Radiation at the Nanoscale by Quantum Mechanics

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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 questionable because temperature fluctuations in the surfaces of nanoscale gaps as required by the fluctuation-dissipation theorem are precluded by quantum mechanics. Instead, near-field heat transfer proceeds by the creation of photons from the thermal energy of surface atoms by quantum electrodynamics allowing Planck theory to remain valid at the nanoscale. Similarities of near-field heat transfer with the Hartman effect and the thermal Casimir force are presented.

Keywords: Near-field radiative heat transfer; Maxwell equations; quantum mechanics; Planck; Einstein-Hopf; fluctuation dissipation theorem, Hartman effect, thermal Casimir

1. Introduction

Planck's theory [1] of BB radiation giving the dispersion of the EM emission of photons with temperature and wavelength (or frequency) provided the basis for QM. BB stands for blackbody, EM for electromagnetic, and QM for quantum mechanics. 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.

Recently, Planck theory is claimed [2] to set an upper limit on radiative heat transfer. But Planck never stated his theory bounded near-field heat transfer, although he was surely aware bringing BBs close together does not increase their thermal energy. Today, tunneling through nanoscale gaps by evanescent waves is thought [2,3] to enhance of heat transfer by 3-4 orders of magnitude above the BB limit given by Planck theory. However, difficulty in experiments limits supporting data to micron and not nanoscale gaps, and therefore claims of near-field enhancement by evanescent waves rely almost entirely on classical EM wave analysis by the Maxwell equations.

2. Purpose

The support of near-field radiative heat transfer by evanescent waves by solutions of Maxwell's equations is questioned because the FDT may not be satisfied for atoms in the gap surfaces. FDT stands for fluctuation dissipation theorem. Instead of evanescent waves, near-field heat transfer is proposed to proceed by QED induced tunneling. QED stands for quantum electrodynamics.

3. 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},

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

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 [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 [3-7] show the near-field heat flux to vary inversely with the square of the gap d dimension, e.g., the Maxwell heat flux Q (Eqn. 23a of [6]).

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

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. 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. However, as a near-field theory, 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 vanishes do evanescent waves provide 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 $1/d^2$ 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 than divergence 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 (1) 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 having vanishing $\Theta(\omega,T)$ in nanoscale gaps.

On the other hand, the Maxwell's equations follow classical physics and permit the surface atoms to fluctuate in temperature consistent [7] with the mainstream assumption for deriving the evanescent heat flux Q between BB surfaces. To illustrate the differences between QM and classical physics, consider the Maxwell solution for between surfaces at 800 and 200 K given by the heat flux $q_{\omega,1\rightarrow 2}^{Net}$ shown in (Fig. 1a of [7]) and reproduced in Fig. 1.

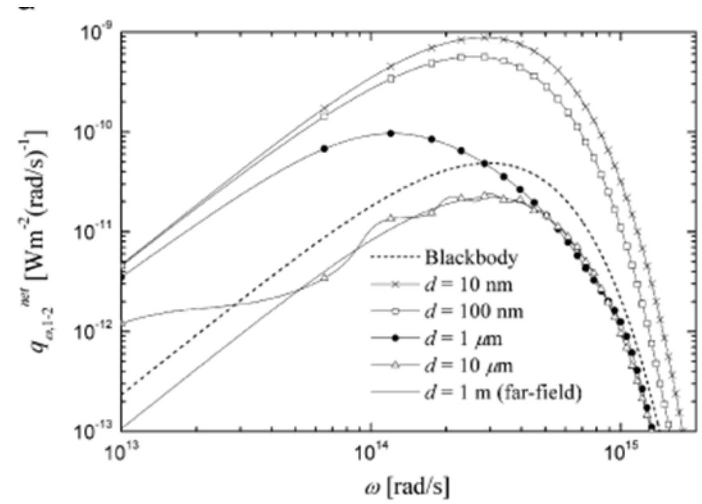

Fig. 1 Maxwell Solutions for Evanescent Waves between Surface Temperatures 800 and 200 K

The Maxwell solutions for gaps d = 100 and 10 nm gaps give peak heat fluxes $q_{\omega,1\rightarrow2}^{Net}$ = 5x10^{-10} and 10^{-9} W/m^2/rad/s at angular frequency ω = 3x10^{14} rad/s as shown in Fig. 1. At this frequency, the evanescent wave is in the NIR having wavelength 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 may not be valid to support the claim that evanescent tunneling enhances near-field heat flux above that of BB radiation.

In the following, the QED alternative to evanescent tunneling in near–field radiative heat transfer is presented for consideration and review.

4. QED Theory

Divergence of near-field heat flux by evanescent waves (2) 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 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 if so, what is the mechanism that allows the SB equation to be valid in the near-field?

In this paper, 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.

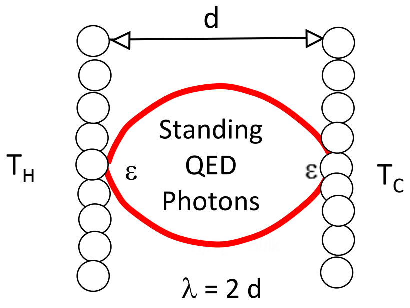

Fig. 2 QED Tunneling by Standing Wave Photons

The QED photon having wavelength λ = 2(d+2ε) is depicted to penetrate distance ε into the atoms of the gap surfaces. For ε << d, λ = 2d.

4.1 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 in Fig. 3.

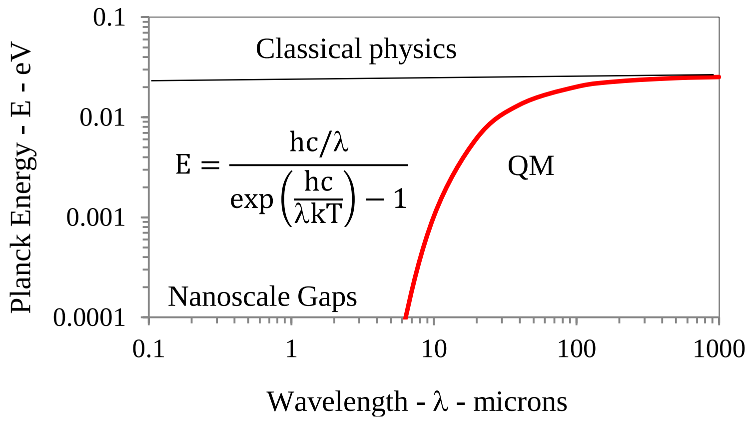

Fig. 3 Atom as a Harmonic Oscillator at 300 K
In the inset: h is Planck's constant, c the speed of light, k Boltzmann's constant,
and T absolute temperature.

Classical physics depicted as 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 > λ/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. Lacking heat capacity, atoms in gap surfaces cannot change in temperature under radiative heat transfer. Unlike classical physics, QM precludes the atom from conserving absorbed EM energy at the nanoscale by an increase in temperature.

4.2 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 λ/2. For the gap d in near-field heat transfer, the frequency f, wavelength λ, and Planck energy E are,

$$f = \frac{c}{\lambda}\,, \qquad \lambda = 2d, \qquad E = hf \tag{3}$$

4.3 QM and the SB Equation

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 the Einstein-Hopf description of QM, surface atoms in gaps d are by definition under EM confinement at wavelength λ = 2d, the consequence of which is the kT energy of surface atoms in gaps < 3 microns is decreased more than 2 orders of magnitude. At nanoscale gaps d < 1 micron, it can safely be concluded the heat capacity of surface atoms vanishes.

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.

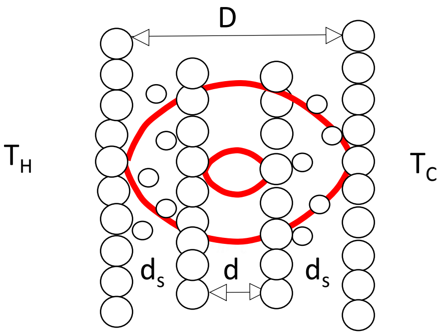

Fig. 4 QM and the SB Equation

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. Lacking 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 + $2d_s$ but otherwise the SB power remains the same. What this means is the SB equation (1) gives the same power for all gaps d < D,

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

4.4 Conservation of 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,

$$\frac{N_P}{A} = \frac{1}{q}\frac{Q_{SB}}{A} = \frac{4\sigma d^2\left(T_H^4 - T_C^4\right)}{hc^2} \tag{5}$$

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The Planck energy E and number density N_p / A of QED photons are shown in Fig. 5.

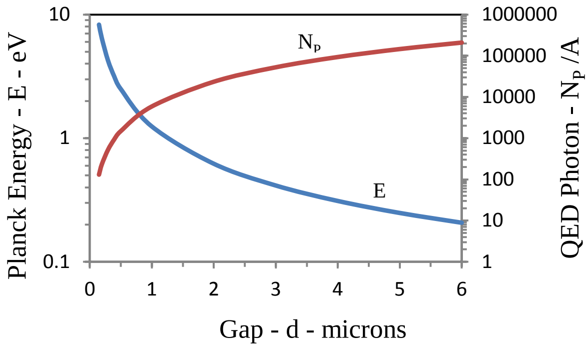

Fig. 5 QED Photon Energy and Number Density

5. Discussion

5.1 Maxwell Equations and QM

5.1.1 Background

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 Einstein-Hopf.

In near-field radiative heat transfer across nanoscale gaps, Einstein-Hopf is indeed included in the solutions [2-3,6-7] of Maxwell's equations. Consistent with NIR evanescent wave moving parallel to a free surface, the atom is not under any EM confinement having full kT energy at wavelengths λ > 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.

5.1.2 QED Induced Radiation

Near-field heat transfer derived [2] with Maxwell's equations in comparison to the BB limit (Fig. 1 of [2]) is reproduced in Fig. 6. 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 (4) remains at the BB limit for all d < D microns, where D is about 3 microns.

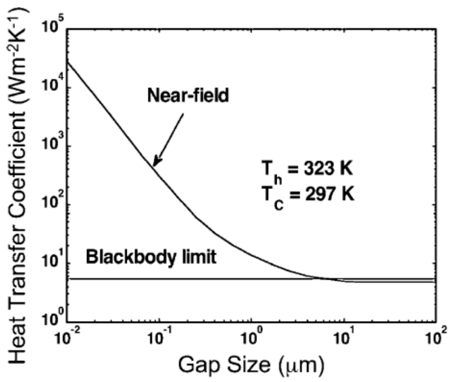

Fig. 6 Near-field and QED induced Heat Transfer

What this means is Planck's theory does indeed limit near-field radiative heat transfer contrary to claims [2] otherwise. QM restrictions on the FDT are recommended in solutions of Maxwell's equations of nanostructures.

5.2 Evanescent Waves and QED Tunneling in Double Prisms

5.2.1 Background

Evanescent wave and QED tunneling in near-field radiative heat transfer find similarity with the tunneling of light between double prisms. It is instructive therefore to view tunneling of BB radiation in the near-field from the broader perspective of tunneling of light.

For over 50 years, the Hartman effect [14] has suggested superluminal velocities may be found in the gap between double prisms. When the prisms are in contact, the light passes straight through, but when there is a gap, the light may either tunnel across or follow the refracted path. Since the time for light to travel across large gaps is found to be the same as for short gaps, the Hartman effect has been interpreted to suggest photons have crossed the gap with superluminal velocity.

In QM tunneling, the Schrodinger equation is used to determine the probability of a particle of energy E incident on a potential barrier V to pass through the barrier, where $E < V$. In classical physics, the particle is totally reflected by the barrier. However, QM differs in that there is a finite, although small, probability that the particle will tunnel through the barrier. However, QED tunneling used to explain near-field heat transfer may also explain the Hartman effect without invoking the Schrodinger equation.

In this regard, Winful [15] argued non-propagating evanescent waves are virtual photons that do not propagate into the outside world. Since the velocity of non-propagating waves is meaningless, the light in the Hartman effect cannot travel at superluminal velocities, but rather only be delayed. However, if the delay time is interpreted as a transit time then the Hartman effect naturally leads to the conclusion that superluminal velocities occur in double prisms.

On the other hand, if the delay in tunneling is the time for accumulating incident photon energy until the barrier can be breached, the Hartman effect may be explained [15] by the saturation of incident photon energy in the barrier. The delay is then the time for the flux of incident photons to saturate before the barrier is breached. Because of this, the Hartman effect may be explained by the saturation of accumulated energy without the need for superluminal velocities.

Regardless, Winful's argument of the time delay for stored energy of evanescent waves necessary to breach the barrier alone is insufficient. Non-propagating evanescent waves cannot propagate irrespective of whether the accumulated energy can breach the barrier. What this means is tunneling of photons through the double prism gap occurs by a more fundamental mechanism that creates real photons from accumulated energy that are indeed capable of propagating to the outside world.

Evanescent waves are not this mechanism, but rather are only a way of supplying EM energy of incident photons to the gap.

5.2.2 QED Tunneling

Similar to QED induced radiative heat transfer; QED provides a way of creating photons from the accumulated EM energy of evanescent waves in the gap. Like QED induced heat transfer, the double prism having resonant wavelength 2d corresponds to a barrier having Planck energy $E_B = hc/2d$. Since the single incident photon with wavelength λ has Planck energy $E = hc/\lambda$, and since $E < E_B$, the incident photon cannot breach the barrier. However, the absorbed EM energy from a number N of incident photons accumulates in the QED cavity until the barrier is breached. At saturation, the number N of incident photons, $N = E_B /E = \lambda/2d > 1$.

QED tunneling by the creation of propagating QED photons supports Winful's interpretation of the Hartman effect by the saturation time of stored incident photon energy in the barrier. Unlike evanescent photons that cannot propagate across the gap, the QED photons not only propagate across the gap, but travel beyond into the outside world. Assuming the Planck energy E of a single incident photon is localized in the QED cavity in time 2d/c, the time t* to create a QED photon from N incident photons is, $t^* = 2Nd/c = \lambda/c$. Consistent with the Hartman effect, the time t* therefore tends to a constant independent of the gap d while depending only on the wavelength λ of the incident photons. However, for $\lambda < 2d$, there is no QED cavity effect with the incident photons localizing in the gap in their natural time, $t^* = \lambda/c$.

Verification of QED tunneling in a double prism may be found in experiments [16] using microwave photons having wavelength λ = 32.8 mm. The Goos-Hanchen (GH) shift reproduced from (Fig. 4 of [17]) is shown in Fig. 7.

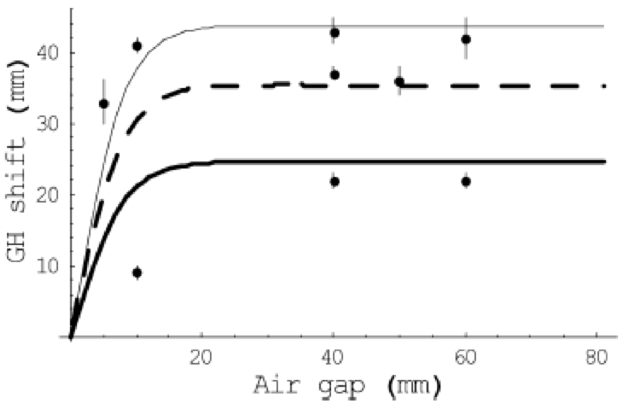

Fig. 7 GH plot of saturation in QED Tunneling through Double Prisms
Legend: 60 mm (thin), 80 mm (dashed), and 120 mm (thick)

GH saturation is reasonably bracketed by QED theory. Fig. 7 shows saturation to occur in air gaps d from 15 to 17 mm for the 60 and 80 mm diameter beams. Setting aside the anomalous data point at d ~ 15 mm for the120 mm beam, QED theory for the 60 and 80 mm beam diameters gives, $0.96 < N < 1.09$.

QED conversion of EM energy from non-propagating evanescent waves to propagating photons that can interact with the outside world need not be limited to the Hartman effect. In this regard, BB thermal radiation is thought to transmit radiation across nanoscale gaps $d << \lambda$ by evanescent waves. Unlike incident photons from an external laser in the double prism, atoms in the surfaces of nanoscale gaps are physically part of the QED cavity, and therefore the surface atoms naturally supply the EM energy needed by QED to create standing wave photons that transfer radiation across the gap. Indeed, QED tunneling in micron gaps may provide a more practical solution in near-field radiative heat transfer than the nanoscale gaps required for evanescent tunneling, e.g., thermal photovoltaic cells having peak efficiency at wavelength $\lambda > 1$ micron may be tuned by selecting gaps $d = \lambda/2$ instead of nanoscale gaps required by evanescent waves.

5.3 Thermal Casimir

5.3.1 Background

In 1948, Casimir by extending the ZPE of QM to the field derived the force between neutral plates separated by a gap. ZPE stands for zero point energy. For flat plates sometimes called perfect mirrors, the ZPE force varies with $1/d^4$. Recently, the thermal Casimir force at ambient temperature was claimed [18] observed for the first time at Yale. With a pendulum with contact made between a sphere and flat plate, the thermal Casmir or ZPE forces are required to vary by $1/d^3$ and not $1/d^4$. It is important to note the thermal Casimir force only depends on temperature and otherwise is independent of the ZPE.

Only later in 1955 did Lifshitz [19] predict the existence of the thermal Casimir force. Like Casimir, Lifshitz only considered the force between neutral plates. The thermal Casimir forces derived with Lifshitz theory are the Drude and Plasma models having different dielectric properties for the plate materials, the correctness [20] of which is controversial. Regardless, the Yale experiment showed significant electrostatic forces that had to be removed to obtain what was thought to be the neutral thermal Casimir force. To compensate the unwanted electrostatic forces, a servo-controlled minimizing potential was used during force measurements.

For large gaps, the thermal Casimir force was found to decrease by $1/d^2$. However, for small gaps, the expected $1/d^3$ force for point to flat contact was not observed. Instead, the force decreased by $1/d^4$ suggesting the affirmation of ZPE Casimir force for perfect mirrors. In large gaps, the ZPE Casimir force is far smaller than the thermal Casimir force, and therefore the higher than expected measured force was therefore interpreted as the thermal - not the ZPE Casmir force.

Lifshitz theory for the thermal Casimir force does not predict the charging of neutral surfaces separated from each other by gaps. Similarly, charging of neutral plates is not predicted in Casimir's theory of the ZPE Casimir force. Since 1948, however, Casimir experiments including MEMS and semiconductors in photolithography unequivocally show charge is created upon bringing otherwise neutral surfaces close to each other.

Subsequent to the Yale experiment, the thermal Casimir force was measured [21] at 4.2 K in the Grenoble experiment. The AFM tests showed Lifshitz theory to predict 50% lower thermal Casimir force than measured. AFM stands for atomic force microscope. Like the Yale experiment at ambient temperature, significant charge was created that is not included in Lifshitz theory. Regardless, absent a theory that predicts charge creation in submicron gaps between neutral surfaces, the 50% discrepancy between Lifshitz theory and experiment cannot be explained.

5.3.2 QED Induced Electrostatic Force

The QED induced electrostatic force is proposed to explain both the ZPE and thermal Casimir force in the Yale and Grenoble experiments. The QED force like Lifshitz theory has a thermal origin, but differs in that it is based on the thermal kT energy of atoms in the gap surfaces. Although both surfaces are at the same temperature, the mechanism of QED photon creation is the same for QED induced heat transfer in the near –field depicted in Fig. 2.

Like QED induced heat transfer in the near-field, the QED force is the consequence of inducing the thermal kT energy of atoms in the plate surfaces to create photons that charge the plates by the photoelectric effect. Since the QED photons in the ZPE and thermal Casimir force have Planck energy E = hc/2d, and since the quantum yield of the gold contact surfaces requires QED photons having E > 5 eV, charging may only occur for gaps d < 0.2 microns.

In correcting for the unwanted electrostatic forces, both Yale and Grenoble experiments used a servo to impose a voltage to minimize the potential across the gap during force measurements. In this way, it was thought removal of the electrostatic force would leave the neutral thermal Casimir force alone to be measured. However, the QED photons created at gaps d < 0.2 microns have high Planck energy leaving residual charges trapped beneath the surface that cannot easily be removed by minimizing potentials of a few 100 mV.

In the Grenoble experiment, the QED force for Au-Au surfaces measured at 4.2 K is shown in Fig. 8. The data depicted as a dashed red line is coincident with the QED force but is displaced downward for clarity. The colors are shown on-line. The classical electrostatic $1/d^2$ force is shown as a green solid curve. The QED force is coincident with the $1/d^4$ curve for d < 600 nm, but for clarity is only shown for d > 700 nm as a solid red line. At large gaps d > 700 nm, the QED force produced under servo-control is higher than the classical electrostatics force. Hence, what is thought to be the thermal Casimir force is actually the QED force

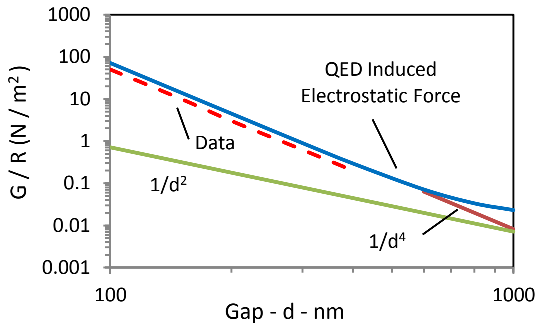

Fig. 8 Thermal Casimir and QED induced Electrostatic Force

The Yale experiment at 300 K is similar to the Grenoble experiment at 4.2 K in that the unwanted electrostatic forces are compensated by servo-control of the minimizing potential. At small gaps, the force varied as $1/d^4$ instead of the expected $1/d^3$; whereas, the $1/d^2$ variation was observed in large gaps. What was thought to be the thermal Casimir force is in fact the QED force. The controversy whether the Drude or Plasma force is the correct thermal Casimir force is resolved – neither is. Neither Lifshitz nor Casimir theories can explain the observed force behavior. Lifshitz theory that does ot predict charge in otherwise neutral surfaces is simply not applicable to the derivation of the thermal Casimir force.

In this regard, near-field radiative heat transfer should be expected to produce charge in nanoscale gaps and induce electrical breakdown. Charge is of significance in ZPE and thermal Casimir force experiments and because of the similarity with QED tunneling should be no different in heat transfer at the nanoscale. Indeed, damage to nanoscale gap surfaces from electrical discharge may very well be the Achilles heel that limits the practical application of evanescent waves as a heat transfer mechanism in near-field heat transfer.

6. Summary and Conclusions

In near-field radiative heat transfer, QED induced tunneling is proposed as an alternative to the mechanism of tunneling by NIR evanescent waves.

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.

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 in the 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 flux by evanescent waves showing the BB limit is exceeded are most likely 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 thermal energy of a body is not increased by bringing it close to another body, near–field enhancement by tunneling of evanescent waves may not be realized in practice. In the alternative, QED induced tunneling allows the SB equation to describe the near-field heat transfer consistent with the BB limit defined by 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.

Similarity of QED induced heat transfer in the near-field is found with the Hartman effect and the thermal Casimir force both of which convert EM energy in nanoscale gaps to QED photons. In the Hartman effect, the EM energy of evanescent waves is converted by QED to real photons that can be transmitted to the outside world; whereas, in Casimir forces, the electrostatic attraction between metal plates is produced from the QED conversion of the thermal energy of surface atoms to photons that charge the plates by the photoelectric effect. Damage of surfaces found in Casimir experiments should by similarity be considered in the design-life of near-field heat transfer prototypes.

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