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NEAR-FIELD RADIATION BY QUANTUM MECHANICS

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ABSTRACT

The Planck theory of BB radiation giving the dispersion of EM radiation with temperature has served well in the radiative heat transfer between surfaces at the macroscale. BB stands for blackbody and EM for electromagnetic. Recently, claims based on solutions of Maxwell's equations that BB radiative heat transfer in the near field is enhanced by 3-4 orders of magnitude above Planck theory - if the surfaces are separated by nanoscale gaps. Evanescent waves are thought to transfer the heat as the gaps are smaller than the half wavelength of BB radiation at surface temperatures. However, the Maxwell solutions are questionable because QM precludes the fluctuations necessary to define the temperatures of the surfaces as required by the FDT. QM stands for quantum mechanics and FDT for fluctuation-dissipation theorem. QM denies atoms under the EM confinement present in the gap between surfaces to have the heat capacity to conserve radiative heat by changes in temperature. Instead, conservation proceeds by the QED induced creation of non-thermal EM radiation having a half wavelength equal to the gap dimension that tunnels the heat across the gap thereby allowing Planck theory to remain valid even in the near-field. QED stands for quantum electrodynamics.

INTRODUCTION

Planck's theory [1] of BB radiation giving the dispersion of the EM emission by photons with temperature and wavelength (or frequency) provided the basis for QM. At the macroscale, Planck's theory has served well in radiative heat transfer provided the gap or spacing between heat transfer surfaces is greater than the half wavelength of BB radiation emitted from the surfaces at temperature.

Recently, Planck theory was stated [2] to set a limit on near-field radiative heat transfer. Although Planck himself never stated his theory bounded near-field radiative heat transfer, he was surely aware contact resistance arising from close BB surfaces is expected to decrease, and certainly not increase heat transfer. If so obvious,

How then did the notion of the near-field increasing heat transfer between bodies separated by nanoscale gaps originate?

Historically, near-field radiative heat transfer began almost 50 years ago based on wavelength interference and tunneling analysis [3] that supported the counter-intuitive conjecture that the heat transfer between BBs is highest at zero surface spacing. Perhaps, the conjecture should have been dismissed at that time based on practical grounds in that it is physically impossible to bring BB surfaces to zero spacing without making thermal contact, i.e., it is extremely unlikely any practical device embodying near-field heat transfer can ever be fabricated to take advantage of the conjecture. Moreover, even if the BB surfaces are close but not contacting, the conjecture may be rejected by QM because atoms in the BB surfaces at nanoscale spacings lack the heat capacity to allow the temperatures to fluctuate consistent with the FDT. In contrast, classical physics allows the atoms the heat capacity for temperatures to fluctuate and satisfy the FDT.

Today, Maxwell's equations are commonplace in the analysis of near-field heat transfer. However, Maxwell's equations are also classical and subject to the same invalidity by QM as the wave interference and tunneling analysis [3]. Nevertheless, the Maxwell's equation solutions that exclude QM restrictions in near-field gaps are used to support the claim [2] that evanescent wave tunneling enhances near-field heat transfer by 3-4 orders of magnitude above the BB limit of Planck theory.

In this paper, QM is shown to require BB surfaces with gaps at zero spacing cannot fluctuate in temperature to allow the FDT requirement in Maxwell's equations to be satisfied to allow any heat transfer, let alone enhancement. In retrospect, the conjecture that significant enhancement in near-field heat transfer occurs as gaps approach zero spacing may be safely dismissed as invalid by QM.

PURPOSE

To show the support of near-field radiative heat transfer by evanescent waves in solutions of Maxwell's equations is questionable because the FDT cannot be satisfied for atoms in the BB surfaces at zero gap spacings, i.e., the near-field solutions of Maxwell's equation are invalid by QM. Instead of evanescent waves, near-field heat transfer is shown to proceed by QED induced tunneling allowing the BB limit in Planck theory to be valid at the nanoscale

BACKGROUND

Planck's theory of BB radiation giving the dispersion of EM radiation emitted from the atom depending on temperature and EM confinement not only provided the basis for QM but also allowed the derivation of the Stefan-Boltzmann (SB) equation for radiative power Q_{SB},

$$Q_{SB} = \sigma A(T_H^4 - T_C^4) \qquad (1)$$

where, σ is the SB constant, A the surface area, T_H and T_C the absolute temperatures of hot and cold surfaces.

Historically, the FDT in heat transfer [4] relates the random movement of dipoles in the Maxwell equations to the temperature of the material. Today, the FDT is implicitly assumed satisfied [2, 5-7] at the nanoscale to justify the application of classical EM wave theory to near-field heat transfer by NIR evanescent surface waves. The temperatures of atoms in the hot and cold gap surfaces are assumed to fluctuate, even though the surface atoms under EM confinement are precluded by QM from having the heat capacity necessary to support temperature fluctuations. Nevertheless by assuming the FDT is satisfied, Maxwell solutions show the near-field heat flux to vary inversely with the square of the gap d dimension, e.g., the Maxwell heat flux Q given by (Eqn. 23a of [6]).

$$Q \approx \frac{1}{\pi^2 d^2} \frac{\mathrm{Im}(\varepsilon_H)\mathrm{Im}(\varepsilon_C)}{|(\varepsilon_H + 1)(\varepsilon_C + 1)|^2} [\Theta(\omega, T_H) - \Theta(\omega, T_C)] \qquad (2)$$

where, $\Theta(\omega, T)$ is the frequency form of the Einstein-Hopf relation and ω is the angular frequency, $\omega = 2\pi c/\lambda$. The imaginary parts of the complex permittivity ε_H and ε_C of the hot and cold surfaces are designated by Im.

But all did not agree with the Maxwell solutions. The argument [8] was made that as the gap vanishes, the heat flux diverges, and therefore BB power is not conserved. The counter argument [9] claimed divergence of the flux does not occur because once thermal contact is established the radiative resistance tends to zero, and therefore the heat flux must be finite as there no longer is any temperature difference. Clearly, heat transfer by evanescent waves is based on a gap without thermal contact, and therefore the temperature difference is required to remain constant as the gap vanishes, thereby supporting the argument [8] that power conservation is indeed violated. Only if the heat flux does not diverge as the gap approaches zero do evanescent waves provide a valid description of near-filed radiative heat transfer.

In this regard, a second counter argument [9] against divergence in evanescence theory depends on whether the materials are lossy or nonlossy. For lossy materials, the heat flux does indeed increase by the $1/d^2$ relation, but between nonlossy materials, the heat transfer is bounded. The fact that the divergence clearly is not borne out by the actual physics [10] is of no consolation to the divergence the heat flux as a theory of evanescent waves in the near-field heat transfer of lossy materials.

However, the QM restriction on the FDT may be a more serious objection to the validity of Maxwell's solutions of evanescent waves in near-field heat transfer. Unlike classical physics, QM rejects the notion atoms in the surfaces of nanoscale gaps have the heat capacity to allow temperatures to fluctuate and satisfy the FDT. The effect of QM on the Maxwell heat flux Q may be assessed from (2) by taking both $\Theta(\omega, T_H)$ and $\Theta(\omega, T_C)$ to vanish. If so, Q also vanishes independent of whether the materials are lossy or have imaginary permittivity. Effectively, QM negates the NIR evanescent frequencies having $\Theta(\omega, T_H) > 0$ allowing only high frequency waves that have vanishing $\Theta(\omega, T)$ in nanoscale gaps.

Conversely, the Maxwell equations follow classical physics and assume the surface atoms fluctuate in temperature consistent with the mainstream assumption [7] for deriving the evanescent heat flux Q between BB surfaces. To illustrate the differences between QM and classical physics, consider the Maxwell solution between surfaces at 800 and 200 K given by the heat flux $q_{\omega,1\to2}^{net}$ shown in (Fig. 1a of [7]) and reproduced in Fig. 1.

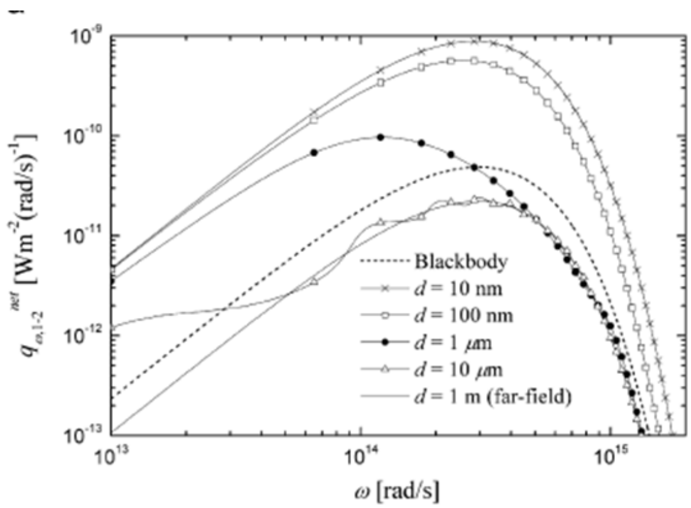

Fig. 1 Maxwell Solutions for Evanescent Waves between Surface Temperatures 800 and 200 K

The Maxwell solutions for gaps d = 100 and 10 nm gaps give peak heat fluxes $q_{\omega,1\to2}^{net} = 5\text{x}10^{-10}$ and 10^{-9} W/m^2/rad/s at angular frequency $\omega = 3\text{x}10^{14}$ rad/s as shown in Fig. 1. At this frequency, the evanescent wave is in the NIR having wavelengh λ = 6.28 microns. The BB radiation flux q_{BB},

$$q_{BB} = \frac{h\omega^3}{8\pi^3 c^2} \frac{1}{\exp\left(\frac{h\omega}{2\pi kT}\right) - 1} \tag{3}$$

is plotted in Fig. 1. At ω = 3x10^{14} rad/s, q_{BB} = 4.8x10^{-11} W/m^2/rad/s. Clearly, Maxwell solutions assuming NIR evanescent tunneling at ω = 3x10^{14} rad/s show heat flux is enhanced in nanoscale gaps by factors of 10 to 20 over BB radiation.

The problem is the atoms in the surfaces of the 100 and 10 nm gaps under EM confinement are precluded by QM from the temperature fluctuations necessary to satisfy the FDT. The effects of EM confinement of surface atoms in nanoscale gaps may be assessed by comparing the Maxwell solutions for gaps d < 1 micron with that in the NIR at ω = 3x10^{14} rad/s. For d < 1 micron having angular frequency ω > 2x10^{15} rad/s, the Maxwell heat fluxes < 10^{-13} W/m^2/rad/s are far less than q_{BB} for the peak BB heat flux in NIR tunneling. On this basis, the Maxwell solutions for nanoscale gaps are not valid to support the claim that evanescent tunneling enhances near-field heat flux above that of BB radiation.

THEORY

Divergence of near-field heat flux by evanescent waves (2) may be traced to the FDT that inherently assumes [2, 5-7] gap surfaces undergo temperature fluctuations when in fact QM precludes temperature fluctuations in surface atoms because of EM confinement. What this means is divergence in evanescent theory may very well be an artifact of the invalid assumption of the FDT being satisfied in the solution of Maxwell's equations, and if so, there is no enhancement above the BB limit. But then what is the mechanism that allows the SB equation to be valid in the near-field?

In the following, standing QED photons are proposed as the mechanism by which the SB radiation tunnels across the gap. The SB equation is otherwise not modified thereby maintaining the validity of Planck theory in the near-field. The QED photons standing between hot T_H and cold T_C surfaces while tunneling SB power across the gap d is depicted in Fig. 2.

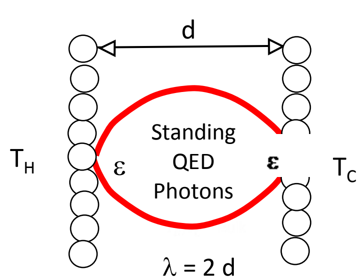

Fig. 2 QED Tunneling by Standing Wave Photons

QM Restrictions

The QM restrictions on the thermal kT energy of the surface atoms depends on the EM confinement given by the Einstein-Hopf relation [11] for the average Planck energy E of the atom as a harmonic oscillator shown at ambient temperature in Fig. 3.

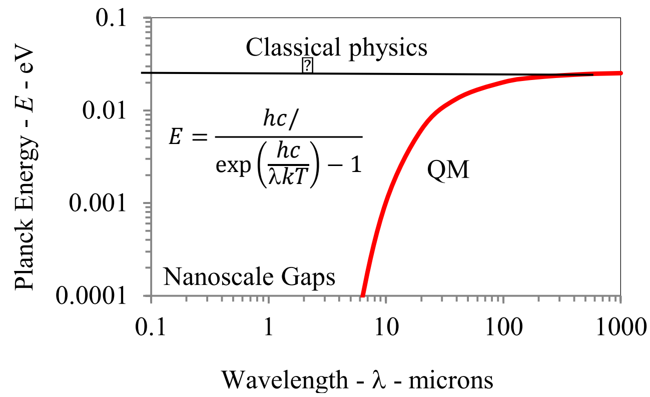

Fig. 3 Atom as a Harmonic Oscillator at 300 K
In the inset: h is Planck's constant, c the speed of light, k Boltzmann's constant, and T absolute temperature.

Classical physics depicted by the horizontal line allows the atom to have kT energy or heat capacity at the nanoscale. QM differs by allowing the atom to only have kT energy for λ > 40 microns. What this means in radiative heat transfer is the atoms in the gap surfaces have bulk temperatures only if the gaps d > $\lambda/2$ = 20 microns. However, this is an upper bound as the heat capacity decreases for d < 20 microns. Fig. 3 shows at λ < 6 microns, the kT energy of the atom is more than 2 orders of magnitude lower than kT. At the nanoscale d < 1 micron, the heat capacity of the atom for all intent and purpose may be assumed to vanish. Unlike classical physics, QM precludes the atom from conserving absorbed EM energy at the nanoscale by an increase in temperature.

EM Confinement

The QED creation of photons in nanoscale gaps requires complex mathematics [12] that is beyond the scope of this paper. However, the QED physical process is simple to understand. Simply put, QED induces the creation of photons having wavelength λ anytime EM energy is supplied to a QM box with walls separated by $\lambda/2$. For the gap d in near-field heat transfer, the frequency f, wavelength λ, and Planck energy E are,

$$f = \frac{c}{\lambda}, \qquad \lambda = 2d, \qquad E = hf \tag{4}$$

QM and the SB Equation

In the Einstein-Hopf description of QM, surface atoms in gaps d are by definition under EM confinement at wavelength $\lambda = 2d$. Fig. 3 shows the kT energy of surface atoms is only available for $\lambda > 40$ microns or $d > 20$ microns. In gaps < 3 microns, the kT energy is decreased more than 2 orders of magnitude. At nanoscale gaps $d < 1$ micron, it can safely be concluded the heat capacity vanishes for atoms in gap surfaces.

What this means is QM requires surface atoms at ambient temperture to only have thermal kT energy at gaps $d > 20$ microns. For gaps $d < 20$ microns, the surface atoms have thermal energy $< kT$, although the change is gradual. On this basis, conservatively assume the bulk temperatures T_H and T_C extend down to and abruptly change at gap D, say $D = 3$ microns. QED photons at gaps d and D are shown standing between surface atoms of large circles and the dead space d_s denoted by a region of small white circles in Fig. 4.

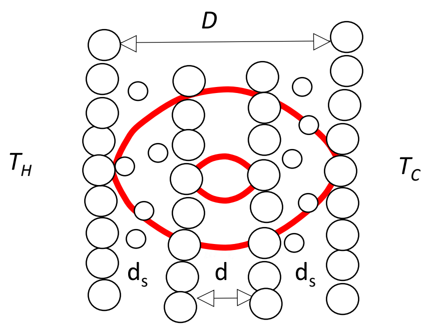

Fig. 4 QM and the SB Equation

The region $d < D$ microns is comprised of the vacuum gap d and dead space $2d_s$ both of which lack heat capacity, the latter being the consequence of QM. Absent heat capacity, thermal conduction is negated as temperatures do not change in the dead spaces, i.e., temperatures in dead space d_s adjacent T_H remain at T_H and those adjacent T_C remain at T_C. However, SB radiation may readily pass through the vacuum and dead spaces. In effect, the lack of heat capacity in the dead spaces d_s increases the vacuum gap from d to $d + 2d_s$ allowing the SB equation (1) to give the same power for all gaps $d < D$,

$$Q_{SB} = \sigma A(T_H^4 - T_C^4) \quad \text{for all } d < D \text{ microns} \qquad (5)$$

Near-field heat transfer derived [2] with Maxwell's equations in comparison to the BB limit (Fig. 1 of [2]) is reproduced in Fig. 5. The Maxwell solutions are observed to exceed the BB limit at $d < 3$ microns and give 3-4 orders of magnitude higher heat transfer at 10 nm. In contrast, QED induced heat transfer (5) remains at the BB limit for all $d < D$ microns, where D is about 3 microns at ambient temperature.

What this means is near-field radiative heat transfer by QED induced radiation follows Planck theory exactly without any enhancement contrary to claims [2, 3] otherwise.

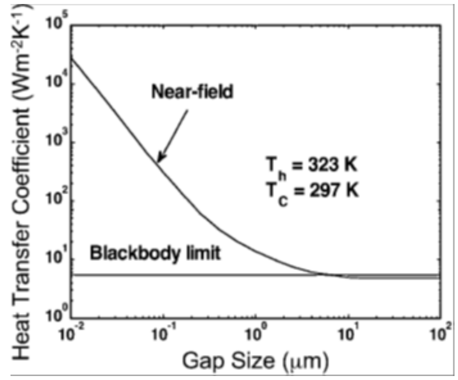

Fig. 5 SB Solutions by Maxwell Equations and QED induced heat transfer

Conservation of EM Energy

Irrespective of the gap $d < D$ microns, the SB power absorbed by the atoms cannot be conserved by an increase in the temperature. Instead, the SB power is conserved by QED creating standing wave photons in the gap d having Planck energy $E = hc/2d$. Single QED photons therefore transfer power q by moving EM energy E of the photon across the gap d at the rate $c/2d$, i.e., the QED photon transfers $q = h(c/2d)^2$. To conserve the SB power, the number density N_P/A of QED photons created,

$$\frac{N_P}{A} = \frac{1}{q}\frac{Q_{SB}}{A} = \frac{4\sigma d^2 (T_H^4 - T_C^4)}{hc^2} \qquad (6)$$

.

The Planck energy E and number density N_p / A of QED photons are shown in Fig. 6.

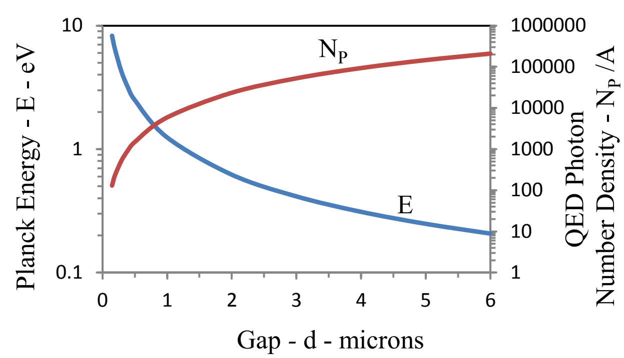

Fig. 6 QED Photon Energy and Number Density

DISCUSSION

Maxwell's Equations and QM

Maxwell's equations provide solutions of EM fields, but in radiative heat transfer a relation between the fields and temperature is required. Traditionally, the FDT satisfies [4] this requirement by relating the oscillations of dipoles to thermal fluctuations, the frequencies of which are given in the QM of Planck's theory by Einstein-Hopf.

QM given by the Einstein-Hopf relation limits the heat capacity of the atom depending on temperature T and the wavelength λ of EM confinement. It is generally accepted [13] that the heat capacity of the atom may be made to vanish by lowering the temperature T to absolute zero. However, cryogenic temperatures are not necessary. Indeed, at ambient temperature, the heat capacity also vanishes if the atom is placed under EM confinement as in the surfaces of nanoscale gaps in near-field heat transfer.

In near-field radiative heat transfer across nanoscale gaps, Einstein-Hopf is indeed included in the solutions [2, 5-7] of Maxwell's equations. Consistent with NIR evanescent waves moving parallel to a free surface, the atom is not under any EM confinement having full kT energy at wavelengths $\lambda > 40$ microns as shown in Fig. 3. However, in a nanoscale gap, the NIR wave normal to the surface is under EM confinement, and therefore the surface atoms are precluded from the heat capacity to produce the temperature fluctuations necessary to satisfy the FDT. Indeed, atoms under EM confinement in nanoscale gaps have virtually no heat capacity compared to the NIR to allow temperatures to fluctuate as required by the FDT.

FDT and Thermal Equilibrium

The near-field enhancement based on Maxwell's equations is questionable because temperature fluctuations in the surfaces of nanoscale gaps as required by the FDT are precluded by QM. However, the argument can be made that the FDT is a QM relation that does not require any temperature fluctuations because the FDT assumes thermal equilibrium (in heat transfer local thermal equilibrium) at a fixed temperature.

However, the argument incorrectly assumes thermal equilibrium occurs at a fixed temperature. A correct statement [7] of the FDT is:

> "In expressing the Poynting vector, the spectral density of the current density is needed… The bridge between the spectral density of the fluctuating current sources and the local temperature of a body is provided by the FDT. It is subjected to the following assumptions: the bodies are in local thermodynamic equilibrium, and equilibrium temperatures T, around which there are fluctuations… the fluctuations are uncorrelated between neighboring volume elements…"

The notion of thermal equilibrium does not mean the temperature is fixed. The fluctuations in local temperature around a point are never fixed, but constantly changing - the average of fluctuations is the local temperature at the point, i.e., the fluctuations define the temperature. Moreover, the neighboring points may have different local equilibrium temperatures.

By QM, the EM confinement of the atoms in the surface of nanoscale gaps precludes any temperature fluctuations, and therefore the equilibrium temperature at a point cannot change. Hence, the FDT is not satisfied and Maxwell's equations are not valid in the near-field.

Similar arguments can be made of the classical wave interference and tunneling analysis [3] that assumed BBs separated by a nanoscale gaps can actually coexist at different temperatures. Like Maxwell's equations, interference and tunneling erroneously assume surfaces separated by a nanoscale gap have distinct and different temperatures are invalid by QM.

SUMMARY AND CONCLUSIONS

The FDT that relates the strength of the oscillations of the dipoles inside a body to temperature fluctuations cannot be *a priori* assumed at the nanoscale. QM precludes atoms under EM confinement between gap surfaces from having the heat capacity necessary to allow temperature fluctuations as required by the FDT to provide valid solutions of Maxwell's equations.

Solutions of Maxwell's equations in near-field heat transfer by evanescent waves showing the BB limit is exceeded are invalid by QM. Maxwell's equations that assume the atom always has heat capacity at the macroscale are simply not valid at the nanoscale.

Given that the heat transfer between BBs is not enhanced by bringing the close together, near–field enhancement by tunneling of evanescent waves may not be realized in practice. Claims that near-field heat transfer that requires nanoscale gaps is verified by experiments may be dismissed because the data reduction assumes surfaces follow bulk temperatures when in fact the temperatures are unknown because the interposed atoms lack the heat capacity allow temperature fluctuations.

In near-field radiative heat transfer, QED induced tunneling is proposed as an alternative to the mechanism of tunneling by NIR evanescent waves. QED induced tunneling allows the SB equation to describe the near-field heat transfer consistent with the BB limit defined by Planck theory.

The QED photons are created as the consequence of the EM confinement of the atoms in surfaces of nanoscale gaps that by QM are precluded from having the heat capacity necessary to conserve absorbed heat by an increase in temperature. Instead, conservation proceeds by the QED induced creation of standing photons at the EM confinement wavelength equal to twice the gap dimension.

Unlike tunneling by NIR evanescent waves, the QED photons tunnel SB power across the gap, although not exceeding the BB limit consistent with Planck theory.

Although QED tunneling does not increase radiative heat transfer beyond the BB limit, the frequency of EM radiation in the gap may be tuned by selecting the gap to be the half-wavelength of the desired radiation. In photovoltaic devices, the BB radiation of any wavelength may be tuned to the wavelength of the peak photocell sensitivity by proper selection of the gap not possible with evanescent waves.

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