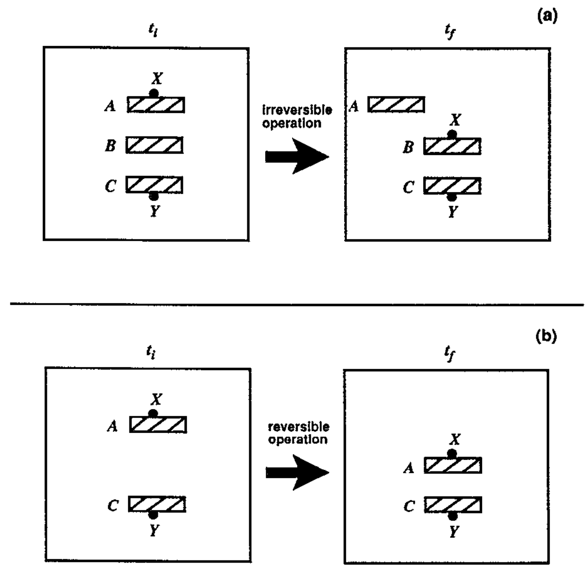

FIG. 1. Examples of an irreversible (a) and a reversible (b) thermodynamic operation on systems X and Y, that are attracted toward each other. (a) The blocks or stops indicated by A, B, and C hold X and Y in place at the initial and final times t_i and t_f. Between these times, stop A is slid to the left, so that X freely accelerates and moves toward Y until hitting and sticking onto stop B. (b) Here a closely related reversible thermodynamic operation is carried out. System X is quasistatistically displaced by slowly moving stop A toward stop C, so that configuration work is done by X and Y on the material stops holding them.

If we now carry out a reversible operation in Fig. 1(b) by quasistatically displacing stop A, then systems X and Y arrive in the same positions as in Fig. 1(a). Here, however, compression or configuration work was done against the structure holding X in place; i.e., the structural form of the "retaining walls" has changed. In Fig. 1(a), no configuration work was done; the retaining structure remained essentially the same between times t_i and t_f, except for the infinitesimal displacement of stop A to the left.

To now make the state of the system in Fig. 1(b) the same as the state of the system in Fig. 1(a), the temperature in Fig. 1(b) must be increased. This operation can be done reversibly via sequentially contacting the system with a series of heat reservoirs with infinitesimally increasing temperatures. In this way also, the example in Fig. 1(b) can be used to calculate the net change in entropy for the irreversible process in Fig. 1(a). This change can be found by adding up dQ/T over all the infinite contact operations, where here dQ is a positive heat flow into the box in Fig. 1(b). Since the entropy of the region outside the containing box in Fig. 1(a) does not change, the net entropy change in the universe for the irreversible operation in Fig. 1(a) is therefore positive, in agreement with the second law of thermodynamics.

Figure 2 provides additional insight. The crosshatched lines from states a to c represent the irreversible, adiabatic, free contraction indicated in Fig. 1(a), while the dark line from a to b represents the reversible, adiabatic contraction in Fig. 1(b). To make the two operations end at the same state, namely c, the system in Fig. 1(b) must be reversibly heated, as indicated by the $b \rightarrow c$ operation in Fig. 2. We note that if the contraction operation of $a \rightarrow b$ is carried out at $T=0$, then in Fig. 2(c) the $a \rightarrow b$ operation would lie at the single point where the R_i and R_f curves come together at $T=0$, due to the third law of thermodynamics [4,5,8]. Likewise the path $a \rightarrow b$ in Fig. 2(b) should become a vertical line at $T=0$, as will be seen shortly in a specific example.

Since the specific shapes of the curves in Fig. 2 depend on the system being analyzed, here we briefly sketch how these curves could be found for a system that can be analyzed in some detail. Consider two dipole harmonic oscillators in a conducting box of volume $\mathcal{V}$, where the oscillators are separated by a distance R that is sufficiently small that the unretarded van der Waals interaction is dominant. Hence, the expressions in Ref. [6] apply:

$$U_{\text{int}} \approx \sum_{A,j} \pi^2 h^2(\varpi_{Aj},T) + \sigma' T^4 \mathcal{V} + C \ , \tag{1}$$

$$W = \sum_{A,j} \int_{\varpi_{Aj,\text{I}}}^{\varpi_{Aj,\text{II}}} d\varpi_{Aj} \pi^2 \frac{h^2(\varpi_{Aj},T)}{\varpi_{Aj}} \ , \tag{2}$$

where

$$h^2(\omega,T) = \frac{\hbar\omega}{\pi^2}\left[\frac{1}{2} + \frac{1}{\exp(\hbar\omega/kT)-1}\right] \tag{3}$$

holds for thermal radiation at temperature T, U_{int} is the internal energy in the box, and W is the work done in displacing the dipole particles. Included in U_{int} is the internal energy in Eq. (22) in Ref. [6] for the dipole oscillators, plus the thermal radiation energy, $U_{\text{EM,in}} \approx (\sigma' T^4 \mathcal{V}) + C$, from Eq. (40) in Ref. [5], where C is a constant and the box dimensions are assumed to be large compared to the distance separating the oscillators. Otherwise, the notation in Ref. [6] applies. Six resonant frequencies ϖ_{Aj} that are each a function of R must be taken into account. The thermodynamic state of this two-particle system is thus specified by only R and T. To simplify the expressions further, if we assume the oscillators are separated along the x direction and are constrained so that oscillations occur only along the y direction, then only two resonant frequencies ϖ_{Aj} exist, namely, $[\omega_0^2 \pm e^2/(mR^3)]^{1/2}$, where ω_0 is the natural resonant frequency of the oscillating particle's motion, and e and m are the charge and mass, respectively, of this same particle.

Knowing R_a, T_a, and R_c, then T_c can be found by considering the irreversible adiabatic free contraction and applying conservation of energy: $U_{\text{int}}(R_a,T_a) = U_{\text{int}}(R_c,T_c)$. To find T_b, with $R_b = R_c$, we can start from state a and follow the adiabatic reversible path $a \rightarrow b$ by demanding that $dU_{\text{int}}(R,T) = (dW/dR)dR$

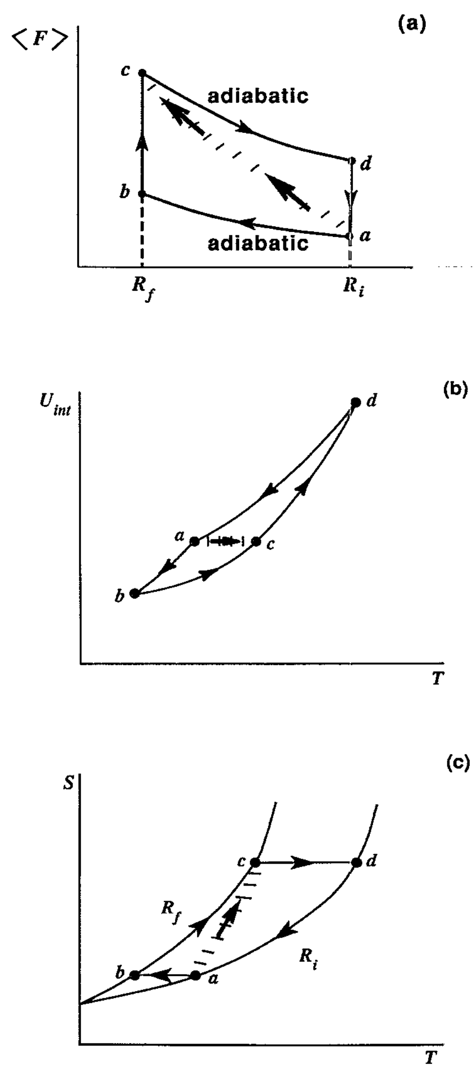

FIG. 2. (a) Plot of externally applied force $\langle \mathcal{F} \rangle$ used to keep apart two systems that attract each other, vs R, the distance between the systems. A thermodynamic reversible set of operations is indicated by the dark lines with arrows, where $a \rightarrow b$ represents an adiabatic contraction from separation R_i to R_f, $b \rightarrow c$ indicates a reversible heating, $c \rightarrow d$ is an adiabatic expansion from R_f to R_i, and $d \rightarrow a$ is a reversible cooling. The crosshatched lines indicate an irreversible, adiabatic, free contraction from a to c. (b) Plot of internal energy U_{int} vs temperature T for the same operations indicated in (a). (c) Corresponding plot of caloric entropy S vs T.

along each infinitesimal part of the path. One obtains

$$dT = dR\,\frac{\sum_{A,j}\left[-\frac{\partial h^2}{\partial\tilde{\omega}_A}+\frac{h^2}{\tilde{\omega}_{Aj}}\right]\frac{d\omega_{Aj}}{dR}}{\frac{4}{\pi^2}\sigma' T^3\mathcal{V}+\sum_{A,j}\frac{\partial h^2}{\partial T}} \quad (4)$$

which can then be integrated to find T_b. As anticipated from Refs. [4] and [6], if $T=0$ at a, then $dT=0$ from Eqs. (3) and (4) for any piece of this path from $a \rightarrow b$, thereby resulting in the $a \rightarrow b$ path in Fig. 2(b) becoming a vertical line at $T=0$. Finally, T_d can be found by starting from T_c and integrating along the reversible, adiabatic path from $c \rightarrow d$. The paths $b \rightarrow c$ and $d \rightarrow a$ in Fig. 2(b) can be obtained directly from Eq. (1) by holding ω_{Aj} fixed while varying T.

As a side comment, we note that a simple thermodynamic system illustrating some of the above properties consists of two nonfluctuating charges q and $-q$ in a large conducting box containing thermal radiation. Here, $U_{\text{int}} \approx -q^2/R + \sigma' T^4 \mathcal{V} + C$. In Fig. 2(a), the two adiabatic curves would lie on top of each other, since the electrostatic force does not depend on temperature. The curves $a \rightarrow b$ and $c \rightarrow d$ would become vertical lines in Fig. 2(b), and the R_i and R_f curves in Fig. 2(c) would lie on top of each other, since $S=\frac{4}{3}\sigma' T^3 \mathcal{V} + S_0$.

In conclusion, our analysis yields nothing strange about having the systems discussed above either generate heat or perform work, such as configuration work. For heat to be generated at $T=0$, an irreversible thermodynamic operation needs to occur, such as by taking the systems out of mechanical equilibrium. When $T \neq 0$, heat can in general be generated for both reversible, nonadiabatic operations, as well as irreversible operations. As for a practical method of energy or heat extraction, this article does not address that question.

[1] R. L. Forward, Phys. Rev. B **30**, 1700 (1984).

[2] H. E. Puthoff, Specul. Sci. Technol. **13**, 247 (1990).

[3] R. P. Feynman and A. R. Hibbs, *Quantum Mechanics and Path Integrals* (McGraw-Hill, New York, 1965), p. 245; see also C. W. Misner, K. S. Thorne, and J. A. Wheeler, *Gravitation* (Freeman, San Francisco, 1973), p. 1202ff.

[4] D. C. Cole, Phys. Rev. A **42**, 1847 (1990).

[5] D. C. Cole, Phys. Rev. A **42**, 7006 (1990).

[6] D. C. Cole, Phys. Rev. A **45**, 8953 (1992).

[7] D. C. Cole, in *Formal Aspects of Electromagnetic Theory,* edited by A. Lakhtakia (World Scientific, Singapore, 1993).

[8] D. C. Cole, Phys. Rev. A **45**, 8471 (1992).

[9] M. Planck, *The Theory of Heat Radiation* (Dover, New York, 1959). This publication is an English translation of the second edition of Planck's work entitled *Waermestrahlung,* published in 1913. A more recent republication of this work is *The Theory of Heat Radiation,* Vol. 11 of The History of Modern Physics and Astronomy (AIP, New York, 1989).