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Short Note

Light at ambient temperature in violation of the Kelvin-Planck Statement of the Second Law ?

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Abstract:

The Kelvin-Planck statement of the second law of thermodynamics precludes the extraction of work from a single thermal reservoir. Very early Carnot showed the efficiency of a heat engine vanishes if operated between reservoirs at the same temperature, or that work cannot be extracted from a single reservoir. Recent attempts to extract work from a single reservoir have relied on exotic quantum Carnot and photon steam engines, but require microwave energy to raise the efficiency of the work extracted above the classical Carnot limit. But exotic quantum engines need not be invoked to extract work from a single reservoir provided a heat engine is devised that produces light as the temperature is lowered to absolute zero. Since means may be devised for the light to lift a weight, and since the temperature approaches absolute zero, work is extracted from a single reservoir in violation of the Kelvin-Planck statement. Rather than performing work, the process finds utility by producing light from the environment at ambient temperature suggesting the Kelvin-Planck statement may need to be refined.

Keywords:

Second law, Kelvin-Planck statement, suppressed IR, cavity QED, frequency up-conversion

Introduction

Traditional statements of the second law [1] include the impossibility of extracting work W from a single reservoir. In the Kelvin-Planck statement,

> It is impossible to construct a device that operates in a cycle and produces no other effect than the production of work W and exchange of heat Q with a single reservoir.

But the Kelvin-Planck statement is but one of more than half dozen [2] common statements of the second law dating back to Carnot 180 years ago. In 1824, Carnot showed the efficiency η of a classical engine (CE) operating between a high T_H and low T_C temperature reservoirs,

$$\eta = 1 - \frac{T_C}{T_H} \tag{1}$$

For the CE supplied by heat from a reservoir and rejecting heat to the same reservoir, the temperatures $T_H = T_C$ and $\eta = 0$, and therefore consistent with the Kelvin-Planck statement the conversion of heat from a single reservoir into work is not possible [3]. However, this limitation may be avoided by a CE converting heat Q from a reservoir at high temperature T_H reservoir and rejecting heat to a reservoir having T_C at absolute zero having an efficiency $\eta = 1$.

Recently, work is proposed [3] extracted from a single reservoir using a quantum engine (QE). The working fluid in the QE is photons that produce radiation pressure in an optical cavity having mirror ends. One mirror functions as the face of a piston while the other is fixed in thermal contact with a reservoir at temperature T_C. Atoms flowing through the optical cavity at temperature T_H form the other thermal reservoir that exchanges heat with the photons. If the atoms flowing in the optical cavity are 2-state systems that emit and absorb radiation at the same frequency, then the efficiency of the QE and CE are the same. But if the atoms are 3-state systems, the lower states may be made coherent by providing microwave energy in the optical cavity. The QE efficiency η_Q is,

$$\eta_Q = \eta - \frac{T_C}{T_H} n \varepsilon \cos\phi \tag{2}$$

where, η is the CE efficiency, ϕ is the phase difference between the lowest atom energy states, ε is a small number that characterizes the magnitude of the quantum coherence, and n is the average number of thermal photons in the cavity mode of length L,

$$n = \frac{1}{\left[\exp\left(\frac{hc}{\lambda k T_H}\right) - 1\right]} \tag{3}$$

where, $\lambda = 2L$. By selecting the microwave energy to produce a phase difference $\phi = \pi$, Equation (2) shows that even for a single reservoir where $T_H = T_C$ the QE efficiency η_Q exceeds the CE efficiency η. Although the QE improves the CE efficiency, the improvement is not significant. Typically, the QE efficiency may improve the CE by a few percent, e.g., for $\eta \sim 0.3$ the $\eta_Q \sim 0.31$.

An alternate approach is to devise a process that uses a CE to extract work from a single reservoir by spontaneously lowering the temperature T_C of the low temperature reservoir to absolute zero. One such process for improving the efficiency of a CE is to extract work W from a single reservoir by producing vacuum ultraviolet (VUV) radiation in the suppression of IR radiation from the surface atoms in a quantum electrodynamics (QED) cavity shown in Figure 1.

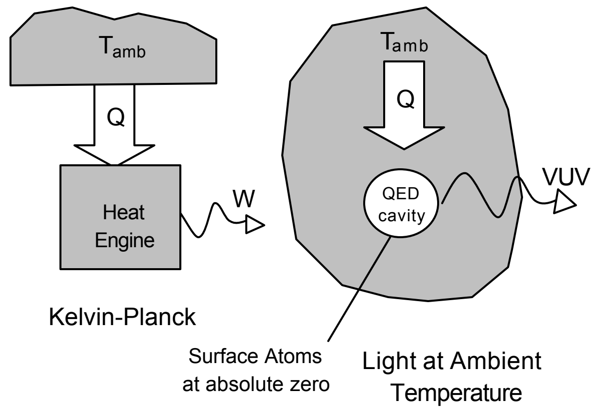

Figure 1 Kelvin-Planck Statement and Light at Ambient Temperature

In order for the process to have utility, the VUV radiation is used to excite a fluorophore in the QED cavity surface to produce visible light. In Figure 1, work W from a single reservoir in the Kelvin-Planck statement is contrasted with the production of VUV radiation in a QED cavity from a single reservoir comprising the environment at ambient temperature. Since the VUV by some means can be devised to lift a weight, the VUV is equivalent to work W. Here, the QED cavity surface atoms serve as the medium in the CE producing visible light. Since there is no difference between the production of VUV and work W from a single reservoir, it may appear that the VUV radiation from the ambient reservoir is precluded by the Kelvin-Planck statement of the second law. But this is not true.

Analysis

The production of VUV by the suppression of IR radiation leaves the surface atoms without kT energy, and therefore the temperature of the atoms spontaneously tends to absolute zero. Consistent with the second law, the surface atoms at absolute zero recover ambient temperature as heat Q from the ambient spontaneously flows into the surface atoms shown in Figures 2 and 3.

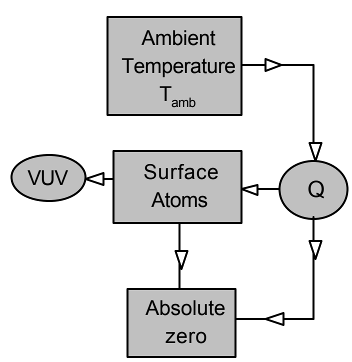

Figure 2 Light at Ambient Temperature

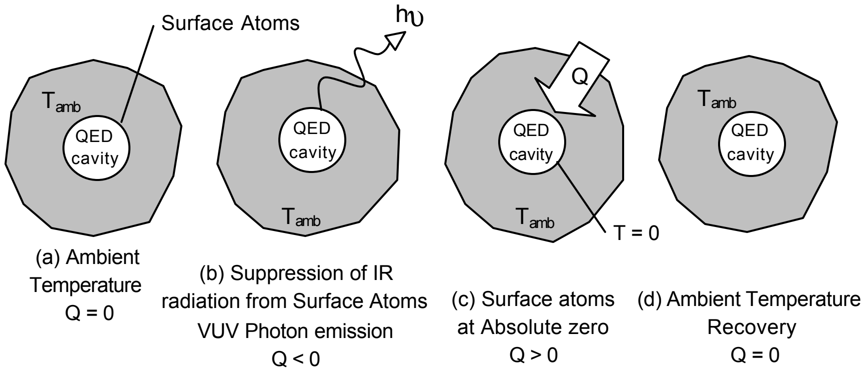

Figure 3 Light at Ambient Temperature

Initially, the QED cavity of radius R is assumed formed in a solid or liquid continuum as shown in Figure 3(a). The QED cavity has resonant wavelength $\lambda = 4R$. By selecting the radius R ~ 0.05 microns, the QED cavity is resonant in the VUV having wavelength $\lambda \sim 0.2$ microns. The temperatures are ambient everywhere, and therefore the atoms in the QED cavity surface tend to emit IR radiation. But long wavelength IR radiation is suppressed in the VUV resonant QED cavity as shown in Figure 3(b). To conserve the loss of IR energy, the EM energy is gained at the resonant frequency of the QED cavity, as all lower QED cavity frequencies are inadmissible. Photons at VUV frequencies are produced, as depicted by the emission of photon hυ. The ambient reservoir loses heat Q < 0.

Once the thermal kT energy of the surface atoms is depleted, the VUV radiation vanishes and the temperature of the surface atoms tends to absolute zero as shown in Figure 3(c). But heat Q flows spontaneously by conduction from the ambient surroundings at temperature T_{amb} into the surface atoms at absolute zero. The surface atoms gain heat Q > 0.

The VUV radiation finds utility by exciting a fluorophore provided in the surface of the cavity to produce a continuous source of VIS light. Recovery of ambient temperature by surface atoms through conductive heat flow from the surroundings is only required to be faster than the lifetime of the fluorophore. After ambient temperature T_{amb} is fully recovered, the heat Q = 0. Since Figure 3(d) is equivalent to Figure 3(a), the thermal kT energy of the surface atoms is recovered, and the cycle is repeated to produce steady light at ambient temperature.

Conclusion

Work in the form of VIS light is spontaneously extracted by a CE from a single reservoir comprising the environment at ambient temperature by suppressing the IR radiation from atoms in the surface of a QED cavity resonant in the VUV. Exotic QE are not required. Although consistent with the second law in that heat can only flow from the ambient to absolute zero, the Kelvin-Planck statement may need to be refined to accommodate the suppression of IR radiation in a QED cavity.

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