# Radiation at the Nanoscale by Quantum Mechanics

Thomas Prevenslik
QED Radiations, Discovery Bay, Hong Kong, CHINA
qedradiation@gmail.com

**ABSTRACT**
Planck's theory of blackbody radiation giving the dispersion of photons with temperature has served well in the radiative heat transfer between surfaces at the macroscale. However, near-field enhancement based on Maxwell's equations is refuted because temperature fluctuations in the surfaces of nanoscale gaps as required by the FDT are precluded by QM. FDT stands for the fluctuation-dissipation theorem and QM for quantum mechanics. Instead, near-field heat transfer proceeds by the QED induced creation of photons from the heat absorbed by surface atoms allowing Planck theory to remain valid at the nanoscale. QED stands for quantum electrodynamics.

## 1. Introduction

Planck's theory [1] of BB radiation giving the dispersion of the EM emission of photons with temperature and wavelength (or frequency) provides the basis for QM. BB stands for blackbody and EM for electromagnetic. At the macroscale, Planck's theory has served well in radiative heat transfer provided the gap or separation between heat transfer surfaces is large compared to the wavelength of the photon emission.

Planck theory is claimed [2] to set an upper limit on radiative heat transfer. But Planck never stated his theory bounded near-field enhancement, although he was surely aware bringing BB surfaces close together does not increase their thermal energy. Today, nanoscale gaps between flat plates are thought [2,3] to provide near–field enhancement of heat transfer exceeding that given by Planck theory. However, difficulty in experiments limits supporting data to micron and not nanoscale gaps, and therefore near-field enhancement relies almost entirely on classical EM analysis of evanescent waves by the Maxwell equations.

## 2. Background

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

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

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

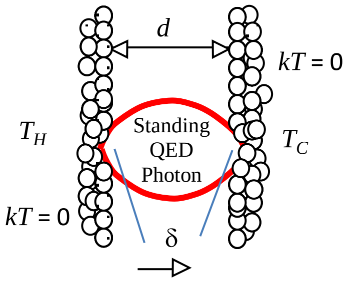
Historically, the FDT in heat transfer [4] related the random movement of dipoles in the Maxwell equations to the temperature of the material. Recently, the FDT is suggested [5-7] for nanostructures allowing classical EM theory to be applied to near-field heat transfer across nanoscale gaps by NIR evanescent surface waves. Consistent with the FDT, 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 from temperature changes by QM. The Maxwell solutions [2,3] show the heat flux to increase inversely with the square of the gap dimension.

However, the argument [8] has been made that as the gap vanishes, the heat flux diverges, and therefore power is not conserved. The counter argument [9] is that divergence of the flux is precluded because thermal contact is established so that the radiative resistance tends to zero, and therefore the heat flux must be finite as there no longer is any temperature difference. As a near-field theory, however, heat transfer by evanescent waves assumes there is always a gap without thermal contact, and therefore the temperature difference remains 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 vanishes are evanescent waves a valid description of nanoscale 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 inverse square of the gap dimension, 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 validity of evanescent waves as radiative heat flux still diverges for lossy materials, thereby placing in question the validity of evanescent waves in near-field heat transfer.

Divergence of near-field heat flux by evanescent waves may be traced to the FDT that inherently assumes [4-7] gap surfaces undergo temperature fluctuations when in fact QM precludes temperature fluctuations in surface atoms because of the EM confinement in nanoscale gaps. Heat absorbed by the gap surface atoms that otherwise is conserved by temperature fluctuations is conserved by the QED induced creation of standing wave photons. What this means is divergence in evanescent theory is an artifact of the invalid assumption of the FDT in the solution of Maxwell's equations. Absent temperature fluctuations, there is no enhancement and Planck's theory is indeed valid in near-field radiative heat transfer.

In this paper, QED induced heat transfer based on standing wave photons is proposed as the mechanism for near-field radiative heat transfer. A single QED photon standing across the gap $d$ is shown in Fig. 1. The QED photon is depicted to penetrate distance $\delta$ into the atoms of the gap surfaces.




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

Fig. 1 Standing QED Photon

## 3. Theory

### 3.1 QM Restrictions

The QM restrictions on the thermal energy of the surface atoms depend on EM confinement given by the Einstein-Hopf relation [11] for the Planck energy $E$ of the atom as a harmonic oscillator is,

$$E = \frac{\frac{hc}{\lambda}}{\exp\left(\frac{hc}{\lambda kT}\right) - 1} \qquad (2)$$

where, $h$ is Planck's constant, $c$ the speed of light, $k$ Boltzmann's constant and $T$ absolute temperature. The Planck energy $E$ with wavelength $\lambda$ is shown in Fig. 2.

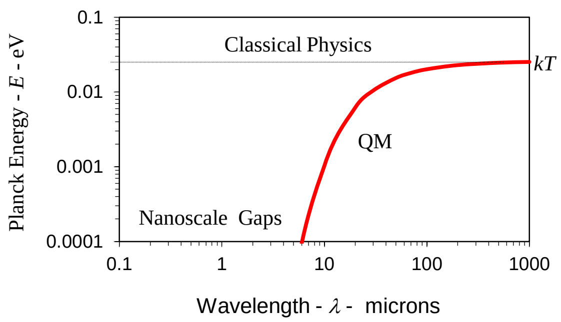



Fig. 2 Atom as a Harmonic Oscillator at 300 K

Classical physics allows the atom to have heat capacity at the nanoscale. QM differs by allowing the atom to only have heat capacity for $\lambda > 50$ microns ($d = \lambda/2 > 25$ microns). Unlike classical physics, QM precludes the atom from conserving absorbed EM energy at the nanoscale by an increase in temperature.

### 3.2 EM Confinement Frequencies

The EM confinement of the QED induced photons in the gap $d$ is analogous to creating photons of wavelength $\lambda$ in a QM box with walls separated by $\lambda/2$. The frequency $f$, wavelength $\lambda$, and Planck energy $E$,

$$f = \frac{c}{\lambda}, \qquad \lambda = 2(d + 2\delta), \qquad E = hf \qquad (3)$$

## 4. Analysis

QM by Planck's theory given by the Einstein-Hopf relation [11] for the harmonic oscillator limits the heat capacity of the atom depending on temperature and the wavelength of EM confinement. Fig. 1 depicts the QED photon standing in gaps $d$ between surfaces having wavelength $\lambda = 2(d+2\delta)$ with the QED photon penetrating to depth $\delta$ in each surface. From Fig. 2, QM requires the heat capacity of the atom to vanish at $\lambda < 6$ microns or $d < d + 2\delta < 3$ microns.

What this means is QM negates the notion of surface temperature in the SB equation for $d < d + 2\delta < 3$ microns, i.e., the SB equation can no longer conserve the radiative heat flow $Q_{SB}$ by the temperatures $T_H$ and $T_C$. Similarly, solutions of Maxwell's equations based on the FDT are negated by QM.

Instead, $Q_{SB}$ is conserved by the QED induced emission of EM radiation from the surface atoms into the gap. $Q_{SB}$ is then induced by QED to create standing wave photons in the gap $d$ having Planck energy $E = hc/\lambda$. A single QED photon therefore transfers heat $q$ by moving EM energy $E$ across the gap $d$ at the rate $c/\lambda$, i.e., the QED photon transfers $q = h(c/\lambda)^2$. The number $N_p$ of QED photons,

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

corresponds to the number of QED photons required to conserve the SB heat flow $Q_{SB}$. Taking $d + 2\delta = 3$ microns to correspond to large gaps where the SB equation is applicable, the heat flow ratio $Q_{qed}/Q_{SB}$ is:

$$\frac{Q_{qed}}{Q_{SB}} = \left(\frac{3}{d + 2\delta}\right)^2 \qquad (5)$$

For $d >> 2\delta$, the ratio $Q_{qed}/Q_{SB}$ increases inversely with the square of the gap $d$ consistent with Maxwell's equations and observed [2,3] in experiments. $Q_{qed}/Q_{SB}$ depends on the QED photon penetration $\delta$ into the surface, but the absorption of quartz [2] and sapphire [3] is not available. For the purposes here, the penetration $\delta$ is taken as, $\delta = w{\cdot}Tr$, where $w$ and $Tr$ are the thickness and transmittance. The sapphire $Tr$ spectrum [12] from the NIR to the UV is given in Fig. 3. For $w = 5$ mm [3], $Q_{qed}/Q_{SB}$ is shown in Fig. 4

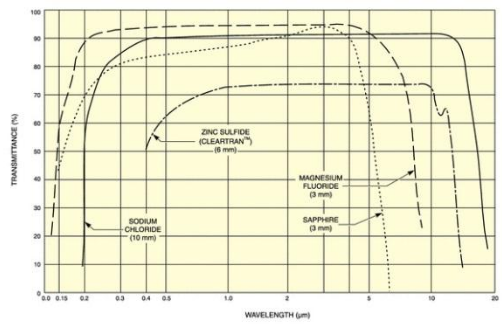



Fig. 3 Transmittance $Tr$ of Sapphire

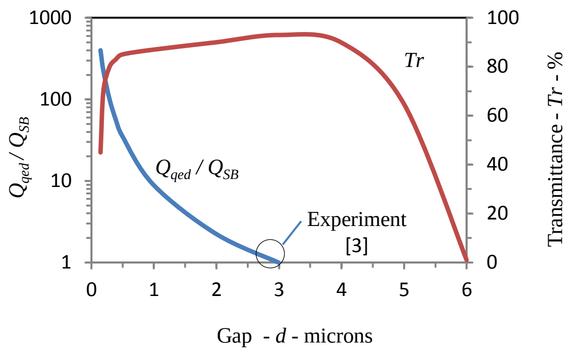



Fig. 4 $Q_{qed}/Q_{SB}$ and $Tr$ for 5 mm Sapphire Plate

The $Q_{qed}/Q_{SB}$ ratio is observed to increase inversely with $d^2$ consistent with Maxwell's equations [2,3] as shown in Fig 4. For sapphire, the UV data is limited to $\lambda = 0.15$ microns corresponding to gap $d = 0.075$ microns shows $Q_{qed}/Q_{SB} \sim 400$. Experimental [3] data at $d = 3$ microns is noted to only be a 50% increase above $Q_{SB}$ and is a very small fraction of $Q_{qed}/Q_{SB}$ at $d < 3$ microns. Over the range of available $Tr$ data, convergence is not observed for sapphire. However, materials other than sapphire may show $Q_{qed}/Q_{SB}$ to converge if $Tr$ increases at $\lambda < 0.15$ microns.

QED radiation conserves BB radiation by creating standing QED photons in the gap. For the sapphire plates [3] having area $A$ = 50 x 50 mm$^2$, the Planck energy $E$ and number $N_P$ of QED photons with gap $d$ are shown in Fig. 5. Gaps $d < 0.25$ microns create UV photons while NIR photons are formed at larger gaps in greater numbers.

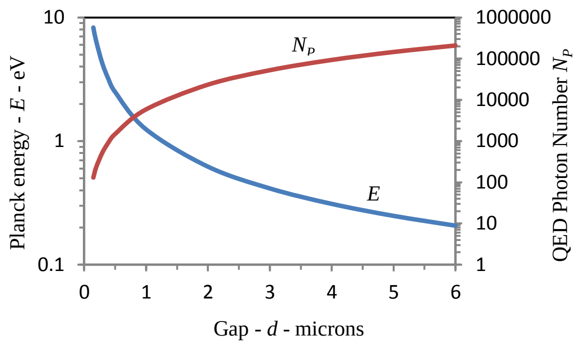



Fig. 5 QED Photon Planck Energy $E$ and Number $N_P$

**5. Discussion**

5.1 Conservation of BB Power

QED induced heat transfer predicts near-field heat flux to increase inversely with $d^2$ consistent with evanescent theory.

But is BB power conserved?

In QED theory, the standing photons are created by conserving the BB radiation from surface atoms in the gap surfaces, and therefore BB power is conserved. However, only QED photons having wavelength $\lambda < 2d$ are allowed in the gap, the Planck energy $E$ of which is given in Fig. 5. QED creates photons of energy $q$ for a given gap $d$ with the necessary number $N_P$ by conserving the BB power.

In Fig. 4, the ratios $Q_{qed}/Q_{SB} > 1$ do not mean thermal energy is created by simply bringing the surfaces of bodies close to each other. It is misleading to consider Equation (5) to standalone as the number $N_P$ of QED photons needs to be included. The correct interpretation is given in Equation (4) that shows the product $qN_P$ is conserved with the BB power. BB power conservation in the near-field is not violated by QED.

In contrast, BB power conservation in near-field radiative heat transfer by evanescent waves [8-10] has been controversial for over the past decade and is not discussed further. It suffices to say that thermal energy cannot be created by bringing bodies close to each other.

5.2 Near-field Heat Transfer Mechanism

Mainstream near-field theory [2-7] relies on the evanescent mechanism of NIR surface waves to transfer heat by tunneling across nanoscale gaps. However, analytical support based on solutions of the Maxwell equations is questionable because of the invalidity of the FDT by QM. In contrast, QED induced heat transfer based on photons standing in the gap is a QM argument independent of Maxwell's equations.

Indeed, Planck considered photons to transfer radiation between surfaces separated by gaps larger than the wavelength of the emitted thermal radiation. However, only high frequency photons having wavelength $\lambda < 2d$ may "fit in" nanoscale gaps. But BB radiation at ambient temperature contains few, if any, high frequency photons.

How then are the photons created?

Atoms in the surfaces of nanoscale gaps under EM confinement are negated from having heat capacity by QM. Fig. 2 shows that photon wavelengths $\lambda < 6$ microns (or gaps $d < 3$ microns) have Planck energy $E < 0.0001$ eV, more than 250 times smaller than $kT$. Effectively, the atom has no capacity to absorb heat.

What this means is heat from the adjacent hot and cold regions that flows into or from the gap cannot be conserved by fluctuations in temperature of the surface atoms. At ambient temperature, Fig. 2 shows the extent of atoms lacking heat capacity corresponds to wavelengths < 6 microns or within 3 microns of gap surfaces. Instead, the heat is conserved by the QED induced creation of photons under the EM confinement imposed by the gap, the standing wave photons thereby acquiring wavelengths $\lambda$ depending on the gap dimension $d$, i.e., $\lambda = 2d$.

Compared to near-field heat transfer by evanescent waves, the QED mechanism based on the conservation of BB power is far simpler and does not require the difficult and complex solutions [2,3] of Maxwell's equations that otherwise are negated by the invalidity of the FDT.

5.3 Maxwell 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 [4-7] 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 the Einstein-Hopf relation [11].

In near-field radiative heat transfer across nanoscale gaps, the QM restriction [11] is indeed included in the solutions [2,3] to the Maxwell's equations as excitation frequencies of the evanescent waves, the dominant wavelengths of which are predicted by Wien's law are in the NIR at about 10 microns at ambient temperature. However, the same QM restriction is not placed on the validity of the FDT applied to atoms in the gap surfaces that are under EM confinement at nanoscale wavelengths. At 300 K, Fig. 2 shows atoms under EM confinement at the nanoscale have virtually no heat capacity compared to the NIR to allow temperatures to fluctuate as required by the FDT.

The QM restriction on the FDT in the solution of Maxwell's equations of near-field heat transfer (Eqn. 23a of [6]) may be understood from the Maxwell heat flux $Q$,

$$Q \approx \frac{1}{\pi^2 d^2} \frac{\mathrm{Im}(\varepsilon_H)\mathrm{Im}(\varepsilon_C)}{|(\varepsilon_H+1)(\varepsilon_C+1)|^2}\left[\Theta(\omega,T_H)-\Theta(\omega,T_C)\right] \quad (6)$$

where, $\Theta$ is the frequency form of the Einstein-Hopf relation in Eqn. (2) and $\omega$ is the circular frequency, $\omega = 2\pi hc/\lambda$. $\varepsilon_H$ and $\varepsilon_C$ are the complex permittivity of the hot and cold surfaces, the imaginary parts of which are designated by Im.

Since FDT is not satisfied for atoms in nanoscale gap surfaces, the effect on the Maxwell heat $Q$ in near-field heat transfer may be assessed from Eqn. (6) by taking both $\Theta(\omega,T_H)$ and $\Theta(\omega,T_C)$ to vanish. Hence, $Q$ also vanishes independent of whether the materials are lossy or have imaginary permittivity. Effectively, the FDT filters the NIR evanescent frequencies allowing only those at high frequency in nanoscale gaps. E.g., the Maxwell heat $Q$ as a function of frequency $\omega$ in (Fig. 1a of [7]) shows the BB peak at about 6 microns is significantly reduced by FDT filtering to evanescent waves having frequencies at submicron wavelengths.

What this means is Planck's theory does indeed limit near-field radiative heat transfer contrary to claims [2] otherwise. However, QM restrictions on the FDT are not included in solutions [13] of Maxwell's equations of nanostructures. In this regard, a review of the FDT is recommended.

## 6. Summary and Conclusions

QED induced heat transfer comprising standing wave photons is proposed to supersede the tunneling of NIR evanescent waves as the mechanism for near-field radiative heat transfer at the nanoscale.

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 the photon tunneling in evanescent waves by NIR surface waves, the QED induced photons directly stand across the gap, thereby allowing near-field radiative heat transfer to proceed by Planck theory.

The FDT relates the strength of the oscillations of the dipoles inside a body to the temperature fluctuations cannot be assumed in the solution of Maxwell's equations because QM precludes atoms in the surfaces of gap surfaces to respond to absorption of heat by changes in temperature.

Solutions of Maxwell's equations in near-field heat flux by evanescent waves showing Planck theory is exceeded are unphysical because the FDT is no longer valid at the nanoscale. Temperature fluctuations in gap surfaces as the measure of dipole motions are precluded by QM because of EM confinement.

QED induced heat transfer predicts a single QED photon in the near-field to increase inversely with the square of the gap consistent with Maxwell's equations, but it is misleading to conclude that the total power diverges because the number of QED photons also decreases. BB power conservation in the near-field is conserved and not violated in QED theory.

Given that the thermal energy of a body is not increased by bringing it close to another body, near–field enhancement by tunneling of evanescent waves simply does not exist. Instead, conservation of EM energy proceeds by QED induced heat transfer, and therefore Planck's theory is indeed an upper bound to near-field radiative heat transfer at the nanoscale.

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