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Photoelectric Effect Induced by Blackbody Radiation: A Theoretical Analysis of a Potential Heat Energy Harvesting Mechanism

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Abstract

The photoelectric effect induced by blackbody radiation could be a mechanism to harvest ambient thermal energy at a uniform temperature. Here, I describe (without going too much into mathematical details) the theoretical model I developed starting from 2010 to study that phenomenon, and I summarize the results of the numerical simulations. Simulations tell us that the process must be there. Moreover, at least two experimental tests have been performed in the past years that seem to corroborate, although not definitely, the alleged functioning of the proposed mechanism. Unfortunately, at present, the obtainable power density is extremely low and inadequate for immediate practical applications.

Keywords: second law of thermodynamics · blackbody radiation · photoelectric effect · thermionic emission · work function · Kirchhoff's loop rule

1   Introduction

If we can get energy from ambient light via the photoelectric effect, why
should it not be possible to harvest ambient thermal energy at a uniform
temperature through the photoelectric effect caused by blackbody radiation?
In the paper, I sometimes refer to this second process as the thermionic emis-
sion[1]. What I will present here is a theoretical analysis of that possibility, and
it stands on my work on that topic dating back to 2010 [1, 2, 3, 4, 5, 6, 7, 8, 9].
I anticipate that the answer is affirmative in principle. Unfortunately, the ob-
tainable power density turns out to be extremely low and inadequate for im-
mediate practical applications. Due to its simplicity, this idea is not new. It
has already been proposed and even experimentally approached (Section 5),
but usually with what appears to be a not fully satisfying theoretical expla-
nation. Here, I describe my contribution to remedying this lack, also because,
as Sir. Eddington put it, you should not put much confidence in experimental
results until they have been confirmed by theory[2].

2   The basic idea

The idea behind the approach proposed in this paper is simple: exploiting
the photoelectric effect of the ambient blackbody radiation (at a uniform
temperature) on materials with different work functions ϕ[3]. The simplest
design to do that is shown in Fig. 1.

   The sketched device is a capacitor, which I dubbed "thermo-charged ca-
pacitor" (or TCC), where two plates, A and B, are housed inside a vacuum
bulb. Plate A and part of plate B are made of the same metal with work func-
tion ϕ_2. Plate B is coated with a semiconductor with a lower work function

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[1]Thermionic emission is usually intended as the boiling off of electrons from a metal
surface due to thermal energy (heat). It is a distinct phenomenon from the ejection of elec-
trons due to the absorption of electromagnetic radiation, which is the photoelectric effect
studied in the present paper. However, when one deals with blackbody radiation, the two
phenomena are strictly intertwined. In fact, blackbody radiation is thermal electromag-
netic radiation in thermodynamic equilibrium with the surrounding matter. Moreover,
thermionic emission acts upon electrons with a similar mechanism (for emission, the ther-
mal energy must be greater than the work function of the material) and works in the same
direction as the effect studied in the present paper (both tend to eject electrons).

[2]Obviously, this is a joke. But, in some circumstances, it has an element of truth.

[3]The work function ϕ is roughly the minimum energy (in eV) required to extract an
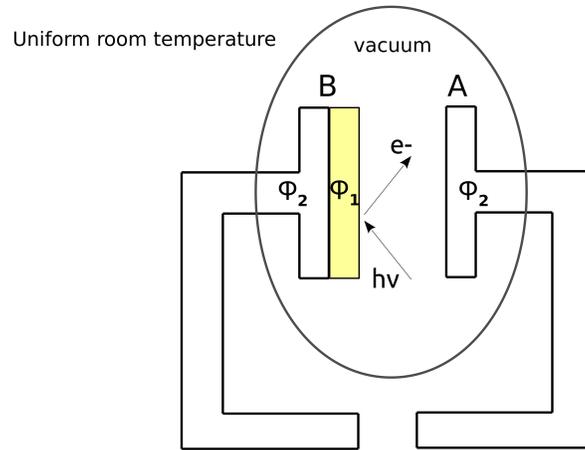electron from the bulk of a material to its surface.

Figure 1: Sketch of a thermo-charged capacitor (TCC)

ϕ_1. The whole device is at a uniform temperature.

Both plates A and B receive photons from the blackbody radiation, but being ϕ_2 greater than ϕ_1, the electrons extracted by the photoelectric effect from the coating of B to plate A are more numerous and with higher kinetic energy K ($K = h\nu - \phi$, where $h\nu$ is the photon energy) than those extracted from plate A to plate B, at least in the early phases of the process.

This behavior is evident when we look at the shape of the spectral radiance vs. the frequency of the blackbody radiation at equilibrium (uniform temperature), Fig. 2.

The spectral radiance being proportional to the number of blackbody photons at a specific frequency, the number of photons in the thermal radiation with energy $h\nu > \phi_1$ is greater than the number of photons with $h\nu > \phi_2$, and thus it is easy to see why more electrons are extracted from B to A and with higher kinetic energy. All that means that an *unbalanced net flux* of electrons should flow from plate B to plate A.

To show how the TCC is expected to work, it may help to consider the following two distinct setups: open-circuit and short-circuit TCC, see Fig. 3. In the case of an open-circuit TCC (Fig. 3, left), we expect that after a suitable interval of time, an equilibrium potential difference ΔV gets established across the plates.

The equilibrium potential difference ΔV is necessarily equal to $(\phi_2 - \phi_1)/e$,
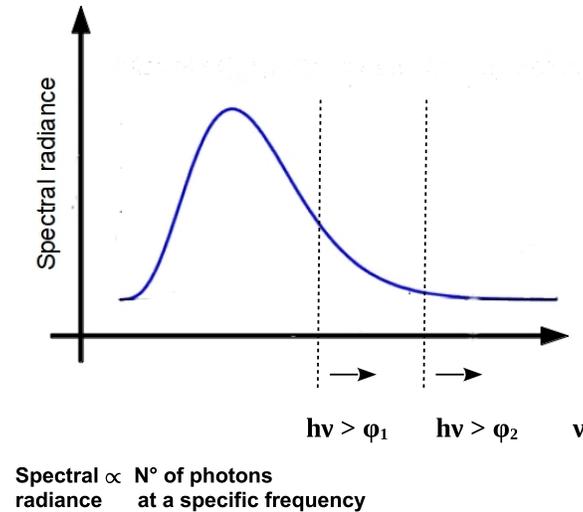
Figure 2: Blackbody radiation at a uniform temperature. The spectral radiance is proportional to the number of blackbody photons at a specific frequency

where e is the electron charge, because only with that value the energy E_B needed by an electron inside the coating to get extracted and reach plate A $(E_B = \phi_1 + e\Delta V = \phi_1 + e(\phi_2 - \phi_1)/e = \phi_2)$ becomes equal to the energy E_A needed by an electron to get extracted from plate A and reach plate B (only ϕ_2). Only in this case, there will be no more imbalance in the two fluxes of electrons.

In the case of a short-circuit TCC (Fig. 3, right), a current i should flow in the circuit. If the resistance of the circuit external to the TCC is negligible, that current is equal to the thermionic current $i_{thermionic}$ across the plates, and the potential difference between the plates is nearly equal to zero.

The small dots between the plates represented in Fig. 3, especially in the open-circuit TCC configuration, is the space charge. In stationary conditions like that of a fully charged open-circuit TCC, electrons are continuously emitted and reabsorbed by the plates in a sort of dynamical equilibrium, and thus they form a cloud. This is well-known among those who used to work with vacuum tubes. Space charge distribution inside a TCC can be modeled mathematically, but it is not difficult to understand that in an open-circuit
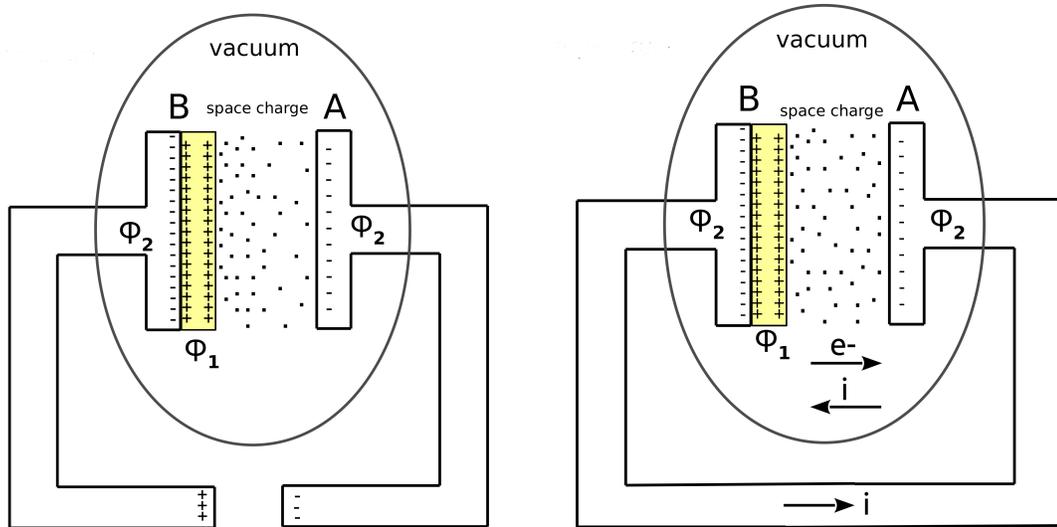
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Figure 3: Open-circuit (left) and short-circuit (right) TCCs

configuration at equilibrium, the electron cloud density decreases from plate B to plate A (fewer and fewer electrons in plate B get enough energy from the blackbody radiation to get closer and closer to plate A).

Notice that this space charge does not change the value of the total stationary potential drop between the plates, which always remains equal to $(\phi_2 - \phi_1)/e$ for the reasons explained above. The space charge interferes only with the uniformity of that potential in the inter-plate space: the potential difference does not change linearly with the distance from the plates as it happens in a standard charged parallel-plate capacitor.

3   Possible objections to the expected functioning

Before presenting the results of the mathematical and numerical modeling of both open-circuit and short-circuit TCCs, let me dwell on two main objections that could be advanced against the functioning described above. It is fundamental to face the following objections and reply to them because, if they were correct, the TCC would not work as expected.

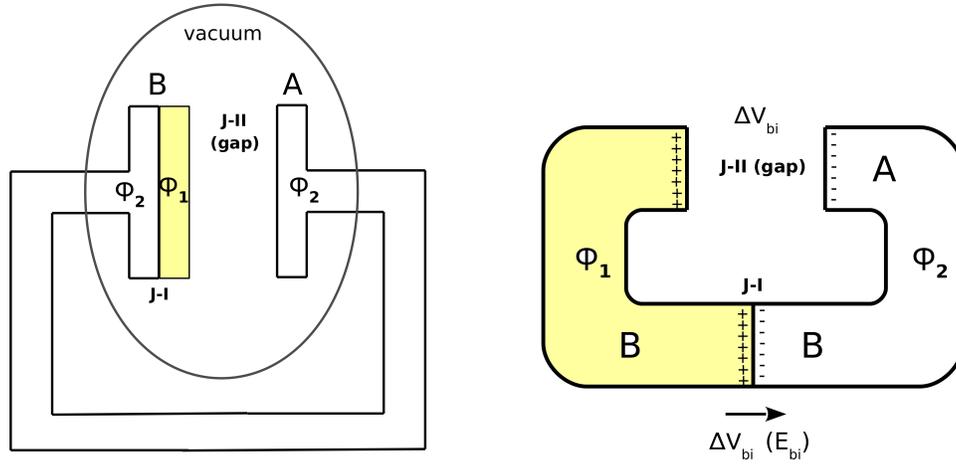To better introduce them, I will use a topological analog of the short-

Figure 4: Short-circuit TCC (left) and its topological analog (right)

circuit TCC in Fig. 3 (right). I refer to the horseshoe-shaped scheme shown on the right-hand side of Fig. 4. The right half of the horseshoe represents plate A, part of plate B, and the connecting wire, and all this stuff has a work function equal to ϕ_2. The left half is the coating of plate B with work function ϕ_1. In both images, J-II indicates the vacuum gap between the plates.

It is known that when two materials with different work functions are physically joined, a potential difference ΔV_{bi} builds up across the contact junction J-I (Fig. 4, right). This potential is known as the *contact potential*, and it is generated by electrons that are pushed from the ϕ_1 material to the ϕ_2 material across J-I by thermally driven forces (thermal agitation).

A higher amount of electrons move from left to right rather than the other way around simply because it's easier to pull electrons out of a lower work function material. This process lasts until a dynamical equilibrium is reached between the thermally driven forces and the electric force due to the built-in electric field across J-I.

Also, in this case, the contact potential ΔV_{bi} across J-I is equal to $(\phi_2 - \phi_1)/e$, and the reason is the same as that shown in Section 2 for the final equilibrium of the thermionic charging process. Across J-I, an electric field builds up as well. It is roughly equal to the contact potential divided by the width of the depletion region x_d, namely the thin layer across J-I where the

diffusion of electrons has taken place.

It is also widely held that as soon as the two halves of the horseshoe are physically joined at J-I, a potential difference, equal and opposite to the contact potential ΔV_{bi} at J-I, should instantaneously build up across the gap J-II.

That potential difference must not be confused with that deriving from the thermionic charging process described in Section 2. It is intended to be instantaneously generated by the movement of electrons in the bulk of the horseshoe just after the physical contact of the materials at J-I. People expect that potential difference across J-II because of an allegedly straightforward application of Kirchhoff's loop rule to the horseshoe scheme in Fig. 4.

The first objection to the TCC functioning is that if this potential difference really formed across J-II, the thermionic charging process across plates A and B would not even start. Since ΔV across J-II is equal to $(\phi_2 - \phi_1)/e$, no net electron flux from plate B to plate A could be possible. As described in Section 2, the energy required for an electron to get extracted from one plate and reach the other plate would be the same (and incidentally, equal to ϕ_2). Thus, there would be no net displacement of electrons across J-II, and therefore there would be no current in the short-circuit TCC.

My reply to that objection is that there is no instantaneous potential difference across J-II caused by physically joining the two materials at J-I. And I can prove it by appealing to the basic definition of potential difference: the potential difference between points a and b is defined as minus the work W done by the forces acting upon a test electron that moves along a(ll) path(s) joining a and b, divided by the electron charge e [4, 6, 7, 8].

Let us apply that definition to the previous horseshoe scheme, see Fig. 5. Namely, $\Delta V_{ba} = V_b - V_a = -W_{ab}/e = -1/e \int_a^b \mathbf{F_{int}} \cdot d\boldsymbol{\gamma}$, where $\mathbf{F_{int}}$ stands for all the forces acting upon the test electron when it moves along the path γ.

If one considers the path γ shown in Fig. 5, it is evident from equilibrium considerations that $\mathbf{F_{int}}$ can be different from zero only across J-I. When the test electron crosses J-I, it does feel only two forces: the thermally driven forces $\mathbf{F_d}$ pushing to the right and the electric force $e\mathbf{E_{bi}}$ due to the built-in electric field pushing to the left, and thus $\mathbf{F_{int}} = \mathbf{F_d} + e\mathbf{E_{bi}}$. By the way, the test electron does feel the thermally driven forces, just like all electrons in the depletion region around J-I.

Since the diffusion forces dynamically sustain the electric field at J-I, these two force fields must always be present across J-I and must always be equal and opposite at equilibrium, namely $\mathbf{F_d} = -e\mathbf{E_{bi}}$. As a matter of fact,
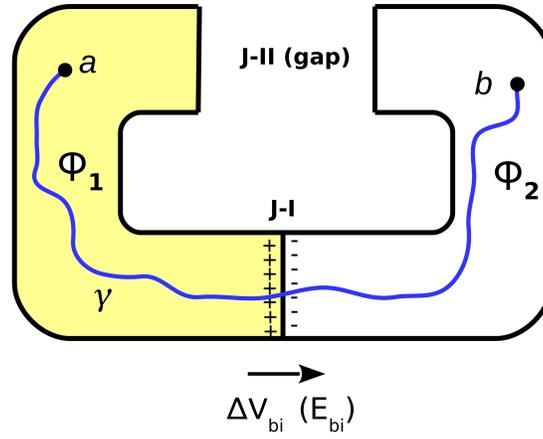
Figure 5: Definition of potential difference between points a and b in the bulk of the horseshoe

if we switched off the thermally driven forces $\mathbf{F_d}$, the built-in electric field $\mathbf{E_{bi}}$ would go to zero. Therefore, the total force $\mathbf{F_{int}}$ is zero on average, and so is the potential difference ΔV_{ba} between points a and b.

All that means that physically joining two different materials at J-I cannot instantaneously cause any potential drop across the gap J-II that would kill the thermionic emission from the outset.

That theoretical result may appear at odds with the fact that a potential difference ΔV is actually detected and measured across J-II among different materials physically joined at J-I. For instance, measuring this ΔV is one of the reasons why the Kelvin probe force microscope (KPFM) has been developed. My explanation for this apparent inconsistency is that KPFM, in fact, measures a potential difference across J-II, but this potential difference is just that generated by thermionic emission across J-II. In the case of a KPFM scan, I am referring to the thermionic emission between the surface of the scanned material and the Kelvin probe tip. The potential difference measured by a KPFM is thus not that due to the contact potential at J-I.

The second objection to the expected functioning of a TCC is that even if a net flux of emitted electrons were possible from left to right across J-II (see, Fig. 5), the current would not flow back across junction J-I. Junction J-I is known to be a Schottky-type rectifying junction: under biasing, electrons easily flow from left to right across J-I but not that easily the other way
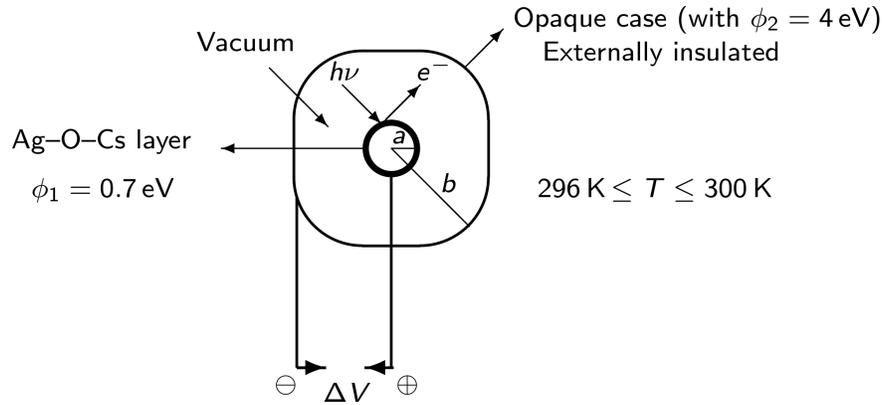
Figure 6: Sketch of the modeled open-circuit spherical TCC

around (from right to left across J-I).

The reply to that objection is simple and more immediate [2, 8]. It is well known that every Schottky junction is characterized by a *reverse leakage current* that overcomes the rectifying barrier even under small reverse biasing. That current may be high or low depending upon several factors. It depends (although slightly) upon the magnitude of the reverse bias. It also depends upon junction materials and preparation. It is proportional to the temperature and has an inverse dependence upon the depletion region width x_d. According to the literature, the reverse leakage current may range from 10^{-8} A/cm^2 to 10^{-2} A/cm^2 (there also exist examples of higher values), and as I will show in the next section, even the lowest value is already enough to allow the circulation of a current through a short-circuit TCC (Fig. 3, right).

4   Numerical simulation and results

I have mathematically modeled the photoelectric effect induced by the electromagnetic radiation following Plank's law (blackbody radiation) on both plates of a spherical capacitor (with different work functions). Here, I describe the results of the numerical simulation. I have studied a spherical TCC (see Fig. 6) because it is easier to treat analytically [2, 8].

For the low work function coating, I have chosen the well-known photocathode material S1 (Ag-O-Cs) with a work function of nearly 0.7 eV. The

inner and outer spheres are made of metal with a work function of 4 eV. The modeled TCC is 40 cm wide ($b = 20$ cm and $a = 10$ cm). The ratio between the outer and the inner radius is taken equal to 2 because it can be proven that this choice maximizes the charging speed in the open-circuit setup [1].

Another significant parameter for the simulation is the quantum efficiency η of the materials. The quantum efficiency is roughly the ratio between the number of electrons extracted by the radiation and the number of photons impinging on the plates. It is a frequency-dependent parameter. I have plugged into the equations only mean values over frequency. I have used highly conservative values for the quantum efficiencies to stress-test the robustness of the process: $\eta_1 = 10^{-5}$ and $\eta_2 = 1$. More realistic values are $\eta_1 \geq 10^{-3}$ ($\geq 0.1\%$) [11] and $\eta_2 \ll 1$. Moreover, I have found the whole process and results to be quite insensitive to the exact value of η_2.

The differential equation that governs the charging process of an open-circuit spherical TCC is the following [2, 8]:

$$\frac{dV(t)}{dt} = \frac{\pi e b}{2\epsilon_0 c^2} \left(\frac{kT}{h}\right)^3 \left(\overline{\eta}_1 \int_{\frac{eV(t)+\phi_1}{kT}}^{\infty} \frac{x^2 dx}{e^x - 1} - 4\overline{\eta}_2 \int_{\frac{\phi_2}{kT}}^{\infty} \frac{x^2 dx}{e^x - 1}\right),$$

where $V(t)$ is the voltage between the spheres, b is the radius of the outer sphere, c is the velocity of light, e is the electron charge, ϵ_0 is the vacuum permittivity, h is the Planck constant, T is the absolute temperature, and k is the Boltzmann constant.

The graph in Fig. 7 shows the charging profile of a spherical open-circuit TCC with the abovementioned parameters.

With more realistic values for η_1 and η_2, the charging process is expected to be sensibly faster (one or two orders of magnitude faster).

When the terminals of the spherical TCC are connected to a resistor R, a current starts to flow across the circuit and settles to a steady-state value i_S. That current is related to the steady-state voltage V_S across R and the TCC as follows [2, 8]:

$$i_s = \frac{2\pi^2 e b^2}{c^2} \left(\frac{kT}{h}\right)^3 \left(\overline{\eta}_1 \int_{\frac{eV_s+\phi_1}{kT}}^{\infty} \frac{x^2 dx}{e^x - 1} - 4\overline{\eta}_2 \int_{\frac{\phi_2}{kT}}^{\infty} \frac{x^2 dx}{e^x - 1}\right),$$

and, obviously, they satisfy Ohm's law $V_S = R \cdot i_S$.

The power density P_S of the short-circuit spherical TCC is then given by $P_S = V_S \cdot i_S / S_a$, where S_a is the surface of the inner sphere. The graph in
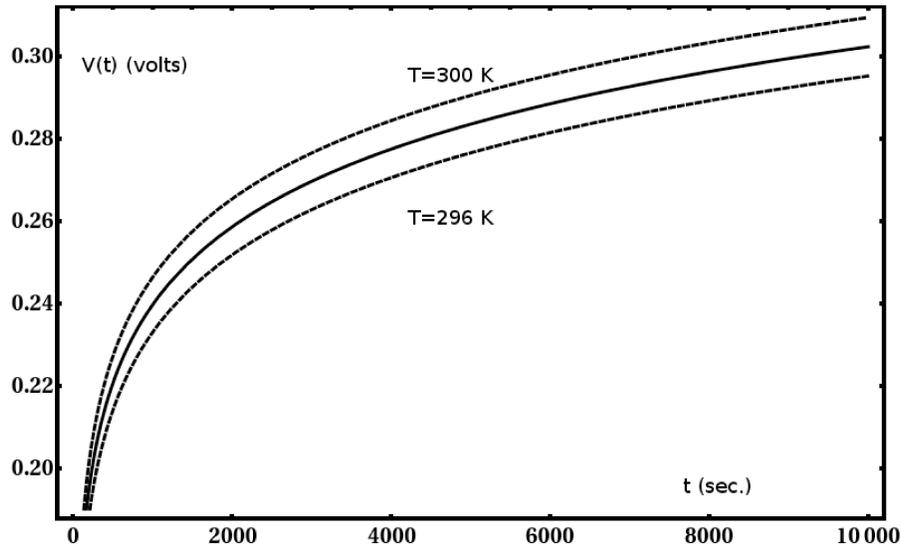
Figure 7: Charging profile of the open-circuit spherical TCC described in the text. Charging profiles for three absolute temperatures (296 K, 298 K, and 300 K) are given

Fig. 8 shows the power density P_S as a function of the steady-state voltage V_S in Watts/cm^2.

By tuning the value of the external resistance R, we can maximize the power output. The maximum is obtained at 0.03 V across a resistance of the order of 10^{10} Ω. Therefore, the maximum power output reachable by the spherical TCC with the abovementioned physical characteristics is nearly 10^{-14} W, with a steady-state current of the order of 10^{-12} A.

By plugging into the equations more realistic values for η_1 and η_2, I expect to have a power output and a current at least two orders of magnitude higher, $P_S \approx 10^{-12}$ W and $i_S \approx 10^{-10}$ A.

The power output of the modeled TCC and the power density represented in Fig. 8 clearly show that the current design has no hope for an immediate application for large-scale ambient energy harvesting. However, it is crucial to experimentally prove it since only this way we will have confirmation that our approach is not at odds with fundamental physics.
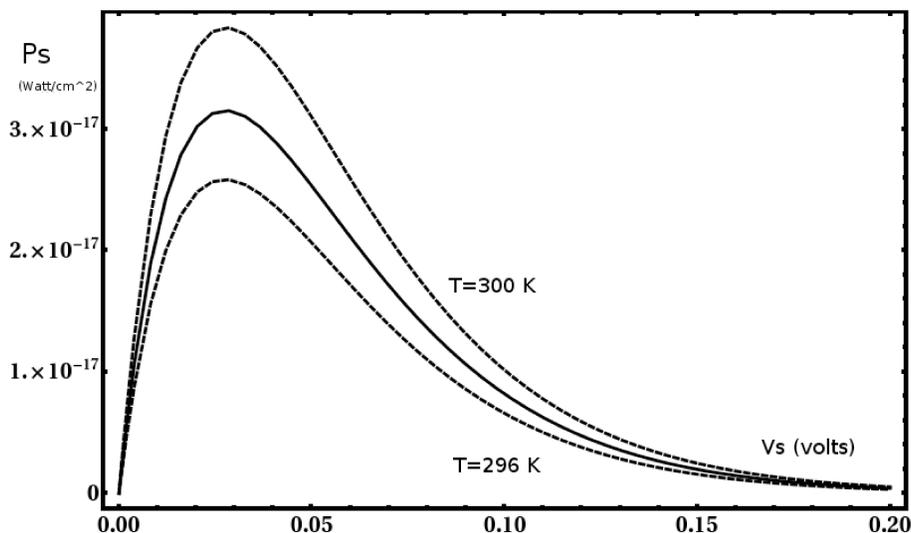
Figure 8: Power output per unit area of the inner sphere versus the steady-state voltage across the TCC and the resistor R (for three values of the ambient temperature)

5   About experimental tests

Before describing the two experiments I became aware of that seem to implement the design described above, let me linger over a few necessary (but not sufficient) prescriptions that every experimental test must comply with to be credible.

They are listed below in no particular order:

- Reduce external disturbance (varying electric and magnetic fields, e.m. pickup, cosmic rays, etc.) by properly shielding the TCC and the measurement equipment with Faraday cages and mu-metal boxes and by performing the test inside an underground laboratory;

- Carefully control the uniformity of the temperature to prevent thermo-electric effects: no significant temperature gradient should be allowed in the space hosting the TCC and the measurement equipment;

- Place two TCCs side by side: they must be the same, except that one does not have any emitting layer on its plates;
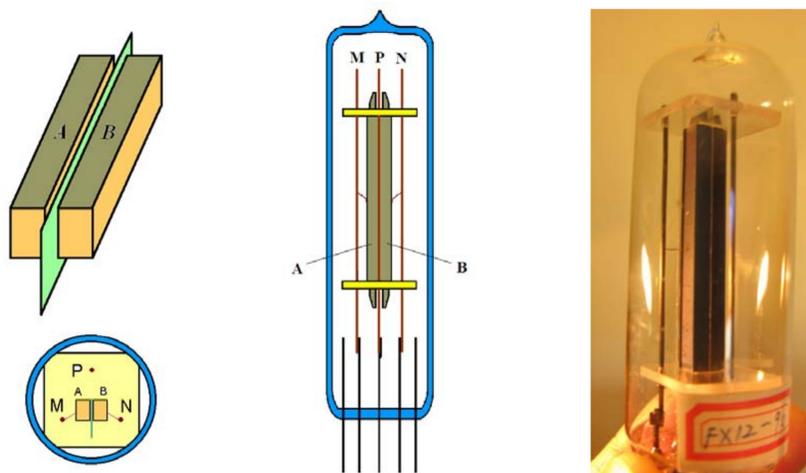
Figure 9: One of the vacuum tubes used by Fu and Fu [10]

- Use an ultra-high input impedance electrometer ($> 10^{10}\,\Omega$). According to the previous simulation, the resistance external to the TCC must be very high.

Another significant check to do would be using multiple equivalent TCCs. They should be connected in series or parallel to see whether the overall voltage and current scale up with the number of TCCs. If they do not, then any possible non-zero voltage and current values for a single TCC could easily be caused by noise in the measurement equipment. This check would be even more important than seeing whether the magnitudes of voltage and current on a single TCC correlate with ambient temperature: even the internal noise of a high-sensitivity electrometer correlates with ambient temperature.

At the end of 2014, I received, as personal communication, a report by Fu and Fu [10] on an experiment conducted on some Ag-O-Cs vacuum bulbs with custom design (see Fig. 9). They were previously employed by the same authors to test the possibility of drawing energy from ambient heat with the help of an external static magnetic field [9]. In that report, they actually implemented and tested the basic scheme of a thermo-charged capacitor like the one sketched in Fig. 1.

How their original vacuum bulbs were manufactured (see Fig. 9) made Fu and Fu able to use the Ag-O-Cs plates A and B, connected in series, as the
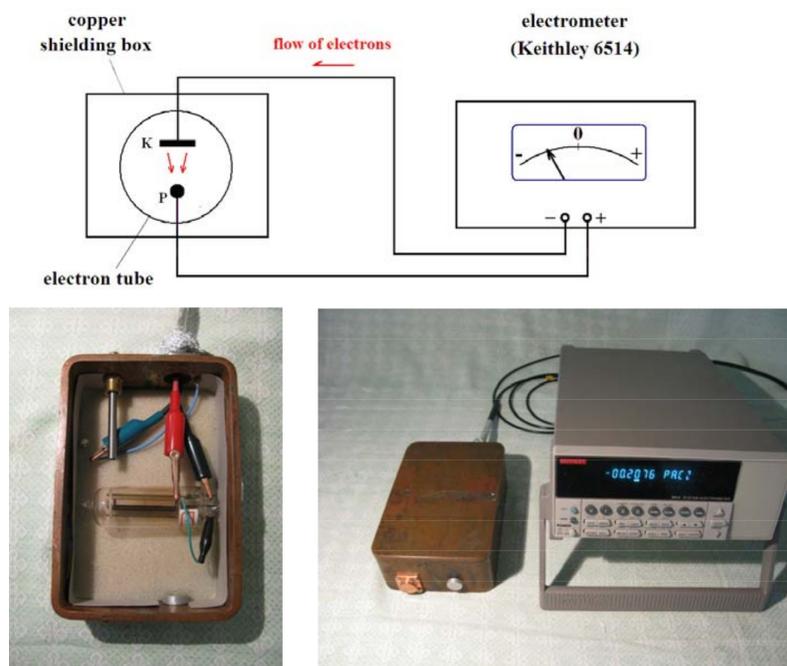
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Figure 10: Schematic of the experiment carried out by Fu and Fu [10]

emitter and a cesium-coated molybdenum supporting rod facing the plates (P) as the collector of a simplified version of a thermo-charged capacitor. A schematic of the experiment, taken from Fu and Fu's report, is given in Fig. 10, where the vacuum tube, a shielding copper box, and the measuring apparatus (electrometer Keithley 6514) are visible.

Fu and Fu measured a stable current exceeding 2×10^{-12} A and a voltage drop of the order of 100 mV. They also verified that both these values change sign once the electrometer's connections to the tube are switched over. Unfortunately, they did not investigate the dependence of the current/voltage output on the number of connected tubes and the value of the external uniform temperature: the measurements described in the report have been taken on a single vacuum tube and at a single external temperature. Their results are extremely interesting and promising and seem to give a direct experimental corroboration of the theory behind the thermo-charging process. Their vacuum tube has probably an emitting surface of a few square centimeters. If we scale down the results presented in the previous Section by two orders
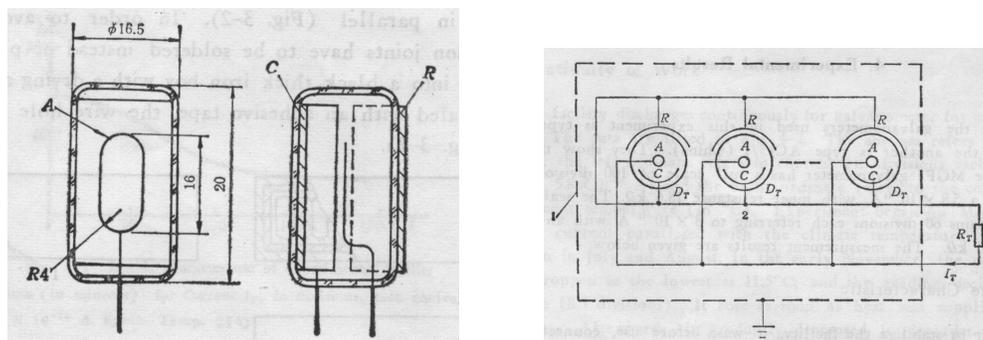
Figure 11: Some of the schematics of the experiment carried out by Xu Yelin [12]

of magnitude in the inner area and use the more realistic value for the quantum efficiency of the emitting surface ($\eta_1 \geq 10^{-3}$), we see that the expected current for a single vacuum tube is of the same order of magnitude as that found by Fu and Fu.

In their report, Fu and Fu also ventured into a theoretical explanation for their results. However, in my opinion, they did not succeed. Unfortunately, their explanation is quite sketchy and presents some flaws at a fundamental level.

In May 2011, a person who read my first papers on the TCC sent me an email and drew my attention to the work of a Chinese researcher, Xu Yelin, which I was not aware of [12]. Yelin performed a large-scale experiment using nearly 700 custom Ag-O-Cs vacuum tubes connected in series (see Fig. 11). Although he did not use any ultra-high input electrometer, he found non-zero current and voltage across the circuit. In particular, at the ambient temperature of 32° C, he measured a peak short-circuit output current of $\approx 5 \times 10^{-8}$ A and a voltage drop of 55 mV across an external resistance of $10^8 \, \Omega$. The interesting fact is that the current and voltage values remained stable for over a year (the duration of the experiment), with variations closely matching the ambient temperature trend.

Even in this case, the emitting surface of a single vacuum tube is of the order of a few square centimeters, and thus the current generated by each tube is of the order of 10^{-12} A. Again, it seems to agree with the results of the simulations presented in the previous Section with $\eta_1 \geq 10^{-3}$.

Yelin proposed a theoretical explanation for his results, but again it appears to be somewhat cursory and plagued by several flaws at a fundamental level. That notwithstanding, Yelin's experiment and results remain fascinating.

To conclude this section, let me describe an indirect and easier way to test the expected functioning of a TCC [8]. Let us use the TCC as a conventional photoelectric device and exclusively illuminate the low work function plate (plate B in Fig. 1) with direct light of arbitrary intensity but with frequency $\nu < \phi_2/h$. The fact that plate A is not illuminated does not count since the light used has a too low frequency to extract electrons from it. In fact, that would be almost like having a TCC immersed in blackbody radiation with a higher intensity than usual and a frequency cutoff at ϕ_2/h.

It should be easy to understand that if we can measure a non-zero potential difference and a non-zero current in the open-circuit and short-circuit configurations, respectively, then the TCC should work as expected even when it is immersed in uniform blackbody radiation as in the original design. The only difference would be in the rapidity with which the potential difference is generated or the magnitude of the current in the short-circuit configuration. Those would be more favorable in the case of the TCC used like a photoelectric device. All this would also help with the measuring procedure. By suitably increasing the intensity of the impinging direct light, the current flowing across a short-circuit TCC can be made macroscopic, and an ultra-high input impedance electrometer would not be needed.

6   Concluding remarks

From a fundamental physics perspective, the theory behind the photoelectric effect induced by blackbody radiation is pretty solid. Moreover, at least two experimental tests have been performed in the past that seem to corroborate, although not definitely, the alleged functioning of the proposed process. More dedicated and specifically designed experiments are needed to get definitive confirmation, along with the simple, although indirect, test described at the end of the previous section. However, due to the extremely low power density output, even in the case of positive experimental results, the question of the immediate application for ambient energy harvesting remains open.

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